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The Effect of Spatial Interference Correlation and Jamming on Secrecy in Cellular Networks

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***Abstract*—Recent studies on secure wireless communication have shed light on a scenario where interference has a desirable impact on network performance. Particularly, assuming independent interference-power fluctuations at the eavesdropper and the receiver, opportunistic secure-information transfer can occur on the legitimate-link. However, interference is spatially correlated due to the common set of interfering sources, which may diminish the opportunistic-secure-spectrum-access (OSSA) probability. We study and quantify the effect of spatial interference correlation on OSSA in cellular-networks and investigate the potential of full-duplex jamming (FDJ) solutions. The results highlight the scenarios where FDJ improves OSSA performance.**

***Index Terms*—interference, correlation, eavesdropper, stochastic geometry, jamming**

I. Introduction

Until recently, network interference has been considered an undesirable performance-limiting parameter for wireless communication. This viewpoint is changing with the emerging requirement for physical layer security since interference may help achieve transmission secrecy [1], [2]. Secure information transmission opportunities arise from the random fluctuations of the interference power at the receiver and eavesdropper. Particularly, exploiting the time intervals where the receiver (eavesdropper) experience low (high) interference, the transmitter can send information at a rate that is higher than the capacity of the eavesdropper link. This leads to the event of opportunistic secure spectrum access (OSSA) in which the eavesdropper cannot decode the message while the legitimate receiver can.

The effect of interference on transmission secrecy is mainly studied and quantified assuming independent interference at the receiver and eavesdropper [1], [2]. However, interference is spatially correlated [3]–[5], and assuming it to be independent would, as we shall see, overestimate the OSSA performance particularly as the eavesdropper gets closer to the receiver. Hence, the OSSA performance should be characterized in terms of the distance between the receiver and eavesdropper. To the best of the authors' knowledge, this problem has not been investigated in the literature. Numerous works have considered the impact of correlated fading between the eavesdropper and receiver in small networks on the achievable secrecy [6], [7]; however, our focus is on independent fading but correlated interference in a large network. This case is more practically relevant since the spacing between legitimate users and eavesdroppers certainly exceeds the coherence length of the fading, while the interference is correlated over much larger distances.

This paper uses stochastic geometry to study and quantify the effect of interference correlation on OSSA in a large cellular network. We condition on a user equipment (UE) located at the origin $\mathbf{o}$, which, under expectation over the point process (PP), becomes the typical UE, denoted as tUE. The eavesdropper closest to the tUE's serving base station (BS) is denoted by tEV. Each UE in the network employs full-duplex jamming (FDJ), independently of other UEs, by transmitting a jamming signal based on the location of the eavesdropper closest to its serving BS. We let S denote the event that the tUE successfully receives its serving BS's message and F denote the event that tEV fails to extract information from that message. The OSSA probability is given by $\mathbb{P}(S \cap F)$. The results show that there exists a separation distance between the tUE and tEV below which employing FDJ for the tUE improves OSSA, otherwise FDJ at the tUE does not improve OSSA but increases network interference and power consumption.

Notation: We denote vectors using bold text, $\|\mathbf{z}\|$ is used to denote the Euclidean norm of the vector $\mathbf{z}$, and $b(\mathbf{z}, R)$ denotes a ball centered at $\mathbf{z}$ with radius R. $\mathcal{L}_X(s) = \mathbb{E}[e^{-sX}]$ denotes the Laplace transform (LT) of the PDF of the RV X. The ordinary hypergeometric function is denoted by ${}_2F_1$.

II. System Model

1) Network Model: We focus on the downlink of a network where the BSs form a homogeneous Poisson PP (PPP) $\Phi_{\rm b}$ with intensity λ. The PP of UEs, $\Phi_{\rm u}$, is obtained by placing a point uniformly at random in each Voronoi cell of $\Phi_{\rm b}$. This is the user model of type I in [8]. These UEs are served in the same time-frequency resource block. Eavesdroppers are distributed according to an arbitrary stationary PP independent of $\Phi_{\rm b}$. A UE employs FDJ if the nearest eavesdropper is closer than a certain distance, and if it does, it transmits with power $P_{\rm u}$, contributing to the aggregate interference. UEs are able to cancel a fraction $1-\nu$ of their own jamming power.

We assume an interference-limited regime where all BSs transmit with the same power $P_{\rm b}$. A Rayleigh fading environment is considered, hence the fading coefficients follow a unit mean exponential distribution. Also, it is assumed that all

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channel gains are independent from one another. A power law path loss model is considered where the signal power decays at the rate $r^{-\eta}$ with the distance r, where $\eta > 2$ is the path loss exponent and we use δ to denote $2/\eta$. We refer to the network described in this section as the *actual network of interest*.

2) Methodology of Analysis: A BS transmits a message at a rate of $\mathcal{R}_t = \log(1+\tau_1)$. According to Wyner's encoding scheme [9], $\mathcal{R}_s = [\mathcal{R}_t - \mathcal{R}_e]^+$ is the rate of secure communication, where $\mathcal{R}_e = \log(1+\tau_2)$ is the cost of securing the message. Hence, for $\mathcal{R}_s > 0$, we require $\tau_1 > \tau_2$. The message can therefore be decoded securely at the tUE if the signal-to-interference-ratio (SIR) exceeds τ_1 (i.e., the event S occurs). For the eavesdroppers, let $F^{\cap}$ be the event that the SIR at each eavesdropper is below τ_2. Since $F^{\cap}$ is cumbersome to analyze, we focus on the event $F \supset F^{\cap}$ that the SIR at tEV is below τ_2. The two main performance metrics are the probability of OSSA, i.e., $\mathbb{P}(S \cap F)$, and the success probability of the tUE, $\mathbb{P}(S)$.[1] To characterize the effect of spatial interference correlation, we also derive the metrics assuming independent interference.

III. SIR Analysis

A. Framework

By construction, the PP of UEs $\Phi_{\rm u}$ is stationary but not Poisson since there is only one UE per cell. It is a *soft-core* process, where the likelihood of having two points very close is much smaller than in a PPP. To enable an analysis of the interference caused by FDJ, we use the approximation in [8], where the PP of UEs as seen from the tUE is a non-homogeneous (but isotropic) PPP with radial intensity function $\lambda(r) = \lambda g(r)$, where $g(r) \approx 1 - e^{-3\sqrt{\lambda}r}$ is the pair correlation function [10, Def. 6.6] of the PP of UEs. This way, the repulsion between the tUE and the interfering UEs is captured.

Since $\Phi_{\rm b}$ is a PPP, the legitimate link distance R is Rayleigh distributed with mean $\frac{1}{2\sqrt{b\lambda}}$ and $b = \frac{13}{10}$, where the correction factor is due to the fact that the tUE resides in the typical cell, not the Crofton cell. Hence we use $f_R(r) = 2b\pi\lambda r e^{-b\pi\lambda r^2}$, $r \geq 0$ (see [8, (12)]). The orientation of a UE w.r.t. its BS, θ, is uniform on $[0, 2\pi]$.

We refer to the network where the UEs, as seen from the tUE, form a PPP with radial intensity function $\lambda(r) = \lambda\left(1 - e^{-3\sqrt{\lambda}r}\right)$ and link distance PDF f_R as the *analytical network of interest*. A UE employs FDJ independently of other UEs with some probability q, which is the probability that the eavesdropper nearest to its serving BS lies closer to the UE than some threshold distance. The PP of jamming UEs, $\Phi_{\rm j}$, is therefore a thinned version of $\Phi_{\rm u}$ with intensity function $\lambda_{\rm j}(r) = q\lambda\left(1 - e^{-3\sqrt{q\lambda}r}\right)$. To characterize the effect of interference correlation as a function of the distance between tUE and tEV, we condition on tEV to be located at $\mathbf{v} = (v, 0)$. It should be noted that in our analysis the tUE does not employ FDJ with probability q, instead we study its performance with and without FDJ. The performance of tUE if it uses FDJ with probability q is easily obtained by averaging the performance with and without FDJ.

[1] The SIR at tEV is not necessarily the largest among all eavesdroppers due to interference and fading (and the BS does not have information about the CSI of the eavesdroppers). Thus, we have $\mathbb{P}(S \cap F) > \mathbb{P}(S \cap F^{\cap})$, but the two probabilities are close thanks to the large-scale path loss.

Let $\mathrm{SIR}_{\rm u}$ and $\mathrm{SIR}_{\rm e}$ be the SIRs at the tUE and tEV, respectively. The distance from the tUE's BS to tEV is $\|\mathbf{R}-\mathbf{v}\|$, where $\mathbf{R}{=}(R\cos\theta, R\sin\theta)$.

$$\mathrm{SIR}_{\rm u} = \frac{P_{\rm b} h_0 R^{-\eta}}{P_{\rm b}\mathcal{I}_{\rm bu} + P_{\rm u}\mathcal{I}_{\rm uu} + \mathbb{1}_J P_{\rm u}\nu} \quad (1)$$

$$\mathrm{SIR}_{\rm e} = \frac{g_0\|\mathbf{R}-\mathbf{v}\|^{-\eta}}{\mathcal{I}_{\rm be} + \frac{P_{\rm u}}{P_{\rm b}}\mathcal{I}_{\rm ue} + \mathbb{1}_J \frac{P_{\rm u}}{P_{\rm b}}\tilde{g}_0 v^{-\eta}}, \quad (2)$$

where $\mathcal{I}_{\rm bu} = \sum_{\mathbf{x}\in\Phi_{\rm b}} h_{\mathbf{x}}\|\mathbf{x}\|^{-\eta}$, $\mathcal{I}_{\rm uu} = \sum_{\mathbf{y}\in\Phi_{\rm j}} h_{\mathbf{y}}\|\mathbf{y}\|^{-\eta}$,

$\mathcal{I}_{\rm be} = \sum_{\mathbf{x}\in\Phi_{\rm b}} g_{\mathbf{x}}\|\mathbf{x}-\mathbf{v}\|^{-\eta}$ and $\mathcal{I}_{\rm ue} = \sum_{\mathbf{y}\in\Phi_{\rm j}} g_{\mathbf{y}}\|\mathbf{y}-\mathbf{v}\|^{-\eta}$.

The fading coefficients from the tUE's BS to itself and tEV are h_0 and g_0, respectively; while $h_{\mathbf{x}}$ ($h_{\mathbf{y}}$) and $g_{\mathbf{x}}$ ($g_{\mathbf{y}}$) are the fading coefficients from the BS located at $\mathbf{x}$ (jamming UE located at $\mathbf{y}$) to the tUE and tEV, respectively. If jamming at the tUE is active, the indicator function $\mathbb{1}_J$ is 1, otherwise it is 0. The fading coefficient from the tUE to the tEV is $\tilde{g}_0$, and ν is the fraction of residual self-interference (RSI) experienced at the tUE because of imperfect cancellation of the jamming signal. We define the probability of successful reception at the tUE as $\mathbb{P}(S) = \mathbb{P}(\mathrm{SIR}_{\rm u} \geq \tau_1)$ and failure to extract information from the received message at tEV as $\mathbb{P}(F) = \mathbb{P}(\mathrm{SIR}_{\rm e} < \tau_2)$.

The normalized interference (i.e. assuming unit transmit power) from the BSs to the tUE (tEV) is denoted by $\mathcal{I}_{\rm bu}$ ($\mathcal{I}_{\rm be}$), and from the jamming UEs to the tUE (tEV) by $\mathcal{I}_{\rm uu}$ ($\mathcal{I}_{\rm ue}$). Additionally, we use the notations $\mathbf{x} = (x\cos\phi, x\sin\phi)$ and $\mathbf{r} = (r\cos\theta, r\sin\theta)$.

Lemma 1: In the analytical network of interest, conditioned on the link distance R, the LTs of the interferences are

$$\mathcal{L}_{\mathcal{I}_\chi}(s) = \exp\left(-\int_{\mathbb{R}^2} \frac{s}{s + \|\mathbf{z}_\chi\|^\eta}\lambda_\chi(\mathbf{x})d\mathbf{x}\right), \quad (3)$$

for $\chi \in \{\mathrm{bu}, \mathrm{be}, \mathrm{uu}, \mathrm{ue}\}$. The intensity functions $\lambda_\chi(\mathbf{x})$ are:
$\lambda_{\rm bu}(\mathbf{x}) = \lambda_{\rm be}(\mathbf{x}) = \lambda\left(1 - \mathbf{1}\{\mathbf{x} \in b(\mathbf{o}, R)\}\right)$
$\lambda_{\rm uu}(\mathbf{x}) = \lambda_{\rm ue}(\mathbf{x}) = q\lambda\left(1 - e^{-3\sqrt{q\lambda}\|\mathbf{x}\|}\right)$.
For $\chi \in \{\mathrm{bu}, \mathrm{uu}\}$, $\mathbf{z}_\chi = \mathbf{x}$ and for $\chi \in \{\mathrm{be}, \mathrm{ue}\}$, $\mathbf{z}_\chi = \mathbf{x} - \mathbf{v}$. For the case of $\mathcal{I}_{\rm bu}$, the LT simplifies to

$$\mathcal{L}_{\mathcal{I}_{\rm bu}}(s) = \exp\left(-\frac{2\pi\lambda s}{(\eta-2)R^{\eta-2}}\, {}_2F_1\left(1, 1-\delta; 2-\delta; \frac{-s}{R^\eta}\right)\right) \quad (4)$$

$$\overset{\eta=4}{=} e^{-\pi\lambda\sqrt{s}\tan^{-1}\left(\sqrt{\frac{s}{R^4}}\right)}. \quad (5)$$

Proof: The LTs follow from the probability generating functional (PGFL) of the PPP. □

B. Marginal Probabilities in the Analytical Network of Interest

The probabilities of the events S and F are

$$\mathbb{P}(S) = \mathbb{P}\left(h_0 \geq \tau_1 R^\eta\left(\mathcal{I}_{\rm bu} + \frac{P_{\rm u}}{P_{\rm b}}\mathcal{I}_{\rm uu} + \mathbb{1}_J\frac{P_{\rm u}}{P_{\rm b}}\nu\right)\right)$$

$$= \int_0^\infty \mathcal{L}_{\mathcal{I}_{\rm bu}}(\tau_1 r^\eta)\mathcal{L}_{\mathcal{I}_{\rm uu}}\left(\frac{P_{\rm u}}{P_{\rm b}}\tau_1 r^\eta\right) e^{-\mathbb{1}_J\frac{P_{\rm u}}{P_{\rm b}}\tau_1\nu r^\eta} f_R(r)dr. \quad (6)$$

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$$\begin{aligned}\mathbb{P}(F)=&\mathbb{P}\left(g_0<\tau_2\|\mathbf{R}-\mathbf{v}\|^\eta\left(\mathcal{I}_{\rm be}+\frac{P_{\rm u}}{P_{\rm b}}\mathcal{I}_{\rm ue}+\mathbb{1}_J\frac{P_{\rm u}}{P_{\rm b}}\tilde{g}_0 v^{-\eta}\right)\right)\\
=&1-\int_{\mathbb{R}^2}\mathbb{E}_{\tilde{g}_0}\left[e^{\frac{-\mathbb{1}_J\tilde{g}_0\|\mathbf{r}-\mathbf{v}\|^\eta}{\frac{P_{\rm b}}{\tau_2P_{\rm u}}v^\eta}}\right]\mathcal{L}_{\mathcal{I}_{\rm ue}}\left(\frac{\|\mathbf{r}-\mathbf{v}\|^\eta}{\frac{P_{\rm b}}{\tau_2P_{\rm u}}}\right)\times\\
&\mathcal{L}_{\mathcal{I}_{\rm be}}\left(\tau_2\|\mathbf{r}-\mathbf{v}\|^\eta\right)\frac{f_R(\|\mathbf{r}\|)}{2\pi}d\mathbf{r}\\
=&1-\int_{\mathbb{R}^2}\frac{\mathcal{L}_{\mathcal{I}_{\rm ue}}\left(\frac{\|\mathbf{r}-\mathbf{v}\|^\eta}{\frac{P_{\rm b}}{\tau_2P_{\rm u}}}\right)\mathcal{L}_{\mathcal{I}_{\rm be}}\left(\tau_2\|\mathbf{r}-\mathbf{v}\|^\eta\right)}{1+\mathbb{1}_J\frac{P_{\rm u}}{P_{\rm b}}\tau_2\|\mathbf{r}-\mathbf{v}\|^\eta v^{-\eta}}\frac{f_R(\|\mathbf{r}\|)}{2\pi}\,d\mathbf{r}.\end{aligned}\tag{7}$$

IV. The Effect of Spatial Correlation

We are interested in the OSSA event $S\cap F$ and the event $S \mid F$ that the tUE has successful reception given that tEV is in SIR outage. The effect of interference correlation on OSSA is demonstrated by comparing the probabilities of these events when the spatial correlation is considered between tEV and tUE, and when its not.

Theorem 1: In the analytical network of interest, the OSSA probability is

$$\begin{aligned}\mathbb{P}(S\cap F)=\mathbb{P}(S)-\int_0^{2\pi}\int_0^\infty&\frac{e^{-\mathbb{1}_J\frac{P_{\rm u}}{P_{\rm b}}\tau_1r^\eta\nu}}{1+\mathbb{1}_J\frac{P_{\rm u}}{P_{\rm b}}\tau_2\frac{\|\mathbf{r}-\mathbf{v}\|^\eta}{\|\mathbf{v}\|^\eta}}\times\\
&e^{-\lambda(\mathcal{B}(r,\theta)+\mathcal{F}(r,\theta))}\frac{f_R(r)}{2\pi}drd\theta\end{aligned}\tag{8}$$

where $\mathbb{P}(S)$ is from (6) and

$$\mathcal{B}(r,\theta)=\int_0^{2\pi}\int_r^\infty\left(1-\frac{\left(1+\tau_1r^\eta x^{-\eta}\right)^{-1}}{1+\tau_2\frac{\|\mathbf{r}-\mathbf{v}\|^\eta}{\|\mathbf{x}-\mathbf{v}\|^\eta}}\right)x\;dxd\phi\tag{9}$$

$$\begin{aligned}\mathcal{F}(r,\theta)=&\int_0^{2\pi}\int_0^\infty q\left(1-e^{-3\sqrt{q\lambda}\|\mathbf{x}\|}\right)\times\\
&\left(1-\frac{\left(1+\frac{P_{\rm u}}{P_{\rm b}}\tau_1r^\eta x^{-\eta}\right)^{-1}}{1+\frac{P_{\rm u}}{P_{\rm b}}\tau_2\|\mathbf{r}-\mathbf{v}\|^\eta\|\mathbf{x}-\mathbf{v}\|^{-\eta}}\right)x\;dxd\phi.\end{aligned}\tag{10}$$

Proof: See Appendix A. □

Corollary 1: In the analytical network of interest, ignoring the fact that interference is correlated at the tUE and tEV, $\mathbb{P}(S\cap F)=\mathbb{P}(S)\mathbb{P}(F)$ and $\mathbb{P}(S\mid F)=\mathbb{P}(S)$.

Proof: Assuming independent interference makes S and F independent. □

V. Numerical Results

The intensity of the BSs and UEs used in this section is $\lambda=10$ /km^2. We take the transmit powers to be $P_{\rm b}=1$ and $P_{\rm u}=0.2$, $\eta=4$ and $\nu=-90$ dB. $\tau_2=\tau_1-0.1$ and $q=0.5$ for all of the figures, and in Figs. 2 and 3 we set $\tau_1=0$ dB.

Fig. 1 is a plot of the different probabilities for the analytical network of interest against τ_1 (and τ_2) when FDJ is employed at the tUE (solid lines) and when it is not (dash-dotted lines). Our assumptions are verified as the simulation for the actual network of interest matches the analysis well.

Fig. 2 is a plot of $\mathbb{P}(S\cap F)$ and $\mathbb{P}(S\mid F)$ without FDJ at the tUE as a function of v. For the comparison, the probabilities

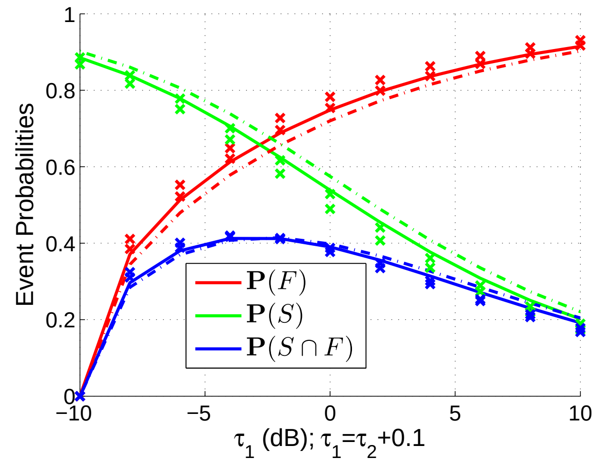

Fig. 1: Probabilities vs. τ_1 (and τ_2) at $v=\frac{1}{2\sqrt{\lambda}}$ for the network with jamming. Solid lines show the analysis when tUE employs FDJ ($\nu=-90$ dB) and dash-dotted lines show when it does not. Markers show the Monte Carlo simulations.

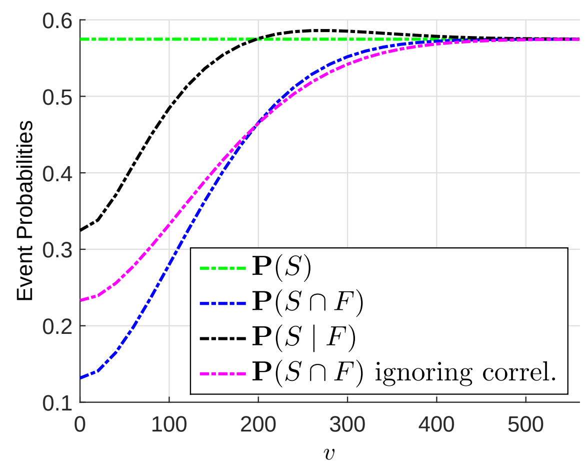

Fig. 2: Probabilities vs. v without FDJ at the tUE. Ignoring correlation results in $\mathbb{P}(S\mid F)=\mathbb{P}(S)$.

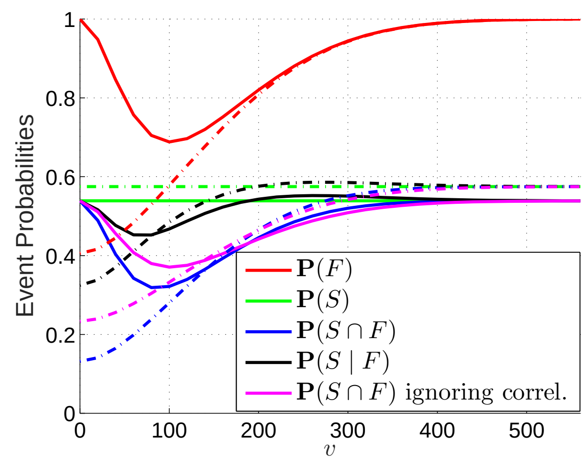

Fig. 3: Probabilities vs. v with $\nu=-90$ dB. Ignoring correlation results in $\mathbb{P}(S\mid F)=\mathbb{P}(S)$. Solid lines represent the tUE employing FDJ and dash-dotted lines represent the tUE without FDJ.

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obtained when interference correlation is ignored are also shown. We observe at smaller values of v the difference between $\mathbb{P}(S \cap F)$ when considering and ignoring interference correlation is significant. This highlights the impact on achievable secrecy when tEV lies near the tUE; not considering interference correlation would give overly optimistic estimates of the OSSA. As v increases, the interference experienced at tEV and tUE decorrelates, and the two curves eventually meet. Further, both curves meet the curve of $\mathbb{P}(S)$ at high v, as larger values of v imply tEV is far and always in outage, thereby simplifying $\mathbb{P}(S \cap F)$ to $\mathbb{P}(S)$.

Fig. 3 is a plot of the probabilities of interest as a function of v both when the tUE employs FDJ (solid lines) and when it does not (dash-dotted lines). It is observed that the curve for $\mathbb{P}(F)$ when the tUE employs FDJ has a dip. This occurs because at smaller values of v, FDJ from the tUE dominates the interference at tEV causing it to be in outage. As v increases, the effect of jamming decreases when compared to the interference until the situation is reversed. When the tUE employs FDJ, $\mathbb{P}(S \mid F)$ (when interference correlation is considered) and $\mathbb{P}(S \cap F)$ reflect this trend. Additionally, due to RSI, for the case of FDJ at the tUE, all the probabilities that are impacted by S are reduced.

In Fig. 3 we observe that at lower v employing FDJ at the tUE significantly enhances secure communication. However, after a certain v, the values of $\mathbb{P}(S \cap F)$ and $\mathbb{P}(S \mid F)$ with FDJ at the tUE do not outperform the case without FDJ. This shows that FDJ at the tUE is useful for enhancing OSSA when the distance between the tUE and tEV is small. However, at larger values of v, the achievable secrecy with FDJ at the tUE is not larger than that without FDJ. This occurs because the FDJ signal from the tUE does not dominate the deterioration of the performance of tEV anymore at larger v. Employing FDJ after this distance is not useful as it increases network interference and is a waste of power; additionally, when ν is large enough to deteriorate $\mathbb{P}(S)$, it reduces the maximum achievable OSSA from the case without FDJ at the tUE.

Due to space constraints we do not include results for other values of ν. With FDJ at the tUE, increasing ν reduces the probabilities of events that include S; the trends for the curves, however, remain the same. It ought to be mentioned that if ν is too high, the OSSA probability would be too low due to very large RSI, making the employment of FDJ at the tUE a hindrance to secure communication even at small v.

VI. CONCLUSION

We analyze the probability of secure communication in the downlink of a Poisson cellular network where UEs have FDJ capability when an eavesdropper lies near the UE under consideration. The interference powers at the UE and eavesdropper are correlated. To highlight the impact of the correlated interference, we compare the results with those obtained if interference was assumed to be independent. We consider two scenarios: with jamming and without jamming by the UE under consideration. We find that in both cases ignoring interference correlation overestimates the probability of secure communication, particularly at smaller distances between the eavesdropper and UE of interest. The numerical results show that there exists a critical distance between the legitimate receiver and eavesdropper after which jamming by the UE under consideration does not enhance the achievable secrecy. We conclude that jamming is an effective solution to combat the negative effect of interference correlation on secrecy when the eavesdropper lies close to the receiver and RSI is tolerable.

APPENDIX A
PROOF OF THEOREM 1

By definition,

$$\mathbb{P}(S \cap F) = \mathbb{P}(S) - \underbrace{\mathbb{E}\left[e^{-\tau_1 R^\eta \left(\mathcal{I}_{\mathrm{bu}} + \frac{P_{\mathrm{u}}}{P_{\mathrm{b}}}(\mathcal{I}_{\mathrm{uu}} + \mathbb{1}_J \nu)\right) - \tau_2 \|\mathbf{R} - \mathbf{v}\|^\eta \left(\mathcal{I}_{\mathrm{be}} + \frac{P_{\mathrm{u}}}{P_{\mathrm{b}}}(\mathcal{I}_{\mathrm{ue}} + \mathbb{1}_J \frac{\tilde{g}_0}{v^\eta})\right)}\right]}_{\mathcal{A}}.$$

Since Φ_{b} and Φ_{j} are PPPs, employing the PGFL of the PPP and the MGF of $\tilde{g}_0 \sim \exp(1)$ we have

$$\mathcal{A} = \mathbb{E}_{R,\theta}\left[e^{-\lambda \mathcal{B}(R,\theta)} e^{-\lambda \mathcal{F}(R,\theta)} \frac{e^{-\mathbb{1}_J \frac{P_{\mathrm{u}}}{P_{\mathrm{b}}} \tau_1 r^\eta \nu}}{1 + \mathbb{1}_J \frac{P_{\mathrm{u}}}{P_{\mathrm{b}}} \tau_2 \frac{\|\mathbf{r}-\mathbf{v}\|^\eta}{\|\mathbf{v}\|^\eta}}\right].$$

Here,

$$\mathcal{B}(r,\theta) = \int_0^{2\pi} \int_r^\infty \mathbb{E}_{h_{\mathbf{x}}, g_{\mathbf{x}}}\left[1 - e^{-\tau_1 \frac{r^\eta h_{\mathbf{x}}}{\|\mathbf{x}\|^\eta} - \tau_2 \frac{\|\mathbf{r}-\mathbf{v}\|^\eta}{\|\mathbf{x}-\mathbf{v}\|^\eta} g_{\mathbf{x}}}\right] x dx d\phi$$

$$\mathcal{F}(r,\theta) = \int_0^{2\pi} \int_0^\infty q\left(1 - e^{-3\sqrt{q\lambda}\|\mathbf{y}\|}\right) \times \mathbb{E}_{h_{\mathbf{y}}, g_{\mathbf{y}}}\left[1 - e^{\frac{P_{\mathrm{u}}}{P_{\mathrm{b}}}\left(-\tau_1 \frac{r^\eta h_{\mathbf{y}}}{\|\mathbf{y}\|^\eta} - \tau_2 \frac{\|\mathbf{r}-\mathbf{v}\|^\eta}{\|\mathbf{y}-\mathbf{v}\|^\eta} g_{\mathbf{y}}\right)}\right] y dy d\phi.$$

Due to the independence of the unit mean exponentially distributed $h_{\mathbf{x}}$ and $g_{\mathbf{x}}$ in $\mathcal{B}(r,\theta)$, and $h_{\mathbf{y}}$ and $g_{\mathbf{y}}$ in $\mathcal{F}(r,\theta)$ and using their MGFs, we obtain (9) and (10).

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