Jamming-Aided Secure Communication in Massive MIMO Rician Channels

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Abstract—In this paper, we investigate the artificial noise-aided jamming design for a transmitter equipped with large antenna array in Rician fading channels. We figure out that when the number of transmit antennas tends to infinity, whether the secrecy outage happens in a Rician channel depends on the geometric locations of eavesdroppers. In this light, we first define and analytically describe the secrecy outage region (SOR), indicating all possible locations of an eavesdropper that can cause secrecy outage. After that, the secrecy outage probability (SOP) is derived, and a jamming-beneficial range, i.e., the distance range of eavesdroppers which enables uniform jamming to reduce the SOP, is determined. Then, the optimal power allocation between messages and artificial noise is investigated for different scenarios. Furthermore, to use the jamming power more efficiently and further reduce the SOP, we propose directional jamming that generates jamming signals at selected beams (mapped to physical angles) only, and power allocation algorithms are proposed for the cases with and without the information of the suspicious area, i.e., possible locations of eavesdroppers. We further extend the discussions to multiuser and multi-cell scenarios. At last, numerical results validate our conclusions and show the effectiveness of our proposed jamming power allocation schemes.

Index Terms—Jamming, massive MIMO, outage, security.

I. INTRODUCTION

Massive multiple-input multiple-output (MIMO) systems, where an enormous number of antennas are deployed at the base station, have become a hot research area in recent years [1], [2]. As the number of antennas goes to infinity, the effect of uncorrelated interferences and noises can tend to zero asymptotically by using only simple linear transmit/receive techniques [3], leading to intensive growth in spectrum and power efficiency [4]. When used for beamforming, massive MIMO leads to sharp beam patterns as well as low power leakage to unintended directions [5]. Due to these attractive properties, massive MIMO becomes a promising technique for future communication systems such as the fifth generation cellular system [6]. In the meanwhile, it can be anticipated that massive MIMO will also become crucial in security related applications.

Secure communication in wiretap channels has been studied for decades since the seminal work [7]. Corresponding studies have been further extended to different type of wiretap channels [8], [9], fading channels [10], [11], MIMO channels [12]–[15], and networks [16], [17]. The research topics span a wide range from information-theoretical contributions such as secrecy capacity analysis and rate region characterization to practical transmission design issues including precoding, user scheduling, and artificial noise (AN)-aided jamming. For a complete review of the most lately approaches, see [18], [19]. Regarding the communication secrecy, the emergence of the massive MIMO technique brings new opportunities and challenges. Recently, physical layer security techniques using massive MIMO have drawn increasing attentions in the literature. In [20]–[23], the secrecy rate in massive MIMO systems has been analyzed using large system analysis and secure precoding schemes were designed. In [24], [25], it has been shown that massive MIMO can benefit the detection of active eavesdropper who performs attacking on the channel training phase [26]. Note that the above-mentioned approaches require either the channel state information (CSI) of eavesdroppers can be known, or their existence can be detected. For the scenarios that eavesdroppers are completely passive and their CSI is unknown, AN-aided jamming [27] can be a feasible solution. Only recently, the AN-aided jamming approach has been applied for massive MIMO systems in [28], [29] and was shown to be beneficial for communication secrecy.

In this paper, we study the secure communication in massive MIMO systems via AN-aided jamming. Differently from [28], we consider the scenario that eavesdroppers are randomly located around a legitimate transmitter equipped with large antenna array, and all channels follow Rician distribution. In this case, the geometric locations (described by both the angle of arrival and distance to the transmitter) of the legitimate receivers and eavesdroppers become essential in the secrecy outage analysis, which highlights the main difference between our work and [28]. The motivation of our paper is based on the following considerations: 1) Since the beam towards the legitimate receiver becomes sharper and the power leakage to other directions becomes trivial in massive MIMO systems, it is doubtful whether jamming is still beneficial for secrecy,
and 2) as the number of antennas grows, the dimension of the jamming space increases and jamming power needs to spread over a large number of directions, which makes conventional uniform jamming inefficient with massive MIMO. Regarding these issues, two questions are raised:

1) Does conventional uniform jamming still benefit the secure communication in massive MIMO systems when \( N_t \) goes to infinity?
2) Is there more efficient scheme rather than uniform jamming in the massive MIMO setup?

In this paper, we will answer these two questions by making the following contributions:

- For the massive MIMO Rician fading channels, we analytically describe the secrecy outage region (SOR) as geometric locations of eavesdroppers that can induce secrecy outage. The concept of SOR further has been used to characterize the secrecy outage probability (SOP).

- With the information of the suspicious area where eavesdroppers are possibly located, we derive analytical expression of the SOP in the presence of one legitimate receiver and multiple passive eavesdroppers. After that, it is proved that conventional uniform jamming is still useful in terms of reducing the SOP when any eavesdroppers are located within a certain distance range to Alice, which we call it as the jamming-beneficial range.

This conclusion provides an answer to the first question.

- For uniform jamming, the optimal signal and jamming power allocation is investigated for different scenarios. We further devise practical directional jamming algorithms, either with or without the information of the suspicious area. The proposed directional jamming schemes use the jamming power more efficiently to further and substantially reduce the SOP, which provides answers to the second raised question.

The rest of this paper is organized as follows: Section II provides system model. Section III describes the SOR, further provides an analytical expression of SOP and a jamming-beneficial range. Optimal jamming power allocation is studied for uniform jamming in Section IV, and in Section V, directional jamming algorithms are proposed. In Section VI, the SOR is discussed for multiuser and multi-cell scenarios. Section VII concludes this paper.

II. SYSTEM MODEL

In this section, we first present the network model. As an important concept in subsequent analysis, we further define the normalized crosstalk between two wireless links and introduce its characteristics. Then, the AN-aided secure transmission and the definition of SOP are described.

A. Network Model

We consider the network shown in Fig. 1 where a transmitter (Alice) equipped with \( N_t \) antennas transmits to a single-antenna user (Bob) in the existence of \( L \) external passive single-antenna eavesdroppers (Eves 1, ..., \( L \)). Alice uses beamforming for the data transmission to Bob, while jamming with AN in other spaces (or directions). We define the set of receivers \( \mathcal{I}_r = \{b, e_1, ..., e_L\} \) where \( b \) denotes Bob and \( e_l \) \((l = 1, ..., L)\) denotes Eve \( l \). Considering Rician fading, the channel between Alice and receiver \( i \) is given by

\[
\mathbf{h}_i = \sqrt{\frac{K_i}{1 + K_i}} \mathbf{h}_i + \sqrt{\frac{1}{1 + K_i}} \mathbf{g}_i, \quad \forall i \in \mathcal{I}_r
\]

where \( K_i \) is the Rician K-factor, \( \mathbf{g}_i \in \mathbb{C}^{N_t \times 1} \) is the i.i.d. fast fading part whose elements follow \( \mathcal{CN}(0, 1) \) distribution (complex normal distribution with zero mean and unit variance). For uniform linear array with inter-antenna spacing \( d_0 \) (in wavelength), the line of sight (LOS) component \( \mathbf{h}_i \) can be written as the steering vector at incident angle \( \theta_i \):

\[
\mathbf{h}_i = \mathbf{s}_i(\theta_i) = \left(1, e^{-j2\pi d_0 \sin \theta_i}, ..., e^{-j2\pi(N_t-1)d_0 \sin \theta_i}\right)^T
\]

where \( \theta_i \) is the LOS angle of receiver \( i \). In addition, we consider large scale fading \( d_i^{-\alpha} \) where \( d_i \) is the distance from Alice to receiver \( i \), and \( \alpha \) is the path loss coefficient.

We consider a practical scenario that Eves are uniformly distributed within an angular range \( \mathcal{A}_e \triangleq [\theta_{\text{min}}, \theta_{\text{max}}] \) and a distance range \( \mathcal{D}_e \triangleq [D_{\text{min}}(\theta_e), D_{\text{max}}(\theta_e)] \), where \( D_{\text{min}}(\theta_e) \) and \( D_{\text{max}}(\theta_e) \) are functions of \( \theta_e \in \mathcal{A}_e \), defining two borders of this area. Throughout this paper, we use

\[
\mathcal{R}_{\text{sus}} \triangleq \{(\theta_e, d_e) \mid \theta_e \in \mathcal{A}_e, d_e \in \mathcal{D}_e\}
\]

to define the suspicious area. In practice, if Alice has only limited information of \( D_{\text{min}}(\theta_e) \) and \( D_{\text{max}}(\theta_e) \), she can assume the two boundaries are defined by constant values, \( d_{\text{min}} \) and \( d_{\text{max}} \). For instance, if Alice knows nothing about \( \mathcal{R}_{\text{sus}} \), she can set \( \mathcal{A}_e = [0, 2\pi] \), \( \mathcal{D}_e = [0, r_{\text{max}}] \), indicating that the suspicious area (from Alice’s point of view) spans the entire space with radius \( r_{\text{max}} \). The effectiveness of this assumption, referred to as “constant boundaries” and defined below, depends on that how accurately it can describe the real \( \mathcal{R}_{\text{sus}} \).

**Definition 1 (Constant Boundaries):** To facilitate practical design, it is convenient to set the two boundaries of \( \mathcal{R}_{\text{sus}} \) to be constants such that \( D_{\text{min}}(\theta_e) = d_{\text{min}},\; D_{\text{max}}(\theta_e) = d_{\text{max}},\; \forall \theta_e \in \mathcal{A}_e \).
\[ F_{s;i,j}(x) = \begin{cases} 1 - F_{\Delta} \left( CP_0 \left( \frac{x}{N_t} \right) \right), & PV_1 \leq \frac{x}{N_t} \leq 1 \\ 1 - F_{\Delta} \left( CP_0 \left( \frac{x}{N_t} \right) \right) + \sum_{m=1}^{M} \left( F_{\Delta} \left( CP_{m,1} \left( \frac{x}{N_t} \right) \right) - F_{\Delta} \left( CP_{m,2} \left( \frac{x}{N_t} \right) \right) \right), & PV_{M+1} \leq \frac{x}{N_t} < PV_M \end{cases} \] (7)

### B. Normalized Crosstalk

For \( h_i, h_j \) (\( j \in I_i \)) defined as (1), the following asymptotic results hold as \( N_t \to \infty \) [30]:

\[
\frac{1}{N_t} h_i^H h_i \cong 1
\]

\[
\frac{1}{N_t} h_i^H h_j \cong \frac{1}{N_t} \sqrt{K_{ij}} t_{ij}, \quad j \neq i.
\]

(4) (5)

where \( \cong \) denotes the approximation that is asymptotically accurate. Where \( K_{ij} = \frac{K_i K_j}{(1+K_i)(1+K_j)} \), and \( t_{ij} \cong \sum_{n=0}^{N_t-1} e^{-j2\pi d_n (\sin \theta_j - \sin \theta_i) n} \).茎

Stemming from (5), we introduce the following definition.

**Definition 2 (Normalized Crosstalk):** Define the normalized crosstalk between nodes \( i, j \) as

\[
s_{ij}(\theta_i, \theta_j) \triangleq \left| \frac{1}{N_t} h_i^H h_j \right|^2 \cong \frac{1}{N_t^2} K_{ij} |t_{ij}|^2.
\]

(6)

**Lemma 1:** The normalized crosstalk \( s_{ij}(\theta_i, \theta_j) \) has the following characteristics:

1. \( s_{ij}(\theta_i, \theta_j) \) is a sinc-like function composed of one main lobe and multiple side lobes.
2. With fixed \( \theta_j \) and random \( \theta_i \sim U(\theta_{\min}, \theta_{\max}) \) which is uniformly distributed between \( \theta_{\min} \) and \( \theta_{\max} \), the CDF of \( s_{ij}(\theta_i, \theta_j) \) can be written as (7) (see top of this page) where the definitions of \( CP_0, CP_{m,1}, CP_{m,2} \) and \( F_{\Delta}(\cdot) \) are referred to Appendix A.
3. With fixed \( \theta_j \), the feasible range of \( s_{ij}(\theta_i, \theta_j) \) is \( 0 \leq s_{ij} \leq s_{ij}^{\max} \), where \( s_{ij}^{\max} \) is determined by the distribution range of \( \theta_i \), i.e., \( A_i \triangleq [\theta_{\min}, \theta_{\max}] \).

**Proof:** See Appendix A

### C. Secrecy Transmission Scheme

We use linear precoding for data transmission, while AN symbols \( s_n \) are sent in the space defined by \( v_n, n = 1, \ldots, N \), to degrade the channels of Eves. For the null space-based jamming [27], it holds that \( N = N_t - 1 \) and \( v_n \in \text{null}(h_i) \). The received signal at receiver \( i \) is given by

\[
y_i = \sqrt{P_i d_i^{-\alpha} h_i^H w_i x_i} + \sum_{n=1}^{N} \sqrt{P_n d_i^{-\alpha} h_i^H v_n} s_n + n_i, \quad \forall i \in \mathcal{R}
\]

(8)

where \( w_i \in \mathbb{C}^{N_x \times 1} \) is the precoder for Bob, \( x_i \) is the unit-norm data symbol, and \( n_i \) is the additive Gaussian noise. Moreover, \( P_i \) and \( P_n \) respectively are the powers allocated to Bob and the \( n \)-th jamming direction, with total power constraint such as \( \sum_{n=1}^{N} P_n = P_{\text{tot}} - P_b \) where \( P_{\text{tot}} \) is the total available transmit power. We define the jamming power allocation coefficient as

\[
\phi \triangleq \frac{P_{\text{jamp}}}{P_{\text{tot}}} = \frac{\sum_{n=1}^{N} P_n}{P_{\text{tot}}},
\]

(9)

For ease of description, we assume that Bob and all Eves share the same noise covariance being \( N_0 \). Moreover, we consider maximum ratio transmission (MRT) for precoding of the data symbol \( x_i \), i.e., \( w_b = \frac{h_i}{||h_i||} \). In this case, according to [5], the SINR at receiver \( i \) is given by

\[
\text{SINR}_i = \frac{P_i d_i^{-\alpha} |h_i^H w_b|^2}{N_0 + d_i^{-\alpha} \sum_{n=1}^{N} P_n |h_i^H v_n|^2}.
\]

(10)

We assume that the Eves are not colluding, but consider the most-capable Eve, which has the maximum receive SINR, to define the secrecy rate as [22]

\[
R_b^s = |\log_2(1 + \text{SINR}_b) - \log_2(1 + \text{SINR}_{e,\text{max}})|^+
\]

(11)

where \( \text{SINR}_{e,\text{max}} \triangleq \max \text{SINR}_{e} \) and \([x]^+ \triangleq \max\{x,0\}\). We say a secrecy outage occurs if \( R_b^s \) is less than a target rate \( R_{\text{th}} \), hence the SOP is defined as

\[
\mathcal{P}_{\text{out}} = \Pr\{R_b^s < R_{\text{th}}\}.
\]

(12)

### III. Secrecy Outage Analysis

In this section, we first introduce the secrecy outage region (SOR) which describes all possible locations of Eves who can cause secrecy outage. Analytical expression of the SOR is derived for uniform jamming, then the SOP is studied with variant shapes of \( \mathcal{R}_{\text{ans}} \). At last, a jamming-beneficial range is derived to show that uniform jamming is still useful in reducing the SOP.

#### A. Secrecy Outage Region

In the large antenna regime, all fast fading effects are completely averaged out as shown in [4] and [5]. Therefore, whether the secrecy outage occurs or not, will be essentially determined by the geometric location of Eve. In this light, we introduce the SOR defined in the following.

**Definition 3 (Secrecy Outage Region):** The SOR is defined in terms of polar coordinates as

\[
\mathcal{R}_{\text{SOR}} \triangleq \left\{ (\theta_e, d_e) \mid \lim_{N_t \to \infty} R_b^s < R_{\text{th}} \right\}.
\]

(13)

Herein, we note that \( R_b^s \) is a function of \( \theta_e \) and \( d_e \).

In the large antenna regime, secrecy outage occurs if there exists at least one Eve within the SOR. If all Eves locate outside of the SOR, the target secrecy rate \( R_{\text{th}} \) can be guaranteed. To characterize the SOR, we first evaluate the received SINRs assuming uniform jamming.
where and, hereafter, we use the notations \( \hat{P}_b = \frac{P}{N_0} \), \( \hat{P}_{jam} = \frac{P_{jam}}{N_0} \) for brevity. Note that in (15), \( s_{e;b}(\theta_e) \) is the normalized cross-talk between Eve and Bob as defined in (6). Considering fixed \( \theta_b \), we hereafter write \( s_{e;b} \) as a function of only \( \theta_e \).

**Proof:** Since \( \text{span}(v_n) = \text{null}(h_b) \), jamming causes no interference at Bob. Applying (4) to (10), we get (14). Noting that \( N = N_t - 1 \) and \( P_n = \frac{N_0}{N_1} \), from (10), we have

\[
\text{SINR}_e = \frac{P_b d_{eb}^{-\alpha} h_e v_n^H v_n}{N_0 + d_{eb}^{-\alpha} \frac{P_{jam}}{N_0} \sum_{n=1}^{N_t-1} |h_n v_n|^2}.
\]

By applying \( \delta \), the numerator of (16) can be written as \( \hat{P}_{b} d_{eb}^{-\alpha} N_t s_{e;b}(\theta_e) \). On the other hand, noting that \( w_b \) and \( v_n, n = 1, ..., N_t - 1 \) constitute a complete orthonormal basis of the \( N_1 \)-dimensional vector space, we have \( \sum_{n=1}^{N_t-1} |h_n w_n|^2 = |h_0 w_0|^2 = N_t (1 - s_{e;b}(\theta_e)) \) in the denominator of (16). Therefore, (15) can be obtained.

**Remark 1:** The result in (14) leads to a constraint on \( \phi \) (defined in (9)), written as

\[
\phi \leq \phi_{\text{max}} = 1 - \frac{2R_{th}}{\hat{P}_{tot} d_{eb}^{-\alpha} N_t} \quad (17)
\]

which stems from the fact that the jamming power cannot be too large, otherwise, even without Eve, the target rate \( R_{th} \) cannot be guaranteed since the remaining signal power is too small. Unless otherwise specified, we assume \( \phi \leq \phi_{\text{max}} \) can always hold via proper power allocation.

From Lemma 2, we characterize the SOR for the uniform jamming as follows.

**Proposition 1:** With uniform jamming in \( \text{null}(h_b) \) and given \( \phi \), the SOR is described as

\[
\mathcal{R}_{\text{SOR}}^{uj}(\phi) = \{ (\theta_e, d_e) | d_e < \tilde{d}_e^{uj}(\phi, \theta_e), s_{e;b}(\theta_e) > C_3(\phi) \}
\]

where

\[
\tilde{d}_e^{uj}(\phi, \theta_e) = (C_1(\phi) s_{e;b}(\theta_e) - C_2(\phi))^\frac{1}{\alpha}
\]

\[
C_1(\phi) = \frac{(1 - \phi) \hat{P}_{tot} N_t 2^{R_{th}}}{1 + (1 - \phi) \hat{P}_{tot} d_{eb}^{-\alpha} N_t - 2^{R_{th}}} + \hat{P}_{tot} \phi
\]

\[
C_2(\phi) = \frac{\hat{P}_{tot} \phi}{\hat{P}_{tot}}
\]

and \( C_3(\phi) \) is given by (22) shown at the top of this page.

**Proof:** Substituting (14) and (15) into (11) and using the definition of SOR in (13), we can obtain the value of \( \tilde{d}_e^{uj}(\phi, \theta_e) \) in (19). Note that the value of \( \tilde{d}_e^{uj}(\phi, \theta_e) \) should be positive, this straightforwardly introduces the constraint on the minimum value of \( s_{e;b}(\theta_e) \) such as \( s_{e;b}(\theta_e) > C_3(\phi) \) where \( C_3(\phi) \) can be readily obtained by letting \( C_1(\phi) s_{e;b}(\theta_e) - C_2(\phi) > 0 \).

From Lemma 1, \( s_{e;b}(\theta_e) \) in (19) is a function with one main lobe and multiple side lobes, resulting in a multi-lobe shaped SOR. In order to gain some insights from this complex shape (as will be shown in the simulations), we focus on several critical security-related metrics as

- **Largest radius of the main lobe** \( (\bar{d}_{e;b}) \) and the \( m \)-th side lobe \( (\bar{d}_{e;m}) \): \( \bar{d}_{e;0} \) and \( \bar{d}_{e;m} \) can be obtained by replacing \( s_{e;b}(\theta_e) \) in (19) respectively with \( K_{e;b} \) and \( K_{e;m} \) (defined in (54) in the proof of Lemma 1). Such that

\[
\bar{d}_{e;0} = (C_1(\phi) K_{e;b} - C_2(\phi))^\frac{\alpha}{\alpha - 1} \quad (23)
\]

\[
\bar{d}_{e;m} = (C_1(\phi) K_{e;m} - C_2(\phi))^\frac{\alpha}{\alpha - 1} \quad (24)
\]

Since \( \bar{d}_{e;0} \) is much larger than \( \bar{d}_{e;m}, \forall m \neq 0 \), \( \bar{d}_{e;0} \) can be considered as the largest distance of the SOR. For any Eve whose distance to Alice is larger than \( \bar{d}_{e;0} \), we can conclude that it causes no secrecy outage regardless of its LOS direction.

- **Largest angle difference** \( \Delta \theta_{\text{max}} \) of the SOR: For any Eve whose angle difference to the LOS direction of Bob is larger than \( \Delta \theta_{\text{max}} \), we can conclude that it causes no secrecy outage regardless of its distance to Alice. If \( s_{e;b}(\theta_e) < C_3(\phi), \forall \theta_e > \theta_e, \) we can write

\[
\Delta \theta_{\text{max}} = \left| \theta_e - \theta_b \right|.
\]
Differently from (18), the constraint on $s_{e;b}(\theta_e)$ vanishes in (26), indicating that the SOR now is extended to the entire angular domain. Moreover, compared with (23), we see that $d_{e,0}$ in no-jamming case [1] on the contrary, is reduced compared to uniform jamming. In conclusion, uniform jamming induces two opposite effects: the beneficial one is that the SOR can be squeezed in angular domain, and the disadvantage is that the SOR is enlarged in Bob’s direction, i.e., the main lobe. Illustration of the SOR changing caused by jamming will be shown later in simulations.

B. SOP Analysis

With a single Eve uniformly distributed in $\mathcal{R}_{\text{sus}}$, using the derived SOR, the SOP is given by

$$\mathcal{P}_{\text{out\_singleEve}} = \frac{\text{Area}(\mathcal{R}_{\text{SOR}}(\phi) \cap \mathcal{R}_{\text{sus}})}{\text{Area}(\mathcal{R}_{\text{sus}})}$$

(27)

where $\text{Area}(\cdot)$ denotes the area of a certain geometric region. Considering that there are $L$ Eves uniformly distributed in $\mathcal{R}_{\text{sus}}$, the SOP of the entire network can be written as

$$\mathcal{P}_{\text{out}} = 1 - (1 - \mathcal{P}_{\text{out\_singleEve}})^L.$$  

(28)

From (27), the SOP is determined by the overlapping area between two geometrical regions. If $\mathcal{R}_{\text{SOR}}(\phi) \cap \mathcal{R}_{\text{sus}} = \emptyset$, zero SOP is achieved. Recalling (4), as well as (23) and (25), two sufficient conditions of $\mathcal{R}_{\text{SOR}}(\phi) \cap \mathcal{R}_{\text{sus}} = \emptyset$ can be written as

$$D_{\text{min}}(\theta_e) > d_{e,0}, \quad \forall \theta_e,$n

or $D_{\text{max}}(\theta_e) = 0,$ \quad $\forall |\theta_e - \theta_b| < \Delta_{\theta_{\max}}$

(29)

where $d_{e,0}$ is defined in (23) and $\Delta_{\theta_{\max}}$ is in (25). The physical insight of (29) is clear: when an Eve is far away or its angle difference to $\theta_b$ is large, it does not cause outage.

For the general case with arbitrary shape of $\mathcal{R}_{\text{sus}}$, $\mathcal{P}_{\text{out}}$ in (27) can be numerically evaluated and further applied to jamming power allocation design. However, due to the non-regular shapes of $\mathcal{R}_{\text{SOR}}(\phi)$ and $\mathcal{R}_{\text{sus}}$, closed-form expressions of $\text{Area}(\mathcal{R}_{\text{SOR}}(\phi) \cap \mathcal{R}_{\text{sus}})$ as well as the SOP in (28) do not exist for the general case. Yet, by considering constant boundaries of $\mathcal{R}_{\text{sus}}$ as described in Definition 1, (27) can be written in an integral form as the following proposition.

**Proposition 2:** With constant boundaries of $\mathcal{R}_{\text{sus}}$, i.e., $\mathcal{A}_e = [\theta_{\min}, \theta_{\max}]$ and $\mathcal{D}_e = [d_{\min}, d_{\max}]$, and uniform jamming in null($h_b$), the SOP can be given as

$$\mathcal{P}_{\text{out}} = 1 - \int_{d_{\min}}^{d_{\max}} F_{s_{e;b}} \left( \frac{z^\alpha + \tilde{P}_{\text{jam}}}{P_b N_t \Delta_{\theta_{\max}}^{\alpha} - P_{\text{jam}}} \right)^L \frac{dz}{d_{\max} - d_{\min}}.$$  

(30)

where $F_{s_{e;b}}(\cdot)$ is defined in (7).

**Proof:** For the ease of analytical description, herein we utilize the CDF of the normalized crosstalk in (7). First, rewrite

$$\mathcal{P}_{\text{out}} = 1 - \Pr\{ R_b^e \geq R_{th} \}$$

(31)

where $F_{\text{SINR}_{\text{e;max}}}(\cdot)$ is the CDF of $\text{SINR}_{\text{e;max}}$, which is given by $F_{\text{SINR}_{\text{e;max}}}(x) = \left( \frac{F_{\text{SINR}_{\text{e}}}(x)}{L} \right)$ since all Eves are independently distributed. Using (15), we have

$$F_{\text{SINR}_{\text{e}}}(x) = \Pr\left( s_{e;b}(\theta_e) \leq \frac{d_{e}^\alpha + \tilde{P}_{\text{jam}}}{P_{\text{jam}} + P_b N_t} \right)$$

(32)

where both $\theta_e$ and $d_e$ are random. Since $\theta_e$ and $d_e$ are independent, (32) can be presented as

$$F_{\text{SINR}_{\text{e}}}(x) = \int_{d_{\min}}^{d_{\max}} F_{s_{e;b}} \left( \frac{z^\alpha + \tilde{P}_{\text{jam}}}{P_b N_t} \right) f_{d_e}(z) dz.$$  

(33)

where $f_{d_e}(z) \triangleq \frac{2z}{d_{\max} - d_{\min}}$ is the PDF of $d_e$, corresponding to the uniform distribution between two boundaries defined by $\mathcal{D}_e = [d_{\min}, d_{\max}]$. Then, $\mathcal{P}_{\text{out}}$ is directly obtained as (30).

Practically, (30) can be used for jamming power allocation. As stated in Remark 1, Alice can arbitrarily adjust the value of the constant boundaries in the design, based on the information about $\mathcal{R}_{\text{sus}}$ that she has. Particularly, if Alice knows nothing about $\mathcal{R}_{\text{sus}}$ (i.e., she assumes $\mathcal{A}_e = [0, 2\pi]$ and $\mathcal{D}_e = [0, r_{\max}]$), minimizing $\mathcal{P}_{\text{out}}$ becomes equivalent to minimizing $\text{Area}(\mathcal{R}_{\text{SOR}}(\phi))$.

C. Jamming-beneficial Range

Based on Proposition 2 we find a jamming-beneficial range defined in $d_{\max}$ (i.e., the larger constant distance boundary of $\mathcal{R}_{\text{sus}}$) as follows.

**Proposition 3:** A constraint on $d_{\max}$ that makes the uniform jamming beneficial in reducing the SOP is given by

$$d_{\max} < \left( \frac{s_{\text{e;max}}^{\alpha} (1 + \tilde{P}_{\text{tot}})}{P_{\text{tot}} d_b \alpha N_t - 2 R_{th}} \right)$$

(34)

where $s_{\text{e;max}}^{\alpha}$ is the largest feasible crosstalk value defined in Lemma 1.

**Proof:** See Appendix B.

**Remark 2:** Proposition 3 shows that when Eves are located close enough to Alice, uniform jamming is always beneficial in reducing the SOP. Clearly, this range expands with larger $d_b$, as well as larger $s_{\text{e;max}}^{\alpha}$ or larger $R_{th}$. On the other hand, the range shrinks with larger $N_t$ or $\tilde{P}_{\text{tot}}$.

Moreover, we note that (34) has a similar form of that described for the SOR without jamming, i.e., $\mathcal{R}_{\text{S}}$ in (26). Recalling the definitions of the largest distance of SOR in (23) and (24), the physical insight of Proposition 3 can be explained as follows: as long as $\mathcal{R}_{\text{sus}} \cap \mathcal{R}_{\text{SOR}}(\phi) \neq \emptyset$, there always exists an optimal $\phi$, with which the SOP can be reduced by uniform jamming, compared with the SOP without jamming. The optimization of $\phi$ is discussed in the next section.

IV. JAMMING POWER ALLOCATION

In this section, considering uniform jamming, we investigate the optimal jamming power allocation that minimizes the SOP.
The problem can be simply described as
\[
\min_{\phi} \mathcal{P}_{\text{out}}, \quad \text{s.t.} \quad 0 \leq \phi \leq 1. \tag{35}
\]
In practice, Alice may have different accuracy levels of information about \( \mathcal{R}_{\text{sus}} \), as follows:
1) Alice knows nothing about the suspicious area, or only partial information about the suspicious area such as \( A_e \) only (or \( D_e \) only); and
2) Alice knows exact information about the suspicious area, i.e., both \( A_e \) and \( D_e \).

For these two cases, we respectively investigate the jamming power allocation in the following.

A. Jamming with None/Partial Information about \( \mathcal{R}_{\text{sus}} \)

When Alice knows nothing about \( \mathcal{R}_{\text{sus}} \), minimizing the SOP becomes equivalent to minimizing the area of SOR, which can be calculated as
\[
\text{Area} \left( \mathcal{R}_{\text{SOR}}^j (\phi) \right) = \int_0^{2\pi} \frac{1}{2} (\tilde{d}_{\phi}^j (\phi, \theta_e))^2 d \theta_e \tag{36}
\]
where \( \tilde{d}_{\phi}^j (\phi, \theta_e) \) is defined in (19). Note that \( \mathcal{R}_{\text{SOR}}^j (\phi) \) is composed of many side lobes. We use \( \mathcal{R}_{\text{SOR},m}^j (\phi) \) to denote the \( m \)-th side lobe, and \( \mathcal{R}_{\text{SOR,I}}^j (\phi) \) to denote a group of side lobes with indices described by the set \( I \). For the case that Alice knows \( A_e \) or \( D_e \), we can simplify the problem by minimizing partial, other than the entire area of \( \mathcal{R}_{\text{SOR}}^j (\phi) \) such as
\[
\text{Area} \left( \mathcal{R}_{\text{SOR,I}}^j (\phi) \right) = \sum_{m \in I'} \text{Area} \left( \mathcal{R}_{\text{SOR,m}}^j (\phi) \right) \tag{37}
\]
where \( I' \) is the set of the concerned side lobe indices, determined by either \( A_e \) or \( D_e \). Using (36) (or (37)) along with (19), the areas can be numerically calculated and the optimal \( \phi \) can be easily founded via one dimensional linear search. Since it is difficult to derive closed-form expression for \( \text{Area} \left( \mathcal{R}_{\text{SOR,I}}^j (\phi) \right) \), we evaluate the area of \( \mathcal{R}_{\text{SOR,m}}^j (\phi) \) in the following corollary for a special case to further provide some discussions.

Corollary 2 (Area of \( \mathcal{R}_{\text{SOR,m}}^j (\phi) \)): With \( \theta_b = 0 \) and the path loss coefficient being \( \alpha = 2 \) (which corresponds the free space propagation), Area (\( \mathcal{R}_{\text{SOR,m}}^j (\phi) \)) can be upper bounded as
\[
\text{Area} \left( \mathcal{R}_{\text{SOR,m}}^j (\phi) \right) \leq \frac{1}{4N_e \pi^2m^2} \left( \frac{K_e b}{\pi^2m^2} C_1 (\phi) - 2C_2 (\phi) \right) \tag{38}
\]
where \( C_1 (\phi) \) and \( C_2 (\phi) \) are defined in (20) and (21).

Proof: See Appendix C.

Remark 3: In (38), it is shown that the area of every side lobe is inversely proportional to \( N_e \), indicating that the SOR side lobes can asymptotically vanish with ultimately large \( N_e \). Moreover, it is inversely proportional to \( m^2 \), which means that the area of the SOR will rapidly decrease for the side lobes with large indices, i.e., with large angle difference to \( \theta_b \). This result indicates that Eves from different directions (i.e., within different side lobes) have different significance in causing secrecy outage, hence should be treated differently in the jamming design.

B. Jamming with Exact Information of \( \mathcal{R}_{\text{sus}} \)

With the information of \( \mathcal{R}_{\text{sus}} \), Alice can calculate and apply the value of \( \mathcal{P}_{\text{out}} \) in the design (at least numerically)\(^3\) using either (28) or (30). Although in practice, (35) can be readily solved by one dimensional linear search, it fails to provide the optimal \( \phi \) in closed form. In the following corollary, we provide closed-form solutions and discussions for a special case.

Corollary 3 (Jamming power allocation for given \( \theta_e \)): For constant boundaries of \( \mathcal{R}_{\text{sus}} \) and given \( \theta_e \), which is equal for all Eves, the optimal \( \phi \) can be determined as
\[
\phi^\text{opt} = \min \{ \phi^\text{opt}_g, \phi^\text{opt}_h \}, \quad \phi^\text{opt}_g \notin [0, 1], \quad \phi^\text{opt}_h \in [0, 1] \tag{39}
\]
where
\[
\phi^\text{opt}_g = \frac{1 - \left( \frac{2R_{\text{th}} - 1}{2R_{\text{th}} - 1 + \frac{1}{\bar{P}_{\text{tot}}d^g_{\text{bc}}(\theta_e)N_t}} \right)}{1 - \bar{P}_{\text{tot}}d^g_{\text{bc}}(\theta_e)N_t}, \quad \phi^\text{opt}_h = \frac{1 - \bar{P}_{\text{tot}}d^g_{\text{bc}}(\theta_e)N_t}{1 - \bar{P}_{\text{tot}}d^g_{\text{bc}}(\theta_e)N_t} \tag{40}
\]

Proof: See Appendix D.

Note when \( \phi^\text{opt}_g = \phi^\text{opt}_h \), the optimal jamming power decreases with \( d_{\text{bc}} \) and \( s_e(\theta_e) \), whereas it will increase when \( \phi^\text{opt}_g = \phi^\text{opt}_h \). The part that dominates the final result in (39) depends on the value of \( \theta_e \). Detailed discussions will be provided in Section VII along with simulations.

V. DIRECTIONAL JAMMING

In this section, we propose directional jamming algorithms to allocate jamming power more efficiently than uniform jamming, based on the following facts:
1) With the information of \( \mathcal{R}_{\text{sus}} \), Alice can perform jamming only to the suspicious directions instead of the entire null space of \( h_b \).
2) Without information of \( \mathcal{R}_{\text{sus}} \), jamming towards different directions also needs to be treated differently, as stated in Remark 3.

At a cost of slightly increasing the implementation complexity compared with uniform jamming, directional jamming is able to substantially reduce the SOP. In following subsections, we present power allocation algorithms for directional jamming with and without the information of \( \mathcal{R}_{\text{sus}} \).

A. Directional Jamming with the Information of \( \mathcal{R}_{\text{sus}} \)

When jamming is not uniformly performed, from (10), the SIR at Eve is represented as
\[
\text{SINR}_e^\text{d} = \frac{P_b d^\alpha_e \| h_e^d w_0 \|^2}{N_0 + d^\alpha_e h_e^d V \text{diag} (p) V^H h_e} \tag{42}
\]
\(^4\)The calculation requires the knowledge of \( \mathcal{D}_e \) and \( A_e \). Clearly, uniform jamming is not optimal in this condition. However, for the ease of analysis, we first devise the optimal power allocation for uniform jamming; then, the resulted jamming power can be allocated directionally to further improve efficiency.
Algorithm 1: Iterative directional jamming without information of $R_{sus}$

1: **Initialization:** Update the information of $\theta_b, d_b$, and $R_{sus}$ at Alice.
2: Assuming null space-based uniform jamming, find

$$\phi^{opt} = \arg\min_{\phi} P_{out}$$

through one dimensional linear search over $\phi \in [0, 1]$.
3: Select a $N$-dimensional subspace $(v_n, n = 1, ..., N)$ and $N \leq N_t$ from null($h_b$) according to (46), where $\theta_{v_n}$ is defined as (45).
4: Equally allocate $P_{jam}^{opt} = \phi^{opt} P_{tot}$ to the selected beams in step 3 such as $\frac{\bar{R}_{\text{jam}}}{N}$.

Algorithm 2 provides a sub-optimal solution which reduces the computational complexity especially when $N_t$ is large (28); and 3) most importantly, the structure of DFT matrix provides very sharp beam pattern towards the physical angle $\theta_{v_n}$ in (45), therefore, the beam selection criterion (46) can be very efficient since with sharper beams, there will be less jamming power leaked outside of $R_{sus}$.

B. Directional Jamming without Information of $R_{sus}$

Without any information of $R_{sus}$, the objective of directional jamming power allocation becomes to minimize the area of $R_{\text{SO}_\text{R}}(\bar{p})$ in (43) for $\theta_b \in [0, 2\pi]$, which is calculated as

$$\text{Area} \left( R_{\text{SO}_\text{R}}(\bar{p}) \right) = \int_0^{2\pi} \frac{1}{2} (\bar{d}_{\text{e}}(\bar{p}, \theta_e))^2 d\theta_e.$$

A general closed-form expression of (47) is not available, and its convexity is unknown. Hence, numerically minimizing $\text{Area} \left( R_{\text{SO}_\text{R}}(\bar{p}) \right)$ is NP-hard. To overcome this, we propose Algorithm 2, which iteratively finds the optimal $n$-th element of $\bar{p}$ while keeping the others fixed.

Algorithm 2 provides a sub-optimal solution which reduces the complexity by degrading the original problem to one-dimensional linear search. However, for large $N_t$, the complexity is still huge since during each main iteration, $N \sim O(N_t)$ times of linear searching are required to fully update $\bar{p}$. Hence, Algorithm 2 is not suitable for some scenarios where $\theta_b$ and $d_b$ change fast. In this light, we propose a simplified algorithm, Algorithm 3, to further reduce the complexity.
Algorithm 3 Simplified directional jamming without information of $\mathcal{R}_\text{sus}$

1: **Initialization**: Update the information of $\theta_b$ and $d_b$ at Alice; Initialize $\text{Area}_{\min} = \infty$;
2: Calculate $s_{e:b}(\theta_m), m = 1, ..., M$. Determine $m_1', m_2'$, satisfying that $s_{e:b}(\theta_{m_1'}) \geq s_{e:b}(\theta_{m_2'}) \geq s_{e:b}(\theta_m), \forall m \neq m_1'$ and $m \neq m_2'$;
3: for $\phi = 0$ to 1 do
4: Find
$$\bar{p}_{\text{boundary}} = \arg \min \text{Area}(\mathcal{R}_\text{dj}^\text{SOR}(\bar{p}_{\text{boundary}})),$$
5: Calculate Area$\text{dj}^\text{SOR}(\bar{p}_{\text{boundary}})$ according to (47);
6: if Area$\text{dj}^\text{SOR}(\bar{p}_{\text{boundary}}) < \text{Area}_{\min}$ then
7: $\text{Area}_{\min} = \text{Area}^\text{dj}^\text{SOR}(\bar{p}_{\text{boundary}})$;
8: $\phi^{\text{opt}} = \phi; \bar{p}_{\text{opt}} = \bar{p}_{\text{boundary}}$;
9: else continue
10: end if
11: end for
12: end for

Algorithm 3, $\theta_m$ is the mean angle of the $m$-th side lobe of $\mathcal{R}_\text{dj}^\text{SOR}(\bar{p})$ ($m = 0$ denotes the main lobe). In Step 4, $\bar{p}_{\text{boundary}}$ follows the structure such as
$$\bar{p}_{\text{boundary}} = \{0, \ldots, \bar{p}_{m_1'}, 0, \ldots, \bar{p}_{m_2'}, 0, \ldots\},$$
where $m_1'$ and $m_2'$ are the indices of the two dominating side lobes, which are located most closely to the main lobe (from both sides). The derivation of Algorithm 3 is described in Appendix [2].

With Algorithm 3, jamming is performed in only two dominating directions in the neighborhood of $\theta_b$, for the reasons that 1) for the region with large angle difference to Bob, allocating much jamming power is inefficient since $\mathcal{R}_\text{dj}^\text{SOR}$ in this region is generally very small; 2) for the directions highly in-line with $\theta_b$, jamming should be avoided as it will cause severe interference to Bob. Note that for every realization of $\phi$, only single time of linear search is required in Step 4. The complexity is irrelative to $N$ (which is large in general), hence can be greatly reduced compared to Algorithm [2]. As a possible extension, more than two dominating directions can be involved in the design while the trade-off between complexity and performance exists.

VI. EXTENSION TO MULTIUSER AND MULTI-CELL SCENARIOS

We focus on the single-cell and single-user scenario in previous sections. In this section, we now show how the SOR can be affected by multiple users and cells. We also provide discussions on the design of secure transmission in these scenarios with future research challenges.

A. Multiuser Transmission

When multiple legitimate users (i.e., multiple Bobs) are presented in massive MIMO systems for Rician channels, the multiuser interference between Bobs is trivial as long as their LOS angles have large difference, which can be readily ensured via user scheduling. On the contrary, the multiuser interference to Eve can be seen as equivalent jamming considering that single-user decoder is adopted at Eve, which is likely to happen when Eves are low-cost devices. Hence, when multiuser beamforming is applied for Bobs, the received multiuser interference at Eve becomes equal to the directional jamming, transmitted towards other Bobs’ directions. Consequently, the SOR of an objective Bob will be shrunk in the directions of the other Bobs. Denote the set of all legitimate users as $\mathcal{T}_\text{MU} = \{b_1, ..., b_u\}$. Similar to (43) and (44), which describe the SOR for directional jamming, the SOR of user $b_u \in \mathcal{T}_\text{MU}$ in the presence of multiple users can now be described as
$$\mathcal{R}_{\text{SOR}}^{\text{MU}, b_u}(\bar{p}_{b_u}) = \{ (d_e, \theta_e) | d_e \leq \mathcal{R}_e^{\text{MU}, b_u}(\bar{p}_{b_u}, \theta_e) \}$$
$$d_e^{\text{MU}, b_u}(\bar{p}_{b_u}, \theta_e) = \left( \frac{2R_b (1 - \phi) P_{\text{tot}} N_s s_{e:b}(\theta_e)}{1 + (1 - \phi) P_{\text{tot}} d_b a N_i - 2R_b} - \bar{s}(\theta_e) H V \text{diag}(\bar{p}_{b_u}) V^H \bar{s}(\theta_e) \right)^{\frac{1}{2}}$$
where $V = [W_b, V_j] \in \mathbb{C}^{N_i \times N}$ spans the equivalent jamming space, in which $W_b = [w_{b_1}, \ldots, w_{b_u}], u' = 1, ..., u, u' \neq u$ spans the signaling space for the other legitimate users, while $V_j \in \text{null}(W_b)$ is the jamming space. Correspondingly, the power allocation vector can be divided into two parts as $\bar{p}_{b_u} = \begin{pmatrix} \bar{p}_{b_u, \text{sig}}^T \bar{p}_{b_u, \text{jam}}^T \end{pmatrix}$ where $\bar{p}_{b_u, \text{sig}} \triangleq \begin{pmatrix} \bar{p}_{b_1, \text{sig}}, \ldots, \bar{p}_{b_{u-1}, \text{sig}}, \bar{p}_{b_u, \text{sig}} \ldots, \bar{p}_{b_u, \text{sig}} \end{pmatrix}$ is the signal power allocation vector for all legitimate users except for $b_u$. For given fixed $\bar{p}_{b_u, \text{sig}}$, in order to minimize Area$\text{dj}^\text{SOR}(\mathcal{R}_\text{MU}, b_u, \bar{p}_{b_u})$ for user $b_u$, the directional jamming algorithms, i.e., Algorithm 2 and 3, can be directly applied herein.

Considering communication secrecy for the entire multiuser transmission system, the optimization problem can be reasonably re-formulated as a min-max problem such as
$$\min_{\bar{p}_{b_u}} \max_{b_u} \text{Area}(\mathcal{R}_\text{MU}, b_u, \bar{p}_{b_u})$$
s.t. $\|\bar{p}_{b_u}\|_1 < P_{\text{tot}}, b_u \in \mathcal{T}_\text{MU}$.

The main challenge in solving (51) is that allocating power for one user affects the SORs of other users. Hence, the power needs to be jointly allocated for all users, and the complexity of such joint optimization can be very high. Hence, it is desirable to develop simplified algorithms for the multiuser scenario.

B. Multi-cell Network

In multi-cell massive MIMO networks, it is commonly assumed that the training pilots are reused among cells. Correspondingly, pilot contamination results in imperfect CSI
estimation as well as nonnegligible multi-cell interference from Alices in adjacent cells. Denote $\theta_{i,b}^l$ as the angular direction of Bob in Cell $i$ seen from Alice in Cell $j$, and Cell 0 as the objective cell where Bob 0 exists. Some major effects of imperfect CSI and multi-cell interference on the SOR of Bob 0 are described as follows:

- Due to pilot contamination from Bobs $i$, $\forall i \neq 0$, the SOR of Bob 0 will be enlarged in the directions of $\theta_{i,b}^l$.
- Multi-cell interference to Bob 0 will isotropically enlarge his SOR. On the other hand, Eves in Cell 0 are equivalently jammed by the multi-cell interference from Alice $j$ in cell $j$, $\forall j \neq 0$, especially in the directions of $\theta_{j,b}^l$ and $\theta_{j,b}^t$. Thereby, the SOR in these directions can be shrunk and the shape can be non-continuous in these regions.

A general analytical description of the SOR in the multi-cell network is challenging, since it is determined not only by the network topology, but also by the locations of all pilot-contaminating users in adjacent cells. Moreover, the complicated shape of the SOR makes difficulties in calculating and minimizing the corresponding area. Nevertheless, in practice, pilot scheduling and reuse schemes can be utilized to alleviate these adverse effects which are caused by pilot contamination, e.g., [24], [25].

### VII. Simulation Results

Simulation results are shown in this section. We set $d_0 = 0.5$, $\alpha = 3$, $P_{\text{tot}} = 1$W, $N_0 = 10^{-2}$nW and for simplicity, assume strong LOS environment such that $K_{e,b} \rightarrow 1$. In this parameter setting, the receive SNR is 20dB when the transmitter-receiver distance is 100m.

At first, using (23) and (24), Fig. 2 provides a description of $\mathcal{R}^u_{\text{SOR}}(\phi)$ in terms of the radius of the main lobe/side lobes. It is shown that the radius of the main lobe is monotonously increasing with $\phi$, indicating that reducing the signal power towards $\theta_0$ enlarges the SOP in this direction. Clearly, allocating additional jamming power to the direction of $\theta_0$ will further enlarge this radius, which suggests that jamming directly in the legitimate user’s direction should be avoided. This conclusion coincides with the concept we followed for the design of Algorithm 3.

Moreover, as $\phi$ increases, the radius of the second side lobe is reduced first and then increases after a certain value, e.g., $\phi \approx 0.7$, indicating an optimal jamming power allocation in terms of minimizing the SOP in this direction. The side lobes with index $m \geq 3$ can be completely eliminated with proper jamming. The results show that we can design jamming based on the partial information of $\mathcal{R}_{\text{sub}}$. For example, in Fig. 2 if we know that Eves are located in the direction ranges of side lobes with indices larger than 3, then, allocating $\phi = 0.2$ is enough to secure the communication and the remaining power can be allocated to data transmission.

Next, we depict the SOP vs. $\phi$ in Fig. 3 with randomly generated $\theta_0$ and $d_0$ within the range $\mathcal{A}_0 = [-15^\circ, 15^\circ]$ and $D_e = [50m, 100n]$, respectively. Note that the smoothless of the curves is not due to the lack of simulation trials, but caused by the fact that $P_{\text{out}}$ is a piecewise function, as shown in (7) and (30). In addition, the SOP rapidly increases to 1 when $\phi$ exceeds $\phi_{\text{max}}$ in (7). From Fig. 3 we can see that 1) the SOP with optimal $\phi$ is much smaller than that without jamming, i.e., $\phi = 0$, as anticipated in Proposition 3 2) the SOP decreases as $N_t$ increases since larger $N_t$ results in higher received power at Bob and less leakage to Eve. Moreover, the optimal $\phi$ increases with $N_t$ because with larger $N_t$, allocating more power to data transmission is not efficient in increasing the achievable rate of Bob because of the logarithmic slope of the rate function; and 3) the SOP is further substantially reduced with directional jamming.

Fig. 3 shows the optimal jamming power coefficient $\phi_{\text{opt}}$ as a function of the normalized crosstalk $s_{e,b}$, for uniform jamming. We compare the derived $\phi_{\text{opt}}$ in (39) with Monte Carlo simulations and show a good match between them. From Fig. 3 we first observe that each curve is divided into two parts, respectively representing that $\phi_0$ or $\phi_\theta$ dominates the optimal result in (39). The division is emphasized using
In this case, jamming in Eve’s channel and the jamming can be a waste of transmit power. However, in the small-$d_b$ region, directional jamming schemes outperform uniform jamming. However, the performance improvement from uniform jamming to directional jamming Algorithm 1 is small because Algorithm 1 directionally allocates jamming power towards
the discussions to multiuser and multi-cell scenarios where future challenges are also described. In conclusion, we claim that uniform jamming still helps the communication secrecy in massive MIMO systems, and the proposed directional jamming outperforms conventional uniform jamming schemes.

APPENDIX A

PROOF OF LEMMA 11

Proof of 1): We can rewrite $s_{i;j}(\theta_i, \theta_j)$ in (6) as a function of $\Delta_{i;j}$ as follows

$$s_{i;j}(\theta_i, \theta_j) = K_{i;j}\Delta_{i;j}.$$  \hspace{1cm} (52)

By applying (31) (14) to $t_{i;j}$ in (6), $s(x)$ in (52) can be represented as

$$s(x) = \begin{cases} \frac{1}{N_t^2} \frac{\sin^2(N_x \pi dx)}{\sin^2(\pi dx)}, & x = 0 \\ \frac{1}{N_t^2} \frac{\sin^2(N_x \pi dx)}{\sin^2(\pi dx)}, & x \neq 0 \end{cases}$$  \hspace{1cm} (53)

which is a sinc-like function, has one main lobe and side lobes with decreasing amplitudes.

Proof of 2): In order to describe the CDF of $s_{i;j}$, we first characterize $s(x)$ in (53) by some cross points and peak values, shown in Fig. 8 and defined in the following.

Definition 4: The cross points and peak values are defined as

- Peak Values: The peak value of the $m$-th side lobe of $s(x)$ can be approximated by

$$PV_m \approx \frac{1}{N_t^2} \frac{1}{\sin^2\left(\frac{\pi m + \frac{\pi}{2}}{N_t}\right)} \approx \frac{1}{\pi^2 \left(m + \frac{1}{2}\right)^2}$$  \hspace{1cm} (54)

which is obtained by noting that $\sin(x) \approx x$ when $x$ is small, and it becomes asymptotically exact as $N_t$ is large. $PV_0 = 1$ corresponds to the main lobe.

- Cross Points: When $u < PV_M$, $CP_{m,i}(u), i = 1, 2$ denotes the $i$-th cross point between $y = u$ and $y = s(x)$ in side lobe $m$ ($m < M$), $CP_{0}(u)$ is the cross point in the main lobe.

Using (52), we have $F_{s_{i;j}}(K_{i;j}u) = \Pr\{s(\Delta_{i;j}) < u\}$. According to Fig. 8 $\Pr\{s(\Delta_{i;j}) < u\}$ can be evaluated by
calculating the probability that $\Delta_{ij}$ falls within the discrete intervals determined by $CP_{m,i}(u)$ and $CP_{0}(u)$. On the other hand, recalling that $\Delta_{ij} \triangleq |\sin \theta_i - \sin \theta_j|$ and $\theta_i$ follows uniform distribution, the CDF of $\Delta_{ij}$ can be written as

\[
F_{\Delta}(z) \triangleq \frac{1}{\theta_{\max} - \theta_{\min}} \left[ \min \left( \sin^{-1}(\min(1, z + \sin \theta_j)), \theta_{\max} \right)
- \max \left( \sin^{-1}(\max(-1, -z + \sin \theta_j)), \theta_{\min} \right) \right].
\] (55)

Using $F_{\Delta}(z)$ to describe the probability that $\Delta_{ij}$ falls within the described intervals leads to (7).

Proof of 3): Given $\theta_0$, the feasible range of $\Delta_{ij}$ is determined by $\mathcal{A}_i$, i.e., the angle range that node $i$ distributed in. Use $\mathcal{X}_A$ to denote this feasible range (shown in Fig. 8), it holds that $\mathcal{X}_A \subseteq [0, 1]$. Given $\mathcal{A}_i$, the feasible range of $s_{ij}$ can be determined as $[0, K_{ij}\beta^*_A]$, where $\beta^*_A \triangleq \max_{x \in \mathcal{X}_A} s(x)$. It is clear that $\beta^*_A \leq 1$, leading us to the conclusion.

APPENDIX B

PROOF OF PROPOSITION 3

For the ease of description, we first define

\[
h(x) \triangleq \frac{2N_i^2R_{bh}}{1 + xd_b^{-\frac{1}{2}}N_i - 2R_{bh}}.
\] (56)

Letting $t = \frac{z^\alpha + \tilde{P}_{jam}}{a_1 + \tilde{P}_{jam}}$ where $a_1 = h(\tilde{P}_b)$, and $t_0 = \frac{z^\alpha}{a_2}$ where $a_2 = h(\tilde{P}_{tot})$, we rewrite (58) as

\[
\mathcal{P}_{out} = 1 - \left\{ \int_{d_{\min}}^{d_{\max}} F_{s_{c:b}}(t) \times \frac{2z}{d^2_{\max} - d^2_{\min}} \, dz \right\}^L.
\] (57)

Since $F_{s_{c:b}}(\cdot)$ is an increasing function, $\mathcal{P}_{out}$ decreases with $t$ in the domain of $F_{s_{c:b}}(\cdot)$. Therefore, if the following conditions are satisfied, we can conclude that jamming is beneficial.

1) There exists a positive value of $\tilde{P}_{jam}$, which holds $t - t_0 > 0$ for any $z \in D_c$; and
2) $z \in D_c$ such that $t_0 < \frac{z^\alpha}{a_2}$

where condition 1) defines the scenario, in which jamming can always result in a larger $t$ than $t_0$ (corresponding to the no-jamming case), thereby leading to lower $\mathcal{P}_{out}$ since it is a decreasing function in $t$. Moreover, condition 2) ensures that $t_0$ is less than the maximum feasible value of $s_{c:b}$, otherwise, $\mathcal{P}_{out}$ is always zero either with or without jamming under condition 1), hence the benefits of jamming cannot be concluded. For 1), it is equivalent to prove that \[ \frac{z^\alpha + \tilde{P}_{jam}}{a_1 + \tilde{P}_{jam}} > \frac{z^\alpha}{a_2} \] (58) has a positive solution of $\tilde{P}_{jam}$. Note that with proper parameter setting that $\phi$ is no larger than $\phi_{\max}$ described in (17), we have $a_1 > 0$ and $a_2 > 0$, and note that if $d^2_{\max} < a_2$ then $z^\alpha < a_2$ holds for any $z$. In this case, (58) can be equivalently rewritten as

\[
\tilde{P}_{jam} > \frac{(a_1 - a_2)z^\alpha}{a_2 - z^\alpha}.
\] (60)

Noting that $\frac{d^2h(x)}{dx} < 0$, it is clear from (60) that $\tilde{P}_{jam} > 0$, thus (59) is a sufficient condition to satisfy 1). On the other hand, as $t_0 \leq \frac{d^2h(x)}{dx} a_2$, a sufficient condition that satisfies 2) is

\[
d^2_{\max} < a_{c:b} a_2.
\] (61)

Here, according to Lemma 1, we have $a_{c:b} \leq 1$. Hence, the intersection of (59) and (61) is equal to (61), and recalling the definition of $a_2$ leads to the final result.

APPENDIX C

PROOF OF COROLLARY 2

First, from (52), (53), $s_{c:b}(\theta_e)$ in the $m$-th side lobe can be presented as

\[
s_{c:b}(\theta_e) = 1 - s_{c:b}(\theta_e) = \frac{K_{e:b} \sin^2(N_i \pi dx)}{N_i^2 \sin^2(\pi dx)}, \quad x \in \left[ \frac{m}{N_i d}, \frac{m + 1}{N_i d} \right].
\] (62)

In (62), sine functions appear in both the numerator and denominator, making it infeasible to obtain closed-form results in further analysis. Hence, we find an upper bound of (62) by fixing the value of $x$ to the left end point of its domain, i.e., $x = \frac{m}{N_i d}$, in the denominator.

\[
s_{c:b}(\theta_e) \leq \frac{K_{e:b} \sin^2(N_i \pi dx)}{\pi^2 m^2}.
\] (63)

For the ease of description, we consider only the condition that $\theta_e > 0$. With $\theta_e = 0$, we can rewrite $x$ (defined as $x = |\sin \theta_e - \sin \theta_0|$) in terms of $\theta_e$ as

\[
x = \sin \theta_e \leq \theta_e.
\] (64)

Note that the side lobes that are close to the main lobe are more important in contributing to the area of the SOR, as a result, the value of $\theta_e$ that should be concerned is very small. Therefore, the upper bound in (64) can be very tight. Combining (63) and (64) we have

\[
s_{c:b}(\theta_e) \leq \frac{K_{e:b} \sin^2(N_i \pi d \theta_e)}{\pi^2 m^2}.
\] (65)

Substitute (65) into (19), and calculate the area by integral, we get

\[
\text{Area}_{\text{SOR},m} = \int_{\theta_e \in A_m} \frac{1}{2} \left( C_1(\phi) s_{c:b}(\theta_e) - C_2(\phi) \right) \, d\theta_e
\leq \int_{\theta_e \in A_m} \frac{1}{2} \left( C_1(\phi) K_{e:b} \pi^2 m^2 \sin^2(N_i \pi d \theta_e) - C_2(\phi) \right) \, d\theta_e
= \frac{1}{N_i \pi d} \int_{m\pi}^{(m+1)\pi} \frac{1}{2} \left( C_1(\phi) K_{e:b} \pi^2 m^2 \sin^2(\eta) - C_2(\phi) \right) \, d\eta
= \frac{1}{4N_i d} \left( \frac{K_{e:b}}{\pi^2 m^2} C_1(\phi) - 2C_2(\phi) \right).
\] (68) (69)
where $A_m = \left[ \frac{mN_d}{N_d} \right]$, is the physical angle range of the $m$-th side lobe. To obtain (66), we use $\alpha = 2$, and (62) is obtained using (63). From (67) to (68), we use the variable substitution $\eta = N_d \pi d \theta_s$, then (69) is obtained by simple integral calculation of elementary functions.

### APPENDIX D

**Proof of Corollary 3**

When $\theta_{ei} = \theta_e$, $\forall l = 1,..., L$, $P_{out}$ in (30) is determined only by $d_e$, such that

$$P_{out} = 1 - \left( \int_{d_{\min}}^{d_{\max}} \frac{2z}{d_{\max}^2 - d_{\min}^2} dz \right)^L$$  

(70)

where

$$d_0(\phi, \theta_e) = \left[ \frac{\bar{h}((1 - \phi) P_{tot} + \phi \tilde{P}_{tot}) + s_{e;b}(\theta_e) - \tilde{P}_{tot}}{\bar{g}(\phi)} \right]^\frac{1}{\frac{1}{2}}$$  

(71)

is the distance threshold. Given $\theta_e$, any Eve with a distance to Alice smaller than $d_0(\phi, \theta_e)$ can cause secrecy outage. Noting this, (70) calculates the overall outage probability by assuming that $d_e$ follows uniform distribution. Clearly, if $\min d_0(\phi, \theta_e) < d_{\min}$, the integral range in (70) becomes $[d_{\min}, d_{\max}]$ hence a zero SOP can be achieved; otherwise if $\min d_0(\phi, \theta_e) > d_{\max}$, a definite outage occurs with probability $1$.

Rewrite $g(\phi)$ in (71) as

$$g(\phi) \triangleq s_{e;b}(\theta_e) g_1(\phi) + (1 - s_{e;b}(\theta_e)) g_2(\phi)$$  

(72)

where $g_1(\phi) \triangleq \bar{h}(1 - \phi) P_{tot}$, $g_2(\phi) \triangleq -\phi \tilde{P}_{tot}$ and $h(\cdot)$ is defined in (56). Clearly, minimizing (70) is equivalent to minimizing (72). Since $g_1(\phi)$ is concave and $g_2(\phi)$ is linear, $g(\phi)$ is concave. Hence, letting $\frac{\partial g_2(\phi)}{\partial \phi} = 0$, the optimal $\phi$ satisfying $\phi < \phi_{\max}$ (as in (14)) is given by $\phi_{\max}^{opt}$. Note that if $d_0(\phi_{\max}^{opt}, \theta_e) < d_{\min}$, setting $\phi_{\max}^{opt} = \phi_{\max}$ is not the only choice since the solution of $d_0(\phi, \theta_e) = d_{\min}$ (if exists), denoted as $\phi_0$, also achieves zero SOP. Therefore, we need to check the value of $\phi_0$ and compare it with $\phi_{\max}^{opt}$ to determine the final optimal jamming power allocation. Note that in (72), the value of $g_1(\phi)$ is usually much less than $g_2(\phi)$. Hence, when $s_{e;b}(\theta_e)$ is not so large, $g(\phi)$ can be well approximated by a linear function as $g(\phi) \approx s_{e;b}(\theta_e) h(\tilde{P}_{tot}) - (1 - s_{e;b}(\theta_e)) \tilde{P}_{tot}$. Using this approximation, we get $\phi_{\max}^{opt} = s_{e;b}(\theta_e) h(\tilde{P}_{tot}) - d_{\max}^2 / \frac{3}{2}$. If $\phi_0 \notin [0, 1]$, it is not a feasible solution in practice. If $\phi_0 \in [0, 1]$, both $\phi_0$ and $\phi_{\max}^{opt}$ are able to achieve zero SOP. In this case, we choose the smaller one between $\phi_{\max}^{opt}$ and $\phi_0$ to save jamming power such that $\phi_{\max}^{opt} = \min\{\phi_{\max}^{opt}, \phi_0\}$.

### APPENDIX E

**Derivation of Algorithm 3**

Algorithm 3 is proposed based on the following assumptions and approximations:

5 To facilitate the analysis, we assume the definite outage will not happen by letting $d_{\max}$ to be large enough such that $d_{\max} > \min_{\theta_e} d_0(\phi, \theta_e)$.

1) Assuming that the angle ranges occupied by every side lobe (and the main lobe) of $R_{SOR}^{dij}(\bar{p})$ are approximately the same (which is $\frac{\pi}{M+1}$), assuming that there are in total one main lobe and $M$ side lobes within the angle range $[\frac{\pi}{2}, \frac{\pi}{2}]$, an upper bound of the integral in (47) can be approximated by

$$\text{Area}_{UB} \left( R_{SOR}^{dij}(\bar{p}) \right) \approx \frac{\pi}{2(M + 1)} \sum_{m=0}^{M} \left( d_m^{dij}(\bar{p}, \theta_m) \right)^2$$  

(73)

where the area of every side lobe is upper bounded by the area of its enclosing sector.

2) We assume that $s(\theta_m)\bar{H}_m = 1$ and $\bar{s}(\theta_m)\bar{H}_m = 0$, $\forall n \neq m$. In practice, by defining $\bar{v}_m = \frac{s(\theta_m)\bar{H}_m}{\bar{s}(\theta_m)\bar{H}_m}$, this assumption is easy to realize with large $N_e$, where asymptotic orthogonality holds. Now, according to (44), $d_m^{dij}(\bar{p}, \theta_m)$ in (75) can be written as

$$d_m^{dij}(\bar{p}, \theta_m) = \left[ (a_m - \tilde{P}_m) \right]^\frac{1}{\theta}$$  

(74)

where $a_m = \frac{(1 - \phi) P_{tot}(N_e + 1)^{R_{EF}^{u}} s_{e;b}(\theta_m)}{1 - (1 - \phi)P_{tot}d_{\min}^2 N_e + 1}$ and $\tilde{P}_m = \frac{P_{tot}}{N_e}$. $\theta$ is the $m$-th element of $\bar{p}$, with $\tilde{P}_m$ being the jamming power allocated on the $m$-th side lobe.

From (73) and (74), and given fixed $\phi$, we rewrite the original area minimization problem as

$$\min_{m=1}^{M} \left( a_m - \tilde{P}_m \right)^\frac{1}{\theta}$$  

(75)

s.t. $\sum_{m=0}^{M} \tilde{P}_m = \phi P_{tot}$, $0 \leq \tilde{P}_m \leq a_m$.  

(76)

By checking the Hessian matrix, it is easy to show that the objective function in (75) is concave. To minimize a concave function, clearly, the optimal solution can be found only on the boundaries of the domain defined by (76). Recalling that the area of the side lobes decreases rapidly with larger lobe index, and being aware that jamming should be avoided within the main lobe to prevent degrading Bob’s channel, we further simplify the problem by checking the boundary of the domain as described in (48). According to these discussions, Algorithm 3 is obtained.

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