

# Equivalent Degrees of Freedom Based Secrecy Outage Analysis for Fluid Antenna Wiretap Channels



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**Abstract:** Fluid antenna systems (FAS) improve wireless reliability by selecting the strongest port within a compact aperture, but the same port-selection capability also changes the physical-layer security behavior of a wiretap channel. Exact secrecy outage analysis is difficult because the legitimate and eavesdropping links each contain many spatially correlated ports, leading to high-dimensional joint distributions. This paper develops a closed-form secrecy outage framework for FAS wiretap channels using the equivalent degrees of freedom (EDoF) principle. Under the Jakes spatial correlation model, the many correlated physical ports are represented by a much smaller set of aperture-limited dominant spatial modes. The resulting model converts the correlated wiretap channel into a tractable competition between the effective selection branches available to Bob and Eve. An eigenvalue-weighted refinement further captures unequal dominant-mode powers. Closed-form and asymptotic results reveal how Bob's aperture determines secrecy diversity, how Eve's aperture strengthens the eavesdropping link, and why proportional Bob-Eve signal-to-noise ratio scaling produces a nonzero secrecy outage floor. Numerical simulations verify the analytical trends and show that the decisive security resource is Bob's aperture-induced EDoF advantage rather than the raw number of selectable ports.

**Keywords:** equivalent degrees of freedom; fluid antenna system; physical-layer security; secrecy outage probability; wiretap channel

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## 1 Introduction

Physical layer security (PLS) exploits the randomness of wireless fading to protect confidential information directly at the physical layer<sup>[1–2]</sup>. In a wiretap channel, secrecy is created by the instantaneous asymmetry between the legitimate receiver Bob and the eavesdropper Eve. This makes spatial diversity especially valuable, because a receiver that can sample more favorable fades than its adversary can reduce secrecy outage without necessarily increasing power or bandwidth.

Fluid antenna systems (FAS) provide a compact way to create such diversity<sup>[3–8]</sup>. Recent hardware-oriented studies further support this practical motivation by showing that reconfigurable ports or activation states can be implemented within compact apertures, including millimeter-wave (mmWave) surface-wave-enabled prototypes, wideband pixel-based designs, multi-

activation structures with a single RF chain, and programmable meta-fluid antennas<sup>[9–13]</sup>. An FAS exposes many candidate ports inside a finite aperture and activates the port with the most favorable channel realization<sup>[3,14]</sup>. Compared with conventional multi-antenna arrays, this architecture can achieve strong selection gains with limited radio-frequency hardware, which makes it attractive for compact and space-constrained terminals<sup>[8–13]</sup>.

FAS-enabled secure transmission has already started to attract attention<sup>[15–17]</sup>, but rigorous secrecy analysis remains difficult. The central challenge is spatial correlation: the port gains of a FAS are strongly coupled through the aperture geometry and the underlying scattering field<sup>[18–20]</sup>. Once Bob and Eve are both allowed to select their best ports, secrecy outage depends on the joint behavior of two maxima over correlated spatial samples, which quickly becomes analytically unwieldy.

This paper addresses that difficulty by transplanting the equivalent degrees of freedom (EDoF) viewpoint from outage

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analysis to the wiretap setting. The key idea is that the number of effective independent spatial modes is controlled by aperture size rather than by the nominal number of physical ports<sup>[21–22]</sup>. Under the Jakes correlation kernel<sup>[23–24]</sup>, a one-dimensional aperture of normalized length  $W$  has approximately the following number of dominant modes:

$$K^* = 2\lceil W \rceil + 1 \quad (1)$$

Therefore, Bob's FAS can be interpreted as selection over  $K_B^*$  effective branches, while Eve's FAS can be interpreted as selection over  $K_E^*$  effective branches. This paper derives closed-form secrecy outage expressions, extends the method to a weighted independent modes (WIM) refinement, and turns the resulting formulas into aperture-based design insights.

## 2 FAS Wiretap System Model

### 2.1 Spatially Correlated FAS Channels

Consider a transmitter Alice sending confidential information to Bob in the presence of a passive Eve. Bob is equipped with a one-dimensional FAS containing  $N_B$  candidate ports over a normalized aperture  $W_B$ , and Eve with a one-dimensional FAS containing  $N_E$  candidate ports over a normalized aperture  $W_E$ .

The physical aperture lengths are  $L_B$  and  $L_E$ , and the normalized apertures are defined as  $W_B = L_B/\lambda$  and  $W_E = L_E/\lambda$ , where  $\lambda$  is the carrier wavelength.

For each receiver  $q$  in  $\{B, E\}$ , the channel vector across all ports is modeled as follows.

$$\mathbf{g}_q = [g_{q,1}, \dots, g_{q,N_q}]^T \sim \text{CN}(0, \eta_q \mathbf{R}_q) \quad (2)$$

Equivalently, the generic model above specializes to the following complete Bob and Eve channel-vector constructions, where  $\mathbf{z}_B$  and  $\mathbf{z}_E$  are independent standard circularly symmetric complex Gaussian vectors:

$$\mathbf{g}_B = [g_{B,1}, \dots, g_{B,N_B}]^T = \sqrt{\eta_B} \mathbf{R}_B^{1/2} \mathbf{z}_B, \mathbf{z}_B \sim \text{CN}(0, \mathbf{I}_{N_B}),$$

$$\mathbf{g}_E = [g_{E,1}, \dots, g_{E,N_E}]^T = \sqrt{\eta_E} \mathbf{R}_E^{1/2} \mathbf{z}_E, \mathbf{z}_E \sim \text{CN}(0, \mathbf{I}_{N_E}).$$

Under the Jakes isotropic scattering model, the spatial correlation matrix is written as

$$[\mathbf{R}_q]_{m,n} = J_0 \left( \frac{2\pi W_q |m - n|}{N_q - 1} \right) \quad (3)$$

Bob and Eve each select their strongest available port, which leads to the following post-selection signal-to-noise ratios (SNRs).

$$\gamma_B = \bar{\gamma}_B X_B, \quad \gamma_E = \bar{\gamma}_E X_E \quad (4)$$

### 2.2 Secrecy Outage Probability

The instantaneous secrecy rate is defined by:

$$C_s = [\log_2(1 + \gamma_B) - \log_2(1 + \gamma_E)]^+ \quad (5)$$

For a target secrecy rate  $R_s$ , the secrecy outage probability is

$$P_{so} = P(C_s < R_s) \quad (6)$$

The outage event can be rewritten in the equivalent threshold form:

$$X_B < \frac{\theta(1 + \bar{\gamma}_E X_E) - 1}{\bar{\gamma}_B} \quad (7)$$

This threshold relation is the core object of the analysis because the secrecy outage is determined jointly by selected FAS gains of Bob and Eve.

For ease of reference, the symbol list is shown in Table 1.

## 3 EDoF Representation of FAS Wiretap Channels

### 3.1 KL Expansion and Spatial Mode Count

The channel correlation matrix admits an eigendecomposition, and the FAS channel can be represented through the Karhunen-Loève (KL) expansion as follows.

$$\mathbf{R}_q = \mathbf{U}_q \mathbf{\Lambda}_q \mathbf{U}_q^H, \mathbf{g}_q = \sqrt{\eta_q} \mathbf{U}_q \mathbf{\Lambda}_q^{1/2} \mathbf{z}_q \quad (8)$$

For the Jakes kernel, the dominant eigenvalues are concentrated in the first few modes, which yields the EDoF count:

$$K_q^* = 2\lceil W_q \rceil + 1 \quad (9)$$

For a finite set of physical ports, the dominant-mode count for both receivers is therefore given in closed form by  $K_q^* =$

Table 1. Parameters and their denotation

| Parameter                                         | Denotation                                       |
|---------------------------------------------------|--------------------------------------------------|
| $q \in \{B, E\}$                                  | Receiver index (Bob/Eve)                         |
| $N_q$                                             | Number of candidate ports                        |
| $W_q = L_q/\lambda$                               | Aperture length normalized by carrier wavelength |
| $\mathbf{g}_q$ and $\mathbf{R}_q$                 | Channel vector and spatial correlation matrix    |
| $\eta_q$                                          | Average channel power                            |
| $\bar{\gamma}_q$ and $X_q$                        | Average SNR and normalized selected gain         |
| $\min\{N_q, 2\lceil W_q \rceil + 1\}$             | Effective dominant-mode count                    |
| $R_s$ and $\theta$ (2 raised to the power $R_s$ ) | Target secrecy rate and its threshold factor     |
| $P_{so}$                                          | Secrecy outage probability                       |

SNR: signal-to-noise ratio

$$\min \{ N_q, 2\lceil W_q \rceil + 1 \}, q \in \{ B, E \}.$$

The outer minimum enforces the physical limit that the number of effective modes cannot exceed the number of sampled ports. In the dense-port regime considered in this paper,  $N_q \geq 2\lceil W_q \rceil + 1$  and the expression reduces to  $2\lceil W_q \rceil + 1$ .

Increasing the port count beyond the number needed to resolve the aperture therefore does not create unlimited independent branches; it mainly oversamples the same spatial field.

### 3.2 EDoF Approximation

The EDoF model replaces the maximum over correlated port gains by the maximum over  $K_q^*$  independent unit-mean exponential gains.

$$X_q^{\text{EDoF}} = \max_{1 \leq k \leq K_q^*} Z_{q,k}, \quad Z_{q,k} \stackrel{\text{i.i.d.}}{\sim} \text{Exp}(1) \quad (10).$$

Hence the cumulative distribution function and the probability density function become:

$$\begin{aligned} F_q(x) &= (1 - e^{-x})^{K_q^*}, \quad x \geq 0, \\ f_q(x) &= K_q^* e^{-x} (1 - e^{-x})^{K_q^* - 1} \end{aligned} \quad (11).$$

The main design implication is aperture-based: Bob's security advantage stems from a larger effective aperture rather than from raw port oversampling alone.

## 4 Closed-Form Secrecy Outage Under EDoF

Theorem 1. Under the EDoF model, the secrecy outage probability (SOP) can be written in the following closed form.

$$P_{\text{so}}^{\text{EDoF}} = \sum_{j=0}^{K_B^*} \binom{K_B^*}{j} (-1)^j \exp\left(-\frac{j(\theta-1)}{\bar{\gamma}_B}\right) \frac{(K_E^*)!}{\prod_{m=1}^{K_E^*} \left(m + \frac{j\theta\bar{\gamma}_E}{\bar{\gamma}_B}\right)} \quad (12).$$

The expression shows that Bob's effective mode count  $K_B^*$  enters through the outer selection expansion, while Eve's effective mode count  $K_E^*$  enters through the Laplace transform of the selected eavesdropping gain.

Corollary 1. If Eve has no FAS, then  $K_E^* = 1$  and the SOP reduces to:

$$P_{\text{so}}^{\text{EDoF}} = \sum_{j=0}^{K_B^*} \binom{K_B^*}{j} \frac{(-1)^j \exp\left(-\frac{j(\theta-1)}{\bar{\gamma}_B}\right)}{1 + \frac{j\theta\bar{\gamma}_E}{\bar{\gamma}_B}} \quad (13).$$

## 5 Refined WIM Secrecy Outage

### 5.1 Eigenvalue-Weighted Effective Branches

The EDoF model treats the dominant modes as equal-power branches. A more accurate approximation is obtained by using

normalized dominant eigenvalue weights:

$$\beta_{q,k} = \frac{\lambda_{q,k} K_q^*}{N_q}, \quad X_q^{\text{WIM}} = \max_{1 \leq k \leq K_q^*} \beta_{q,k} Z_{q,k} \quad (14).$$

The corresponding WIM cumulative distribution function is

$$F_q^{\text{WIM}}(x) = \prod_{k=1}^{K_q^*} (1 - e^{-x/\beta_{q,k}}) \quad (15).$$

This refinement preserves the same aperture-based interpretation as the EDoF model while retaining the nonuniform powers of the dominant eigenmodes.

### 5.2 Quantitative Approximation Error

For the setting in Fig. 3, define the absolute approximation error as  $\varepsilon = |P_{\text{so}}^{\text{model}} - P_{\text{so}}^{\text{MC}}|$ . At -5 dB, the EDoF and WIM errors are  $1.46 \times 10^{-3}$  and  $9.70 \times 10^{-3}$ , respectively. Around the transition region at 1 dB, WIM reduces the error from  $9.34 \times 10^{-3}$  to  $5.21 \times 10^{-3}$ , a 44.2% reduction. At 9 dB, the corresponding errors are  $1.42 \times 10^{-3}$  and  $4.40 \times 10^{-3}$ . Thus, eigenvalue weighting improves the local transition-region fit but is not uniformly more accurate over all SNRs; the simpler EDoF model can be closer when the maximum-over-ports dependence dominates the eigenvalue imbalance. At 13 dB, the Monte Carlo (MC) SOP is  $5.0 \times 10^{-5}$ , while the EDoF and WIM absolute errors are  $2.92 \times 10^{-6}$  and  $8.05 \times 10^{-5}$ ; above 15 dB, the 80 000-trial MC curve reaches its resolution limit of  $1.25 \times 10^{-5}$ , so relative-error percentages are not statistically meaningful.

## 6 Asymptotic Secrecy Behavior and Design Insights

### 6.1 Fixed Eve SNR

Theorem 2. If Eve's average SNR is fixed and Bob's average SNR grows large, the secrecy outage behaves asymptotically as:

$$P_{\text{so}}^{\text{EDoF}} \sim \frac{G_{\text{sec}}}{\bar{\gamma}_B^{K_B^*}}, \quad G_{\text{sec}} = \mathbb{E}\left[\left(\theta(1 + \bar{\gamma}_E X_E) - 1\right)^{K_B^*}\right] \quad (16).$$

Therefore, the secrecy diversity order is  $K_B^*$ . Eve's aperture changes the coding-gain-like constant through the distribution of  $X_E$ , but it does not change the asymptotic slope when Eve's average SNR is fixed.

### 6.2 Proportional Bob and Eve SNRs

If Eve's average SNR scales proportionally with Bob's, then the secrecy outage converges to a nonzero floor:

$$\bar{\gamma}_E = \alpha \bar{\gamma}_B, \quad P_{\text{so},\infty}^{\text{EDoF}} = \sum_{j=0}^{K_B^*} \binom{K_B^*}{j} (-1)^j \frac{(K_E^*)!}{\prod_{m=1}^{K_E^*} (m + j\alpha\theta)} \quad (17).$$

This shows that the secrecy outage probability cannot be forced to zero by transmit-power growth alone when Bob and Eve scale together. The decisive design quantity is the EDoF pair  $(K_B^*, K_E^*)$  created by the two apertures.

The target secrecy rate shifts this floor through  $\theta$ , where  $\theta$  is 2 raised to the power of  $R_s$ . Since increasing  $R_s$  enlarges the outage event for every channel realization, the floor is monotonically nondecreasing in  $R_s$ . For example, with  $(K_B^*, K_E^*) = (7, 3)$  and  $\alpha=1$ , the floor increases from 0.332 at  $R_s=0.1$  bit/s/Hz to 0.467, 0.636, and 0.877 at  $R_s=0.5$  bit/s/Hz, 1 bit/s/Hz, and 2 bit/s/Hz, respectively. Hence, a higher confidential-rate requirement must be supported by a larger Bob-side EDoF advantage or a lower relative Eve link quality.

The new insight of the proposed framework is that secrecy behaves in aperture steps rather than in raw-port steps. Once Bob crosses an integer aperture threshold, two additional effective modes appear immediately; once Eve crosses such a threshold, the wiretap link becomes measurably more dangerous.

## 7 Numerical Results

This section evaluates the closed-form formulas numerically and compares them with Monte Carlo simulations of the correlated FAS channels. The simulation setup adopts the same Jakes correlation model and the same secrecy-rate definition as those used in the analysis.

The figures in this paper are arranged from the most basic trend to the most adversarial setting. They first show the effect of Bob's average SNR and aperture, and then illustrate the Bob-Eve aperture competition. Next, they illustrate the agreement among EDoF, WIM, and exact correlated-channel simulation, and finally demonstrate the high-SNR secrecy floor.

Compared with existing secrecy analyses that rely mainly on high-dimensional simulation, fitted correlation parameters, or nominal port count, the proposed EDoF/WIM framework expresses secrecy directly in terms of the aperture-induced mode counts and dominant eigenvalue weights of Bob and Eve. This yields clearer design rules and lower evaluation complexity.

### 7.1 Impact of Bob's Aperture

Fig. 1 verifies the secrecy diversity statement by varying Bob's average SNR under several Bob apertures. Increasing  $W_B$  enlarges  $K_B^*$  and steepens the outage decay. The figure shows that secrecy gain is achieved in aperture-controlled steps rather than by merely adding more densely packed ports.

### 7.2 Bob-Eve Aperture Competition

Fig. 2 sweeps Bob's normalized aperture  $W_B$  parameterized by Eve's aperture  $W_E$ . The staircase follows from  $K_B^* = \min\{N_B, 2\lceil W_B \rceil + 1\}$ : within one integer aperture interval, denser sampling resolves the same spatial field and does not create another independent mode. Crossing the next wavelength-normalized boundary expands the resolvable spatial bandwidth and introduces a conjugate pair of spatial

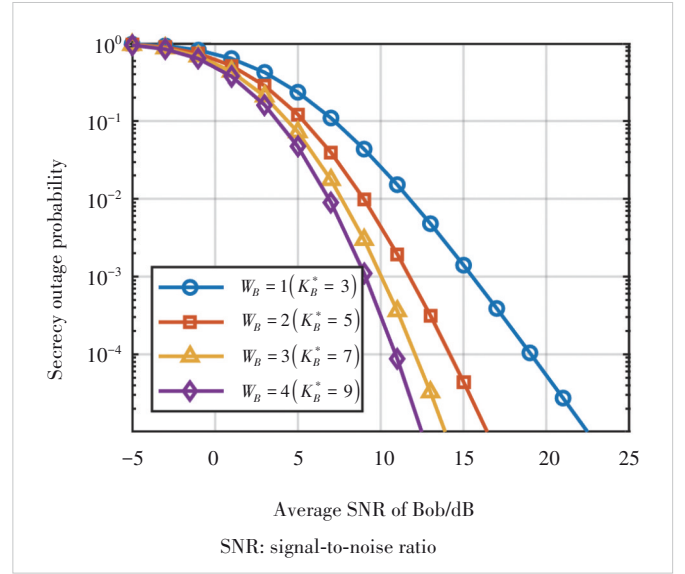


Figure 1. Secrecy outage probability versus Bob's average SNR for  $W_E = 1$ ,  $\gamma_E = 0$  dB, and  $R_s = 0.5$  bit/s/Hz

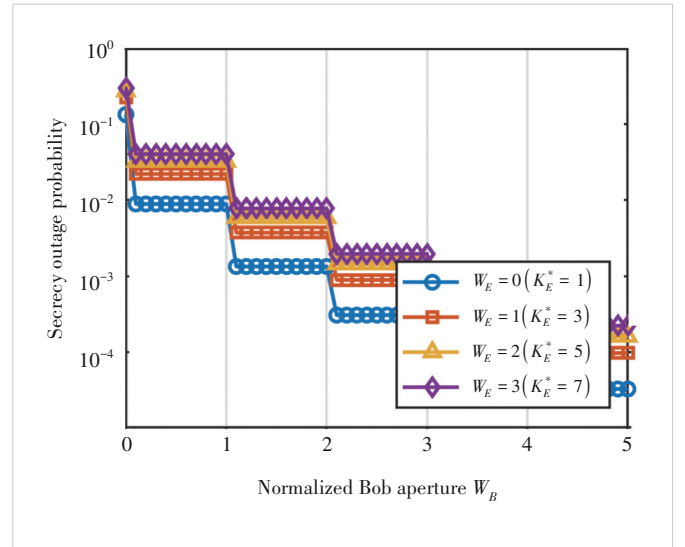
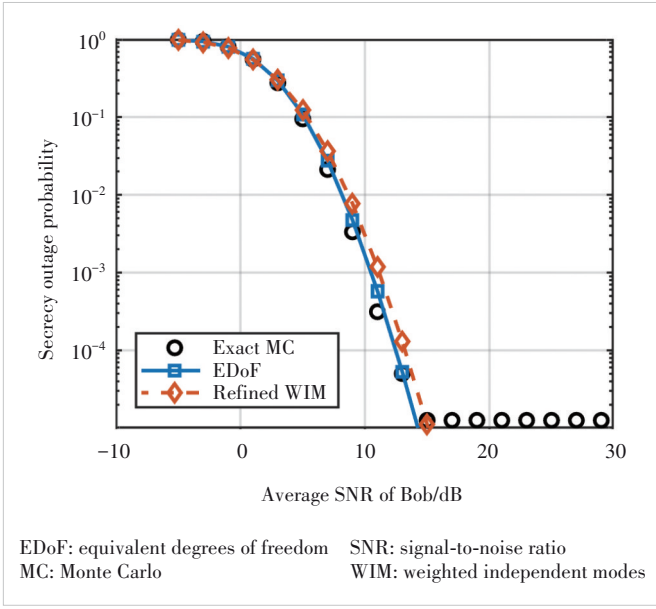


Figure 2. Secrecy outage probability versus Bob's normalized aperture for  $\gamma_B = 15$  dB,  $\gamma_E = 5$  dB, and different Eve apertures

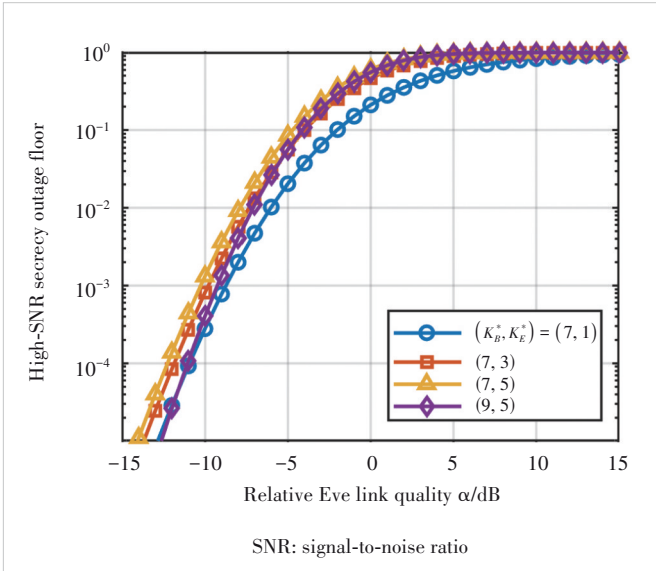
modes, such that  $K_B^*$  increases by 2 and the SOP drops abruptly. The curves therefore expose the Bob-Eve aperture gap more directly than a raw port-count description.

### 7.3 EDoF and WIM Validation

Fig. 3 compares the EDoF and refined-WIM formulas with exact Monte Carlo simulation results for correlated FAS channels. Both analytical curves capture the SNR trend. The WIM model explicitly accounts for nonuniform dominant eigenvalues and improves the fit near the 1 dB transition point, whereas the equal-power EDoF approximation is closer at some other SNRs. This is consistent with the quantitative error audit in Section 5.2.



**Figure 3. EDoF and refined-WIM secrecy outage validation against exact Monte Carlo simulation for  $N_B = 40$ ,  $N_E = 30$ ,  $W_B = 3$ ,  $W_E = 2$ , and  $\bar{\gamma}_E = 0$  dB**



**Figure 4. High-SNR secrecy outage floor versus the relative Eve link quality  $\alpha$  for different EDoF pairs  $(K_B^*, K_E^*)$  and  $R_s = 0.5$  bit/s/Hz**

### 7.4 High-SNR Secrecy Floor

Fig. 4 visualizes the proportional-SNR secrecy floor versus the relative Eve link quality  $\alpha$ . The floor rises with  $K_E^*$  and falls with  $K_B^*$ . At  $\alpha=0$  dB and  $R_s=0.5$  bit/s/Hz, increasing the EDoF pair from (7, 5) to (9, 5) lowers the floor from 0.611 to 0.558, while reducing Eve's mode count from five to three at  $K_B^*=7$  lowers it further to 0.467. Therefore, under a benchmark constraint  $W_B + W_E = W_T$ , the floor is minimized by assigning the controllable aperture budget to Bob until the next integer  $W_B$

threshold is crossed, rather than spending it on additional ports inside the same interval. In practice, Eve's aperture is not controlled by the legitimate designer;  $W_E$  should be treated as a threat upper bound, and the actionable rule is to enlarge Bob's aperture (or constrain the region in which Eve can deploy) until  $K_B^*$  exceeds the anticipated  $K_E^*$  by the largest feasible margin.

## 8 Conclusions

This paper presents a standalone EDoF-based secrecy outage framework for FAS wiretap channels. By using the spectral concentration of the Jakes correlation kernel, a correlated FAS with many physical ports is reduced to a selection system with  $K_q^* = \min\{N_q, 2\lceil W_q \rceil + 1\}$  effective branches. The results show that Bob's aperture controls secrecy diversity, Eve's aperture controls the strength of the selected wiretap link, and proportional Bob-Eve SNR scaling creates a nonzero secrecy outage floor. The Jakes model assumes a one-dimensional aperture, isotropic two-dimensional scattering, identical diffuse angular statistics, and ideal narrowband stationarity; its compact EDoF law therefore need not remain exact in directional, clustered, nonstationary, blocked, or three-dimensional urban channels. Future work will replace the Jakes kernel with correlation matrices obtained from standardized 3GPP urban micro-cell and urban macrocell channel models, extract effective mode counts from their eigenvalue spectra, and test whether the same EDoF/WIM secrecy structure extends to wideband, planar-aperture, mutual-coupling, and hardware-impaired FAS implementations. Overall, the central security resource is the aperture-induced EDoF advantage rather than the raw number of selectable ports.

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## Biographies

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