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Physical-Layer Security for Frequency Diverse Array-Based Directional Modulation in Fluctuating Two-Ray Fading Channels

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Abstract—The frequency diverse array (FDA)-based directional modulation (DM) technology plays an important role in the physical-layer security (PLS) transmission of 5G and beyond communications. In order to meet the tremendous increase in mobile data traffic, a new memory-efficient design for the FDA-DM-based PLS transmission is urgently demanded. In this paper, an analytical symmetrical multi-carrier FDA model is proposed in three dimensions, namely, range, azimuth angle, and elevation angle, differing from the conventional analytical approach with only range and azimuth angle considered. Then, a single-point (SP) artificial noise (AN) aided FDA-DM scheme is proposed, which reduces the memory consumption significantly compared with the conventional zero-forcing (ZF) and singular value decomposition (SVD) approaches. Moreover, the PLS performance of the proposed FDA-DM scheme is analyzed in fluctuating two-ray (FTR) fading channels for the first time, including the average secrecy capacity (ASC) and the secrecy outage probability (SOP). More importantly, the closed-form expressions for the lower bound on ASC and the upper bound on SOP are derived, respectively. The effectiveness of the analytical expressions is verified by numerical simulations. This work opens a way to lower the memory requirements for DM-based PLS transmission of 5G and beyond communications.

Index Terms—Directional modulation; fluctuating two-ray fading; frequency diverse array; physical-layer security; secrecy capacity; secrecy outage probability.

I. INTRODUCTION

PHYSICAL-LAYER security (PLS) technology, as a promising and powerful alternative to complement and even possibly replace encryption-based approaches, has been brought to the forefront by plenty of researchers [1]–[3]. The

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key idea of PLS is to fully exploit the characteristics of wireless channels to secure the transmission link from the legitimate transmitter to the desired receiver in the presence of unauthorized eavesdroppers [4], [5]. Owing to the promising benefits of PLS technology, it has been intensively investigated to safeguard 5G and beyond wireless communications [6], [7]. However, implementing the PLS transmission can result in considerable memory consumptions, which imposes stringent requirements on the 5G nodes or devices. In addition, the tremendously increasing mobile data traffic also requires considerable memory consumptions. Therefore, it is highly necessary to lower the memory consumption of the PLS transmission strategy for 5G and beyond communication system.

The directional modulation (DM) technology [8], which is capable of steering the standard baseband symbols along a desired direction while simultaneously distorting the received signals along other directions, has been regarded as a useful PLS transmission strategy for 5G millimeter-wave (mmWave) wireless communications [9], [10]. Traditionally, DM technology is implemented using phased arrays (PA) [11], which only achieves one-dimension security in the direction while loses security if the eavesdropper is in the same direction as the legitimate receiver. Compared with the PA-based DM technology, the frequency diverse array (FDA), exhibiting an extra range-dimension dependence apart from angle [12], [13], has been applied into DM implementations to realize two-dimension security in both range and angle.

Specifically, the FDA was first utilized in [14] to achieve range-angle dependent secure DM transmissions with fixed linear frequency increments. The work in [15] utilized the FDA with non-linear frequency increments to decouple range- and angle-dependent transmit beam patterns for DM transmissions. The FDAs with random and time-modulated frequency increments were exploited for secure DM transmissions in [16] and [17], respectively. FDA was also used in [18], [19] to establish secure DM transmissions for proximal legitimate user and eavesdropper. In addition to the single-user FDA-DM schemes [14]–[19], multi-user FDA-DM schemes were also investigated intensively by means of the spread spectrum technology [20], optimization algorithms [21], singular value decomposition (SVD) [22], weighted-type fractional Fourier transform (WFRFT) [23], and cooperative-receiver index modulation [24], respectively. Inspired by the frequency diversity, the works in [25], [26] designed a random-subcarrier-

selection method for DM synthesis, which achieved range-angle dependent secure precise transmission as well.

In the DM transmission schemes, artificial noise (AN) plays an important role [4]. Most of the AN-aided DM transmission schemes employ zero-forcing (ZF) method to design the orthogonal precoding matrix to remove the interference of AN for legitimate receivers [16], [18], [21], [27]-[29]. The SVD method provided another way to redesign the orthogonal precoding matrix [22]. These ZF or SVD-aided design approaches, however, consume too much memory to store the designed orthogonal matrix and AN. It still remains a challenge to design a memory-efficient secure DM transmission scheme for 5G and beyond communication systems. Moreover, the afore-mentioned DM-related works [14]-[29] only considered the line-of-sight (LoS) channels in free space. Regarding the FDA-DM transmission in multipath fading channels, the authors in [30], [31] and [32] investigated the PLS performance of the FDA-DM communication system in Rayleigh and Nakagami- m fading channels, respectively.

However, on the one hand, the works in [30]-[32] about FDA-DM transmissions in fading channels utilized ZF-based AN method, which demands high memory requirements as well. On the other hand, these conventional fading models like Rayleigh, Rician and Nakagami- m fading cannot accurately fit the random small-scale fluctuations in real communication environments [33]. Recently, the fluctuating two-ray (FTR) fading model was proposed in [33], [34], which is a generalization of the existing fading models and can provide a better fit for small-scale fading measurements in mmWave communications. The authors in [35], [36] and [37] generalized the FTR fading model into arbitrary fading parameter case, cascaded case, and squared case, respectively. More recently, the average secrecy capacity (ASC), the secrecy outage probability (SOP) and the symbol error rate (SER) of FTR fading channels were analyzed in [38], [39] and [40] without AN (NoAN), respectively. The power adaption algorithm and wireless-powered UAV relay communication in FTR fading channels were investigated in [41] and [42], respectively.

To the best of our knowledge, there is no specific work in the state-of-the-art that aims to reduce the memory consumption of the FDA-DM scheme for 5G and beyond communications and to analyze the PLS performance of the FDA-DM scheme in FTR fading channels. We are the first to make this effort by proposing a memory-efficient single-point (SP) AN-aided FDA-DM scheme for 5G and beyond communications, and analyzing its PLS performance in FTR fading channels for the first time. Overall, the main contributions of our work are as follows:

- 1) Different from the conventional analytical approach which only considers range and azimuth angle dimensions, an analytical model for the symmetrical multi-carrier FDA is proposed in three dimensions, i.e., range, azimuth angle and elevation angle.
- 2) A memory-efficient FDA-DM scheme is further proposed with the assistance of single-point AN, which significantly outperforms the conventional ZF method [16], [18], [21], [27]-[32] and the SVD method [22]. The

Fig. 1. The proposed FDA-DM scheme in FTR fading channels.

proposed memory-efficient FDA-DM scheme provides an efficient strategy to lower the memory requirements for the PLS transmissions of 5G and beyond communications.

- 3) The ASC and the SOP of the proposed FDA-DM scheme are analyzed in FTR fading channels for the first time. We also derive the closed-form expressions for the lower bound on ASC and the upper bound on SOP. Numerical experiments are conducted to compare the PLS performances of the proposed SP and the conventional ZF [16], [18], [21], [27]-[32], SVD [22] and NoAN [38]-[40] methods.

The remainder of this paper is organized as follows. Section II proposes an analytical model of symmetrical multi-carrier FDA in three dimensions. A memory-efficient FDA-DM scheme is proposed in Section III with the assistance of single-point AN, where the comparison between the proposed SP method and the conventional ZF and SVD methods is also provided. Section IV analyzes the ASC and the SOP performances of the proposed FDA-DM scheme in FTR fading channels. Numerical results are conducted in Section V in order to verify the advantages of the proposed FDA-DM scheme. Finally, Section VI makes a conclusion for the whole paper and points out the future work.

Notations: In this paper, $j = \sqrt{-1}$ indicates imaginary unit. The operators $(\cdot)^T$ and $(\cdot)^H$ represent the transpose and the Hermitian transpose of a matrix. The set of complex numbers is denoted by $\mathbb{C}$. The notation $\mathbb{E}(\cdot)$ refers to the expectation of a random variable, while $\text{tr}(\cdot)$ represents the trace of a matrix. In addition, $\max\{\cdot\}$ and $|\cdot|$ refer to the maximum value of a set of real numbers and the modulus of a complex number, respectively. $\mathcal{N}(0, \sigma^2)$ and $\mathcal{CN}(0, \sigma^2)$ refer to the real and complex Gaussian distributions with zero mean and variance σ^2 , respectively. $\mathcal{U}[\cdot, \cdot)$ is the uniform distribution. Finally, the probability function is denoted by $\text{Pr}(\cdot)$.

II. FDA MODEL IN THREE DIMENSIONS

Most of the state-of-the-art analyzes the FDA only in two dimensions [12]-[23], namely, range and azimuth angle. In this paper, we take an extra dimension, elevation angle, into consideration and establish an analytical FDA model in three dimensions, i.e., range, azimuth angle, and elevation angle. Different from the conventional rectangular/circular antenna arrays that use the “space diversity” (planar antennas) to generate 3-dimension coordinate [43], the linear frequency diverse arrays utilize the “frequency diversity” (different frequencies on different antennas) to produce range-angle dependent 3-dimension beampatterns [44].

As shown in Fig. 1, the FDA consists of $2N + 1$ antenna elements with equal element spacing d , which is set as half wavelength of the central carrier. These elements are symmetrically and linearly arrayed on the x -axis with the central element located at the coordinate origin. For each element, there are L subcarriers to transmit. The radiated frequency of the l -th ($l = 0, \dots, L - 1$) subcarrier of the n -th ($n = -N, \dots, 0, \dots, N$) element is designed as

$$f_{n,l} = f_0 + \Delta f_{n,l} \quad (1a)$$

$$= f_0 + \Delta f \ln(|n| + 1) \ln(l + 1), \quad (1b)$$

where f_0 is the central radiated frequency, Δf refers to a fixed frequency increment, and $\Delta f_{n,l} = \Delta f \ln(|n| + 1) \ln(l + 1)$ represents the frequency increment between the central frequency and the l -th subcarrier of the n -th element, which satisfies

$$|\Delta f_{n,l}| \ll f_0. \quad (2)$$

In order to derive the steering vector of the FDA, we consider that each element of the transmitter transmits sinusoidal signals with L subcarriers. The l -th subcarrier signal transmitted by the n -th element at time t can be expressed as

$$x_{n,l}(t) = \exp\{i2\pi f_{n,l}t\}. \quad (3)$$

Let r , θ and ψ represent the range, azimuth angle and elevation angle, respectively, as shown in Fig. 1. For an arbitrary receiver located at (r, θ, ψ) , the overall observed signal in the far field can be written as

$$y(r, \theta, \psi) = \sum_{n=-N}^N \sum_{l=0}^{L-1} x_{n,l} \left(t - \frac{r_n}{c} \right) \quad (4a)$$

$$= \sum_{n=-N}^N \sum_{l=0}^{L-1} \exp \left\{ i2\pi f_{n,l} \left(t - \frac{r_n}{c} \right) \right\}, \quad (4b)$$

where c denotes light speed and r_n refers to the path length from the n -th element to the observation point. With some basic geometric operations, the path length r_n can be approximated by [44]

$$r_n \approx r - nd \sin \theta \cos \psi. \quad (5)$$

Taking (1) and (5) into (4b) yields (6). The constraint in (2) implies that the last term in the summation, $\Delta f_{n,l} nd \sin \theta \cos \psi / c$, can be omitted, so (6) can be further approximated as

$$\begin{aligned} y(r, \theta, \psi) &\approx \exp \left\{ i2\pi f_0 \left(t - \frac{r}{c} \right) \right\} \\ &\times \sum_{n=-N}^N \sum_{l=0}^{L-1} \exp \left\{ i2\pi \left[\Delta f_{n,l} \left(t - \frac{r}{c} \right) + \frac{f_0 nd \sin \theta \cos \psi}{c} \right] \right\}. \end{aligned} \quad (7)$$

The terms inside the summation of (7) are decided by the geometry and the frequency-offset scheme of the FDA. Therefore, the sub-steering vector caused by the L subcarriers of the n -th antenna element can be written as [45]

$$\mathbf{a}_n(r, \theta, \psi) = \left[\exp \{ \phi_{n,0} \} \cdots \exp \{ \phi_{n,l} \} \cdots \exp \{ \phi_{n,L-1} \} \right]^T, \quad (8)$$

which is a vector with size $L \times 1$. The l -th phase term $\phi_{n,l}$ in (8) is given by

$$\phi_{n,l} = i2\pi \left[\Delta f_{n,l} \left(t - \frac{r}{c} \right) + \frac{f_0 nd \sin \theta \cos \psi}{c} \right]. \quad (9)$$

Overall, the normalized steering vector of the symmetrical multi-carrier FDA can be obtained by combining the $2N + 1$ sub-steering vectors $\mathbf{a}_n(r, \theta, \psi)$, i.e.,

$$\begin{aligned} \mathbf{h}(r, \theta, \psi) &= \frac{1}{\sqrt{(2N+1)L}} \\ &\times \left[\mathbf{a}_{-N}^T(r, \theta, \psi) \cdots \mathbf{a}_n^T(r, \theta, \psi) \cdots \mathbf{a}_N^T(r, \theta, \psi) \right]^T, \end{aligned} \quad (10)$$

which is a vector with size $(2N + 1)L \times 1$, and satisfies $\mathbf{h}^H(r, \theta, \psi) \mathbf{h}(r, \theta, \psi) = 1$.

III. LOW-MEMORY-CONSUMPTION FDA-DM SCHEME IN FTR FADING CHANNELS

We consider a multi-input single-output single-eavesdropper (MISOSE) wiretap channel model, where both the legitimate receiver (Bob) and the eavesdropper (Eve) are equipped with a single antenna. A legitimate transmitter (Alice), equipped with a $(2N + 1)$ -element symmetrical FDA with each element having L subcarriers, intends to deliver confidential information to Bob, while a malicious Eve at a different location tries to crack the confidential information via its received signal. The coordinate origin is set as the central element of Alice's FDA, as analyzed in Section II. We also assume both Bob's and Eve's channels undergo independent and quasi-static FTR fading.

A. Alice's Transmit Signal

The transmit signal of Alice consists of two parts. The first is the normalized baseband modulation symbol $s \in \Omega$ and $\mathbb{E}(|s|^2) = 1$, where Ω is the alphabet of the baseband modulation symbols with the size of M . The second is the inserted single-point AN z , which follows a complex Gaussian distribution, i.e., $z \sim \mathcal{CN}(0, 1)$. To match the $(2N + 1)L$ FDA subcarriers of Alice, the baseband symbol s and the inserted AN z should be precoded with a normalization vector $\mathbf{p}_1$ and an orthogonal vector $\mathbf{p}_2$, respectively, which require

$$\mathbf{h}_B^H \mathbf{p}_1 = 1, \quad (11)$$

$$y(r, \theta, \psi) \approx \sum_{n=-N}^N \sum_{l=0}^{L-1} \exp \left\{ i2\pi (f_0 + \Delta f_{n,l}) \left(t - \frac{r - nd \sin \theta \cos \psi}{c} \right) \right\} \quad (6a)$$

$$= \exp \left\{ i2\pi f_0 \left(t - \frac{r}{c} \right) \right\} \sum_{n=-N}^N \sum_{l=0}^{L-1} \exp \left\{ i2\pi \left[\Delta f_{n,l} \left(t - \frac{r}{c} \right) + \frac{f_0 nd \sin \theta \cos \psi}{c} + \frac{\Delta f_{n,l} nd \sin \theta \cos \psi}{c} \right] \right\}. \quad (6b)$$

TABLE I
COMPARISON FOR MEMORY REQUIREMENTS OF DIFFERENT FDA-DM SCHEMES

Items	ZF [16], [18], [21], [27]-[32]	SVD [22]	Proposed SP
Orthogonal matrix/vector	$\mathbf{P}_2^{\text{ZF}} = \mathbf{I}_{(2N+1)L} - \mathbf{h}_B \mathbf{h}_B^H$	$\mathbf{h}_B^H = \mathbf{U} [\mathbf{D} \mathbf{0}] [\mathbf{V}_1 \mathbf{V}_0]^H$, $\mathbf{P}_2^{\text{SVD}} = \mathbf{V}_0$	$\mathbf{p}_2^{\text{SP}}$ = Orthogonal vector of $\mathbf{h}_B^H$
Size of orthogonal matrix/vector	$(2N+1)L \times (2N+1)L$	$(2N+1)L \times 2N$	$(2N+1)L \times 1$
Artificial noise	$\mathbf{z}^{\text{ZF}} \in \mathbb{C}^{(2N+1)L \times 1}$	$\mathbf{z}^{\text{SVD}} \in \mathbb{C}^{2N \times 1}$	$\mathbf{z}^{\text{SP}} \in \mathbb{C}$
Size of artificial noise	$(2N+1)L \times 1$	$2N \times 1$	1
Total size	$(2N+1)^2 L^2 + (2N+1)L$	$2N(2N+1)L + 2N$	$(2N+1)L + 1$
Memory complexity	$\mathcal{O}(N^2 L^2)$	$\mathcal{O}(N^2 L)$	$\mathcal{O}(NL)$

and

$$\mathbf{h}_B^H \mathbf{p}_2 = 0, \quad (12)$$

where $\mathbf{h}_B = \mathbf{h}(r_B, \theta_B, \psi_B)$ is the normalized steering vector at Bob's location, (r_B, θ_B, ψ_B) . Since the angle and range estimation algorithms, such as [48], [49], could be applied to help Alice estimate Bob's location, we assume (r_B, θ_B, ψ_B) is *a priori* perfectly known at Alice. If the practical measurement errors are considered, the robust method in [27] could be useful to improve the robustness of the proposed DM scheme.

Therefore, the transmitting signal vector which feeds Alice's $2N+1$ antenna elements can be expressed as

$$\mathbf{x} = \beta_1 \sqrt{P_s} \mathbf{p}_1 s + \alpha \beta_2 \sqrt{P_s} \mathbf{p}_2 z, \quad (13)$$

where P_s is the total transmitting power; $\alpha = 1/\sqrt{\text{tr}(\mathbf{p}_2 \mathbf{p}_2^H)}$ is the power normalization factor for the inserted AN; β_1 and β_2 are power splitting factors for the baseband symbol and the inserted AN, respectively, which satisfy the following constraint,

$$\beta_1^2 + \beta_2^2 = 1. \quad (14)$$

For the design of $\mathbf{p}_1$ and $\mathbf{p}_2$, we first review the ZF method [16], [18], [21], [27]-[32] and the SVD method [22] briefly, and then propose a memory-efficient SP method.

1) *ZF method*: The normalization vector is directly designed as the normalized steering vector at Bob's location, i.e., $\mathbf{p}_1^{\text{ZF}} = \mathbf{h}_B$. In addition, the orthogonal matrix of the ZF method is designed as $\mathbf{P}_2^{\text{ZF}} = \mathbf{I}_{(2N+1)L} - \mathbf{h}_B \mathbf{h}_B^H$, which is actually a matrix with the size of $(2N+1)L \times (2N+1)L$. In order to match the orthogonal matrix $\mathbf{P}_2^{\text{ZF}}$, the inserted AN of the ZF method should be randomly valued from $\mathbf{z}^{\text{ZF}} \in \mathbb{C}^{(2N+1)L \times 1}$.

2) *SVD method*: Similar to the ZF method, the normalization vector of the SVD method is also designed as $\mathbf{p}_1^{\text{SVD}} = \mathbf{h}_B$. But for the design of the orthogonal matrix, the SVD method first solves the SVD of $\mathbf{h}_B^H$, i.e., $\mathbf{h}_B^H = \mathbf{U} [\mathbf{D} \mathbf{0}] [\mathbf{V}_1 \mathbf{V}_0]^H$, from which a null space of $\mathbf{h}_B^H$ can be obtained. Then, the orthogonal matrix $\mathbf{P}_2^{\text{SVD}}$ can be directly designed as $\mathbf{P}_2^{\text{SVD}} = \mathbf{V}_0$, which is a matrix with the size of $(2N+1)L \times 2N$. Consequently, the inserted AN of the SVD method has to be changed as $\mathbf{z}^{\text{SVD}} \in \mathbb{C}^{2N \times 1}$ in order to match the orthogonal matrix $\mathbf{P}_2^{\text{SVD}}$.

3) *Proposed SP method*: The normalization vector in this paper is designed as $\mathbf{p}_1^{\text{SP}} = \mathbf{h}_B$ as well. Different from the ZF and SVD methods which insert an AN vector in the transmit signal, the proposed SP method only requires a single-point AN as shown in (13). Therefore, the orthogonal vector $\mathbf{p}_2^{\text{SP}}$ can be designed as an arbitrary orthogonal vector of $\mathbf{h}_B^H$

rather than a matrix. Comparatively, $\mathbf{p}_2^{\text{SP}}$ can be an arbitrary column vector of $\mathbf{P}_2^{\text{ZF}}$ or $\mathbf{P}_2^{\text{SVD}}$. In the following analysis, $\mathbf{p}_2$ specifically refers to the proposed $\mathbf{p}_2^{\text{SP}}$.

4) *Comparison for the ZF, SVD and SP methods*: In order to illustrate the advantage of the the proposed SP method, Table I compares these three different design methods in terms of memory consumption to store the orthogonal matrix/vector and the AN. From Table I, the proposed SP method reduces the memory complexity from $\mathcal{O}(N^2 L^2)$ and $\mathcal{O}(N^2 L)$ to $\mathcal{O}(NL)$, which significantly outperforms the ZF and SVD methods.

In addition, Figs. 2(a) and (b) depict the numerical results for the total memory required and the ratio of SP method to ZF or SVD methods versus N and L , respectively, which verify the excellent advantage of low memory consumption for the proposed SP method. For example, when $N = 10$ and $L = 7$, the proposed SP method only requires approximately 0.6803% total memory of the ZF method or 5% total memory of the SVD method. Figs. 3(a) and (b) further show the total memory consumptions and the corresponding ratios versus N and L , respectively, which demonstrates that the proposed SP method can save much more memory than the conventional ZF and SVD methods as well.

B. Bob's Received Signal

After Alice transmits the signal, the received signal of Bob located at (r_B, θ_B, ψ_B) can be written as

$$y(r_B, \theta_B, \psi_B) = \epsilon_B \mathbf{h}_B^H \mathbf{x} + \xi_B \quad (15a)$$

$$= \epsilon_B \beta_1 \sqrt{P_s} \mathbf{h}_B^H \mathbf{p}_1 s + \epsilon_B \alpha \beta_2 \sqrt{P_s} \mathbf{h}_B^H \mathbf{p}_2 z + \xi_B \quad (15b)$$

$$= \epsilon_B \beta_1 \sqrt{P_s} s + \xi_B, \quad (15c)$$

where ξ_B is the complex additive white Gaussian noise (AWGN) with zero mean and variance δ_B^2 , i.e., $\xi_B \sim \mathcal{CN}(0, \delta_B^2)$. In addition, ϵ_B represents the FTR fading coefficient which is defined as [35]

$$\epsilon_B = \sqrt{\zeta_B} U_B \exp\{j\varphi_B\} + \sqrt{\zeta_B} V_B \exp\{j\vartheta_B\} + X_B + jY_B, \quad (16)$$

where ζ_B is a Gamma distributed random variable with zero mean and probability density function given by

$$f_{\zeta_B}(\zeta_B) = \frac{m_B^{m_B} \zeta_B^{m_B-1}}{\Gamma(m_B)} \exp\{-m_B \zeta_B\}. \quad (17)$$

Moreover, U_B and V_B are constant amplitudes with specular components modulated by a Nakagami- m_B random variable.

Fig. 2. Total memory required to store the orthogonal matrix/vector and the AN versus N ; and the ratio of the proposed SP method to ZF or SVD methods versus (a) N ($L = 7$) and (b) L ($N = 10$).

Fig. 3. (a) Total memory required to store the orthogonal matrix/vector and the AN of the proposed SP method and the conventional ZF and SVD methods and (b) The ratio of total memory of the SP method to that of the ZF or SVD methods versus N and L .

φ_B and ϑ_B are statistically independent and uniformly distributed random phases, i.e., $\varphi_B, \vartheta_B \sim \mathcal{U}[0, 2\pi)$. $X_B + \imath Y_B$ refers to the diffuse component with X_B and Y_B following a Gaussian distribution, i.e., $X_B, Y_B \sim \mathcal{N}(0, \sigma_B^2)$. The FTR fading parameters can be calculated by $K_B = \frac{U_B^2 + V_B^2}{2\sigma_B^2}$ and $\Delta_B = \frac{2U_B V_B}{U_B^2 + V_B^2}$. It can be observed from (15c) that only the useful signal is left for Bob while the inserted AN has been removed, which guarantees the effective transmission between Alice and Bob.

C. Eve's Received Signal

Similarly, the received signal of Eve located at (r_E, θ_E, ψ_E) , $(r_E, \theta_E, \psi_E) \neq (r_B, \theta_B, \psi_B)$, can be expressed as

$$y(r_E, \theta_E, \psi_E) = \epsilon_E \mathbf{h}_E^H \mathbf{x} + \xi_E \quad (18a)$$

$$= \epsilon_E \beta_1 \sqrt{P_s} \mathbf{h}_E^H \mathbf{p}_1 s + \epsilon_E \alpha \beta_2 \sqrt{P_s} \mathbf{h}_E^H \mathbf{p}_2 z + \xi_E \quad (18b)$$

$$= \underbrace{\epsilon_E \beta_1 \sqrt{P_s} \rho_1 s}_{\text{Distorted Signal}} + \underbrace{\epsilon_E \alpha \beta_2 \sqrt{P_s} \rho_2 z}_{\text{Artificial Noise}} + \underbrace{\xi_E}_{\text{AWGN}}, \quad (18c)$$

where $\xi_E \sim \mathcal{CN}(0, \delta_E^2)$ indicates the complex AWGN, $\mathbf{h}_E = \mathbf{h}(r_E, \theta_E, \psi_E)$ refers to Eve's normalized steering vector, $\rho_1 = \mathbf{h}_E^H \mathbf{p}_1$, and $\rho_2 = \mathbf{h}_E^H \mathbf{p}_2$. Additionally, the fading coefficient ϵ_E is defined as

$$\epsilon_E = \sqrt{\zeta_E} U_E \exp\{\imath \varphi_E\} + \sqrt{\zeta_E} V_E \exp\{\imath \vartheta_E\} + X_E + \imath Y_E, \quad (19)$$

which undergoes the FTR fading with the parameters $(m_E, K_E, \Delta_E, \sigma_E^2)$.

It is worth noting that Eve's received signal in (18c) consists of three items. The first is the useful signal distorted by ρ_1 and the second is the inserted AN, both of which can be regarded as interference for Eve as long as Eve's location differs from Bob's, thereby guaranteeing the PLS transmission between Alice and Bob.

IV. PHYSICAL-LAYER SECURITY ANALYSIS

In this section, we will analyze the PLS performances of the proposed FDA-DM scheme including the ASC and the SOP, which are important metrics to measure the performances of DM schemes [50].

A. PDF And CDF

Before analyzing the ASC and the SOP of the proposed FDA-DM scheme, the probability density functions (PDFs) and cumulative distribution functions (CDFs) of Bob's and Eve's signal-to-inference-plus-noise ratios (SINRs) are first derived in this section.

According to (15c), the received signal of Bob is simply the summation of the useful signal and AWGN, so Bob's SINR can be written as

$$\gamma_B = \frac{|\epsilon_B|^2 \beta_1^2 P_s \mathbb{E}(|s|^2)}{\delta_B^2} = \beta_1^2 \lambda_B, \quad (20)$$

where $\lambda_B = |\epsilon_B|^2 P_s \mathbb{E}(|s|^2) / \delta_B^2$ is Bob's signal-to-noise ratio (SNR) in the FTR fading channel without splitting AN, the average of which can be calculated by $\bar{\lambda}_B = \mathbb{E}(|\epsilon_B|^2) P_s \mathbb{E}(|s|^2) / \delta_B^2 = 2\sigma_B^2(1 + K_B) P_s / \delta_B^2$ [35].

Similarly, we can obtain Eve's SINR by observing (18c) as follows,

$$\gamma_E = \frac{|\epsilon_E|^2 \beta_1^2 |\rho_1|^2 P_s \mathbb{E}(|s|^2) / \delta_E^2}{|\epsilon_E|^2 \alpha^2 \beta_2^2 |\rho_2|^2 P_s \mathbb{E}(|z|^2) / \delta_E^2 + 1}. \quad (21)$$

Let $\lambda_E = |\epsilon_E|^2 P_s \mathbb{E}(|s|^2) / \delta_E^2$, which indicates Eve's SNR in the FTR fading channel without splitting AN, the average of which can be calculated by $\bar{\lambda}_E = \mathbb{E}(|\epsilon_E|^2) P_s \mathbb{E}(|s|^2) / \delta_E^2 = 2\sigma_E^2(1 + K_E) P_s / \delta_E^2$. Moreover, taking the assumption $\mathbb{E}(|s|^2) = \mathbb{E}(|z|^2) = 1$ into (21) yields

$$\gamma_E = \frac{\beta_1^2 |\rho_1|^2 \lambda_E}{\alpha^2 \beta_2^2 |\rho_2|^2 \lambda_E + 1} \quad (22a)$$

$$= \frac{\eta \lambda_E}{\mu \lambda_E + 1}, \quad (22b)$$

where $\eta = \beta_1^2 |\rho_1|^2$ and $\mu = \alpha^2 \beta_2^2 |\rho_2|^2$.

The PDFs and CDFs of the SNR in FTR fading channel without splitting AN, λ_i ($i \in \{B, E\}$), can be obtained, respectively, by [35]

$$f_{\lambda_i}(x) = \frac{m_i^{m_i}}{\Gamma(m_i)} \sum_{j_i=0}^{\infty} \frac{K_i^{j_i} d_{j_i}}{j_i! j_i!} \frac{x^{j_i}}{(2\sigma_i^2)^{j_i+1}} \exp\left\{-\frac{x}{2\sigma_i^2}\right\}, \quad (23)$$

and

$$F_{\lambda_i}(x) = \frac{m_i^{m_i}}{\Gamma(m_i)} \sum_{j_i=0}^{\infty} \frac{K_i^{j_i} d_{j_i}}{j_i! j_i!} \Upsilon\left(j_i + 1, \frac{x}{2\sigma_i^2}\right), \quad (24)$$

where $j_i!$ denotes the factorial of the integer j_i ; $\Gamma(\cdot)$ and $\Upsilon(\cdot, \cdot)$ refer to the ordinary Gamma function [51, Eq. (8.310.1)] and the lower incomplete Gamma function [51, Eq. (8.350.1)], respectively. In addition, the term d_{j_i} in (23) and (24) is expressed as

$$\begin{aligned} d_{j_i} &\triangleq \sum_{k=0}^{j_i} \binom{j_i}{k} \left(\frac{\Delta_i}{2}\right)^k \sum_{l=0}^k \binom{k}{l} \Gamma(j_i + m_i + 2l - k) \\ &\times \exp\left\{i \frac{(2l - k)\pi}{2}\right\} \left[(m_i + K_i)^2 - (K_i \Delta_i)^2\right]^{-\frac{j_i + m_i}{2}} \\ &\times \mathcal{L}_{j_i + m_i - 1}^{k - 2l} \left(\frac{m_i + K_i}{\sqrt{(m_i + K_i)^2 - (K_i \Delta_i)^2}}\right), \end{aligned} \quad (25)$$

where $\binom{k}{l}$ denotes that k chooses l , and $\mathcal{L}(\cdot)$ represents the associated Legendre function of the first kind [51, Eq. (8.702)]. By observing (20), the PDF and CDF of Bob's SINR γ_B can be calculated, respectively, by

$$f_{\gamma_B}(x) = \frac{1}{\beta_1^2} f_{\lambda_B}\left(\frac{x}{\beta_1^2}\right), \quad (26)$$

and

$$F_{\gamma_B}(x) = F_{\lambda_B}\left(\frac{x}{\beta_1^2}\right). \quad (27)$$

Before deriving the PDF and CDF of Eve's SINR γ_E , it is worth noting that the lower and upper bounds on γ_E are 0 and $\tau = \eta/\mu$, respectively, which can be directly obtained by replacing $\lambda_E \rightarrow 0$ and $\lambda_E \rightarrow \infty$ into (22). Therefore, the CDF of γ_E can be acquired by

$$F_{\gamma_E}(x) = \Pr(\gamma_E \leq x) \quad (28a)$$

$$= \Pr\left(\frac{\eta \lambda_E}{\mu \lambda_E + 1} \leq x\right) \quad (28b)$$

$$= \Pr\left(\lambda_E \leq \frac{x}{\eta - \mu x}\right) \quad (28c)$$

$$= \begin{cases} F_{\lambda_E}\left(\frac{x}{\eta - \mu x}\right), & 0 < x < \tau \\ 1, & x \geq \tau \end{cases} \quad (28d)$$

Consequently, the PDF of γ_E can be calculated by

$$f_{\gamma_E}(x) = \frac{dF_{\gamma_E}(x)}{dx} \quad (29a)$$

$$= \begin{cases} \frac{\eta}{(\eta - \mu x)^2} f_{\lambda_E}\left(\frac{x}{\eta - \mu x}\right), & 0 < x < \tau \\ 0, & x \geq \tau \end{cases} \quad (29b)$$

B. ASC

For the analysis of ASC, both Bob's and Eve's channel state information (CSI) is assumed to be fully available at Alice, which could be acquired by CSI estimation methods, such as [46], [47]. Practically, it may apply to the scenario where a base station (Alice) serves two independent single-antenna users, who request secure downlink transmissions from Alice. In such a scenario, on the one hand, the users ask for a downlink transmission request from Alice, such that their CSI could be available at Alice; on the other hand, the users do not want the other one to obtain their own private information in case of privacy disclosure, which means they could play dual roles as Bob or Eve for each other. Using the PDFs and CDFs of Bob's and Eve's SINRs in (26)-(29), the instantaneous secrecy capacity can be defined as

$$C_s(\gamma_B, \gamma_E) = \left[\log_2(1 + \gamma_B) - \log_2(1 + \gamma_E)\right]^+, \quad (30)$$

where $[\cdot]^+ = \max\{\cdot, 0\}$. If we further assume Bob's and Eve's channels experience independent fading, the ASC can

be calculated by [38]

$$\begin{aligned}\bar{C}_s(\gamma_B, \gamma_E) &= \int_0^\infty \int_0^\infty C_s(\gamma_B, \gamma_E) f(\gamma_B, \gamma_E) d\gamma_B d\gamma_E \quad (31a) \\ &= \underbrace{\frac{1}{\ln 2} \int_0^\infty \ln(1 + \gamma_B) f_{\gamma_B}(\gamma_B) F_{\gamma_E}(\gamma_B) d\gamma_B}_{\mathcal{I}_1} \\ &\quad + \underbrace{\frac{1}{\ln 2} \int_0^\infty \ln(1 + \gamma_E) f_{\gamma_E}(\gamma_E) F_{\gamma_B}(\gamma_E) d\gamma_E}_{\mathcal{I}_2} \\ &\quad - \underbrace{\frac{1}{\ln 2} \int_0^\infty \ln(1 + \gamma_E) f_{\gamma_E}(\gamma_E) d\gamma_E}_{\mathcal{I}_3}, \quad (31b)\end{aligned}$$

where $f(\gamma_B, \gamma_E) = f_{\gamma_B}(\gamma_B) f_{\gamma_E}(\gamma_E)$ is the joint PDF of γ_B and γ_E .

Before deriving the ASC, we define a function as

$$\Psi(v_1, v_2, v_3, v_4, v_5, \tau) = \int_0^\tau \mathcal{G}(t) dt, \quad (32)$$

where

$$\mathcal{G}(t) = \ln^{v_1}(1+t) \frac{t^{v_2}}{(\tau-t)^{v_3}} \exp\left\{-v_4 t - \frac{v_5 t}{\tau-t}\right\}. \quad (33)$$

Using standard calculation softwares like MATHEMATICA or MATLAB, (32) can be easily calculated. To provide a closed-form insight, an approximated expression for (32) when $\tau < \infty$ can be obtained by applying Gaussian-Legendre quadrature formula [52, Eq. (25.4.30)], i.e.,

$$\Psi(v_1, v_2, v_3, v_4, v_5, \tau) = \frac{\tau}{2} \int_{-1}^1 \mathcal{G}\left(\frac{\tau}{2}t + \frac{\tau}{2}\right) dt \quad (34a)$$

$$\approx \frac{\tau}{2} \sum_{i=1}^q \omega_i \mathcal{G}\left(\frac{\tau}{2}t_i + \frac{\tau}{2}\right), \quad (34b)$$

where t_i ($i = 1, 2, \dots, q$) is the i -th zero point of the q -th order Legendre polynomial [51, Eq. (8.910.2)], and ω_i is the i -th coefficient [52, Eq. (25.4.29)]. Actually, the approximation in (34) can achieve a perfect agreement with the actual values even with small orders. To illustrate this perfect agreement, we take $(v_1, v_2, v_3, v_4, v_5) = (2, 4, 5, 0.5, 10.5)$ (Case I) and $(v_1, v_2, v_3, v_4, v_5) = (1, 3, 4, 0.6, 15.5)$ (Case II) as examples. Fig. 4 shows the comparisons of actual and approximated values by Gauss-Legendre quadrature for the function $\Psi(\tau)$, from which it can be obtained that the Gauss-Legendre quadrature can provide nearly accurate approximation with the actual $\Psi(\tau)$ even with small orders, like $q = 10, 20$.

Specially, an accurate closed-form expression for (32) when $\tau \rightarrow \infty$ can be written as [30, Eq. (10)]

$$\mathcal{S}(u, v) = \Psi(1, u-1, 0, v, 0, \infty) \quad (35a)$$

$$= \int_0^\infty \ln(1+t) t^{u-1} \exp\{-vt\} dt \quad (35b)$$

$$= (u-1)! \exp\{v\} \sum_{k=1}^u \frac{\Gamma(-u+k, v)}{v^k}. \quad (35c)$$

Since the full CSI of both Bob's and Eve's channels is available at Alice, the ASC can be obtained in Lemma 1 by substituting (26), (27), (28d) and (29b) into (31).

Fig. 4. Comparisons of actual and approximated values by Gauss-Legendre quadrature for $\Psi(\tau)$. Case I: $(v_1, v_2, v_3, v_4, v_5) = (2, 4, 5, 0.5, 10.5)$, Case II: $(v_1, v_2, v_3, v_4, v_5) = (1, 3, 4, 0.6, 15.5)$.

Lemma 1: The ASC of the proposed FDA-DM scheme in FTR fading channel is given by

$$\bar{C}_s(\gamma_B, \gamma_E) = \mathcal{I}_1 + \mathcal{I}_2 - \mathcal{I}_3, \quad (36)$$

where the expressions of $\mathcal{I}_1$, $\mathcal{I}_2$ and $\mathcal{I}_3$ are listed in (37), (38) and (39), respectively.

Proof: Please see Appendix A.

Asymptotically, when the diffuse component power $\sigma_E^2 \rightarrow \infty$, a closed-form expression of the lower bound on the ASC is given in Lemma 2. In fact, the condition $\sigma_E^2 \rightarrow \infty$ indicates the worst scenario where Eve can achieve the best SINR. Given a fixed FTR fading parameter $K_E = \frac{U_E^2 + V_E^2}{2\sigma_E^2}$, $\sigma_E^2 \rightarrow \infty$ implies $U_E^2 + V_E^2 \rightarrow \infty$, and further $|\epsilon_E|^2 \rightarrow \infty$. According to (21), $|\epsilon_E|^2 \rightarrow \infty$ indicates $\lambda_E = |\epsilon_E|^2 P_s \mathbb{E}(|s|^2) / \delta_E^2 \rightarrow \infty$, and further $\gamma_E \rightarrow \tau = \eta/\mu$, which is exactly the upper bound on Eve's SINR.

Lemma 2: When $\sigma_E^2 \rightarrow \infty$, the lower bound on the ASC of the proposed FDA-DM scheme in FTR fading can be written in the following closed-form expression,

$$\begin{aligned}\bar{C}_s^{\text{Low}}(\gamma_B, \gamma_E) &= \frac{m_B^{m_B}}{\ln 2 \Gamma(m_B)} \sum_{j_B=0}^{\infty} \frac{K_B^{j_B} d_{j_B}}{j_B! j_B! (2\beta_1^2 \sigma_B^2)^{j_B+1}} \\ &\quad \times \left[\mathcal{S}(j_B+1, \frac{1}{2\beta_1^2 \sigma_B^2}) - \Psi(1, j_B, 0, \frac{1}{2\beta_1^2 \sigma_B^2}, 0, \tau) \right] \\ &\quad - \frac{\ln(1+\tau)}{\ln 2} [1 - F_{\gamma_B}(\tau)].\end{aligned} \quad (40)$$

Proof: Please see Appendix B.

C. SOP

Different from ASC, the calculation of SOP does not require Alice to obtain Eve's CSI, which means Alice has to encode the confidential information at a certain rate R_0 . From the information-theoretic perspective, the perfect secrecy can be achieved if $R_0 \leq C_s$; otherwise, the secrecy outage will occur.

The SOP is defined as the probability that the instantaneous secrecy capacity C_s falls below a target secrecy rate R_0 , i.e.,

$$P_{\text{out}} = \Pr \{C_s(\gamma_B, \gamma_E) < R_0\} \quad (41a)$$

$$= \Pr \left\{ \log_2 \frac{1 + \gamma_B}{1 + \gamma_E} < R_0 \right\}, \quad (41b)$$

which can be mathematically calculated in Lemma 3.

Lemma 3: The SOP of the proposed FDA-DM scheme in FTR fading can be obtained by

$$\begin{aligned} P_{\text{out}} = & \frac{m_B^{m_B}}{\Gamma(m_B)} \frac{m_E^{m_E}}{\Gamma(m_E)} \sum_{j_B=0}^{\infty} \sum_{j_E=0}^{\infty} \frac{K_B^{j_B} d_{j_B} K_E^{j_E} d_{j_E} \tau}{j_B! j_E! j_E! (2\mu\sigma_E^2)^{j_E+1}} \\ & \times \left[\Psi(0, j_E, j_E + 2, 0, \frac{1}{2\mu\sigma_E^2}, \tau) \right. \\ & - \sum_{n=0}^{j_B} \frac{1}{n!} \exp\left(-\frac{2R_0 - 1}{2\beta_1^2 \sigma_B^2}\right) \sum_{k=0}^n \binom{n}{k} \frac{2^{kR_0} (2R_0 - 1)^{n-k}}{(2\beta_1^2 \sigma_B^2)^n} \\ & \left. \times \Psi(0, j_E + k, j_E + 2, \frac{2R_0}{2\beta_1^2 \sigma_B^2}, \frac{1}{2\mu\sigma_E^2}, \tau) \right]. \end{aligned} \quad (42)$$

Proof: Please see Appendix C.

Lemma 4: When $\sigma_E^2 \rightarrow \infty$, the upper bound on the SOP of the proposed FDA-DM scheme in FTR fading can be written as

$$P_{\text{out}}^{\text{UP}} = \frac{m_B^{m_B}}{\Gamma(m_B)} \sum_{j_B=0}^{\infty} \frac{K_B^{j_B} d_{j_B}}{j_B! j_B!} \Upsilon\left(j_B + 1, \frac{2R_0(1 + \tau) - 1}{2\beta_1^2 \sigma_B^2}\right). \quad (43)$$

Proof: Please see Appendix D.

V. NUMERICAL RESULTS

In this section, Monte Carlo experiments are conducted to verify the theoretical analysis, where the ZF method [16], [18], [21], [27]-[32], the SVD method [22], and the NoAN method [38]-[40] are included. The detailed parameters are listed in

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Central frequency, f_0	30 GHz
Fixed frequency increment, Δf	20 kHz
Number of FDA elements, $2N + 1$	21
Number of subcarriers for each element, L	7
Total transmit power, P_s	30 dBm
Power splitting factor, β_1	0.9
AWGN variance, δ_B^2, δ_E^2	1
FTR parameters, (m_B, K_B, Δ_B)	(2.3, 10, 0.5)
FTR parameters, (m_E, K_E, Δ_E)	(5.3, 15, 0.35)
Location of Bob, (r_B, θ_B, ψ_B)	(1 km, 20° , 30°)
Location of Eve, (r_E, θ_E, ψ_E)	(1.5 km, -20° , 25°)
Number of Monte Carlo experiments	10^5

Table II. For fair consideration, the AWGN powers δ_B^2 and δ_E^2 are set as identical fixed values, and the total transmit power P_s is set as a fixed value as well, which means Alice-Bob and Alice-Eve AWGN channels have the same quality.

A. ASC

Fig. 5(a) depicts the ASC of the proposed FDA-DM scheme versus $\bar{\lambda}_B$ in FTR fading channels, where the analytical results well match the simulated results with 10^5 Monte Carlo experiments. First, it holds for all four PLS approaches that the ASC climbs with increasing $\bar{\lambda}_B$ when $\bar{\lambda}_E$ is fixed. Second, compared with ZF and SVD approaches, the proposed SP method can achieve almost the same ASC. Although there is actually a very small penalty on ASC, the proposed SP method is still much more competitive considering the considerable memory savings. Moreover, compared with the NoAN approach, there is a positive lower bound on the ASC when $\bar{\lambda}_E \rightarrow \infty$, which means an absolutely positive ASC can always be realized

$$\begin{aligned} \mathcal{I}_1 = & \frac{m_B^{m_B} m_E^{m_E}}{\ln 2 \Gamma(m_B) \Gamma(m_E)} \sum_{j_B=0}^{\infty} \sum_{j_E=0}^{\infty} \frac{K_B^{j_B} d_{j_B} K_E^{j_E} d_{j_E}}{j_B! j_B! j_E! (2\beta_1^2 \sigma_B^2)^{j_B+1}} \\ & \times \left(\Psi(1, j_B, 0, \frac{1}{2\beta_1^2 \sigma_B^2}, 0, \tau) - \sum_{n=0}^{j_E} \frac{1}{n! (2\mu\sigma_E^2)^n} \Psi(1, j_B + n, n, \frac{1}{2\beta_1^2 \sigma_B^2}, \frac{1}{2\mu\sigma_E^2}, \tau) \right) \\ & + \frac{m_B^{m_B}}{\ln 2 \Gamma(m_B)} \sum_{j_B=0}^{\infty} \frac{K_B^{j_B} d_{j_B}}{j_B! j_B! (2\beta_1^2 \sigma_B^2)^{j_B+1}} \left(\mathcal{S}(j_B + 1, \frac{1}{2\beta_1^2 \sigma_B^2}) - \Psi(1, j_B, 0, \frac{1}{2\beta_1^2 \sigma_B^2}, 0, \tau) \right). \end{aligned} \quad (37)$$

$$\begin{aligned} \mathcal{I}_2 = & \frac{m_B^{m_B} m_E^{m_E}}{\ln 2 \Gamma(m_B) \Gamma(m_E)} \sum_{j_B=0}^{\infty} \sum_{j_E=0}^{\infty} \frac{K_B^{j_B} d_{j_B} K_E^{j_E} d_{j_E} \tau}{j_B! j_E! j_E! (2\mu\sigma_E^2)^{j_E+1}} \\ & \times \left(\Psi(1, j_E, j_E + 2, 0, \frac{1}{2\mu\sigma_E^2}, \tau) - \sum_{n=0}^{j_B} \frac{1}{n! (2\beta_1^2 \sigma_B^2)^n} \Psi(1, j_E + n, j_E + 2, \frac{1}{2\beta_1^2 \sigma_B^2}, \frac{1}{2\mu\sigma_E^2}, \tau) \right). \end{aligned} \quad (38)$$

$$\mathcal{I}_3 = \frac{m_E^{m_E}}{\ln 2 \Gamma(m_E)} \sum_{j_E=0}^{\infty} \frac{K_E^{j_E} d_{j_E} \tau}{j_E! j_E! (2\mu\sigma_E^2)^{j_E+1}} \Psi(1, j_E, j_E + 2, 0, \frac{1}{2\mu\sigma_E^2}, \tau). \quad (39)$$

Fig. 5. ASC $\bar{C}_s$ versus (a) Bob's and (b) Eve's average SNRs $\bar{\lambda}_B$ (dB) and $\bar{\lambda}_E$ (dB) in FTR fading channels. ($f_0 = 30$ GHz, $\Delta f = 20$ kHz, $N = 10$, $L = 7$, $\beta_1 = 0.9$)

Fig. 6. SOP P_{out} versus Bob's average SNR $\bar{\lambda}_B$ (dB) with (a) $R_0 = 0.2$ bits/s/Hz and (b) $R_0 = 0.5$ bits/s/Hz in FTR fading channels. ($f_0 = 30$ GHz, $\Delta f = 20$ kHz, $N = 10$, $L = 7$, $\beta_1 = 0.9$)

as long as $\bar{\lambda}_B$ is big enough. By contrast, the ASC of NoAN approach reduces to zero when $\bar{\lambda}_E \rightarrow \infty$.

Fig. 5(b) illustrates the ASC of the proposed FDA-DM scheme versus $\bar{\lambda}_E$ in FTR fading channels. As expected, that the ASC decreases with increasing $\bar{\lambda}_E$ when $\bar{\lambda}_B$ is fixed. Differently, the ASCs of the proposed SP and the conventional ZF and SVD methods reduce to a positive lower bound, while the ASC of the NoAN method declines to zero. Similar to Fig. 5(a), almost the same ASC can be achieved for the proposed SP and the conventional ZF and SVD methods while the proposed SP distinguishes from the conventional ZF and SVD methods with much lower memory consumption as analyzed in Section III.A.

B. SOP

Figs. 6(a) and (b) present the SOP of the proposed FDA-DM scheme versus $\bar{\lambda}_B$ in FTR fading channels with $R_0 = 0.2$ and 0.5 bits/s/Hz, respectively. Comparing Figs. 6(a) and (b), it holds for all four PLS methods that the SOP decreases with smaller R_0 . Given a specific R_0 and $\bar{\lambda}_E$, as expected, the

SOP drops as $\bar{\lambda}_B$ increases. Compared with the conventional NoAN method, the proposed SP method can achieve much lower SOP. More importantly, there exists an upper bound on SOP when $\bar{\lambda}_E \rightarrow \infty$ for the proposed SP method, while the SOP of the conventional NoAN method roars to 1. On the other hand, the proposed SP method can achieve almost the same SOP as the conventional ZF and SVD approaches with much lower memory consumption.

Figs. 7(a) and (b) illustrate the SOP of the proposed FDA-DM scheme versus $\bar{\lambda}_E$ in FTR fading channels with $R_0 = 0.2$ and 0.5 bits/s/Hz, respectively. Analogous to Figs. 6(a) and (b), it can also be observed that a smaller R_0 produces a smaller SOP. With a specific R_0 , the SOPs of the proposed SP method and the conventional ZF and SVD methods increase to an upper bound along with increasing $\bar{\lambda}_E$. But for the conventional NoAN method, it roars rapidly to 1 when $\bar{\lambda}_E$ increases. The advantage of the proposed SP method is verified again that much lower memory consumption yet achieves almost the same SOP as the ZF and SVD methods.

Fig. 7. SOP P_{out} versus Eve's average SNR $\bar{\lambda}_E$ (dB) with (a) $R_0 = 0.2$ bits/s/Hz and (b) $R_0 = 0.5$ bits/s/Hz in FTR fading channels. ($f_0 = 30$ GHz, $\Delta f = 20$ kHz, $N = 10$, $L = 7$, $\beta_1 = 0.9$)

TABLE III
IMPROVED OR LOST PERFORMANCES OF THE PROPOSED SP METHOD COMPARED WITH ZF AND SVD METHODS ($f_0 = 30$ GHz, $\Delta f = 20$ kHz, $N = 10$, $L = 7$, $\beta_1 = 0.9$, $\bar{\lambda}_B = 20$ dB, $\bar{\lambda}_E = 10$ dB, AND $R_0 = 0.2$ bits/s/Hz)

Items	ZF [16], [18], [21], [27]-[32]	SVD [22]	Proposed SP	$\frac{[ZF-SP]}{ZF} \times 100\%$	$\frac{[SVD-SP]}{SVD} \times 100\%$
Memory Consumption	21756	2960	148	99.32% (Improved)	95% (Improved)
ASC, $\bar{C}_s$ (bits/s/Hz)	5.77768102	5.77764192	5.77757348	0.0018% (Lost)	0.0012% (Lost)
SOP, P_{out} ($\times 10^{-4}$)	7.47269793	7.47377494	7.47559205	0.0387% (Lost)	0.0243% (Lost)

C. Benefit and Detriment

In order to demonstrate the improvement or loss of performances, we take $f_0 = 30$ GHz, $\Delta f = 20$ kHz, $N = 10$, $L = 7$, $\beta_1 = 0.9$, $\bar{\lambda}_B = 20$ dB, $\bar{\lambda}_E = 10$ dB, and $R_0 = 0.2$ bits/s/Hz as an example. Table III illustrates the improved or lost performances of the proposed SP method compared with conventional ZF and SVD methods, where the total memory consumption, the ASC and the SOP are presented. We can obtain that compared with the ZF (or SVD) method, the proposed SP method can save 99.32% (or 95%) total memory while only cost 0.0018% (or 0.0012%) loss of the ASC, and 0.0387% (or 0.0243%) loss of the SOP. Therefore, for the proposed SP method, the benefit of significant memory savings outweighs the detriment of very tiny secrecy degradation.

D. Discussions on a Multi-Antenna Eve

In this section, the secrecy performance with a multi-antenna Eve is discussed. We assume the multi-antenna Eve is equipped with J antennas, and the channel coefficient vector from Alice to Eve's J antennas is denoted by $\epsilon_E = [\epsilon_{E,1} \cdots \epsilon_{E,j} \cdots \epsilon_{E,J}]^T$, of which the j -th entry ($j = 1, 2, \dots, J$), $\epsilon_{E,j}$, undergoes FTR fading with parameters $(m_{E,j}, K_{E,j}, \Delta_{E,j}, \sigma_{E,j}^2)$. Then, the received signal vector of the multi-antenna (MA) Eve located at (r_E, θ_E, ψ_E) can be

obtained by

$$\mathbf{y}^{MA}(r_E, \theta_E, \psi_E) = \epsilon_E \mathbf{h}_E^H \mathbf{x} + \boldsymbol{\xi}_E \quad (44a)$$

$$= \epsilon_E \beta_1 \sqrt{P_s} \mathbf{h}_E^H \mathbf{p}_1 s + \epsilon_E \alpha \beta_2 \sqrt{P_s} \mathbf{h}_E^H \mathbf{p}_2 z + \boldsymbol{\xi}_E \quad (44b)$$

$$= \underbrace{\epsilon_E \beta_1 \sqrt{P_s} \rho_1 s}_{\text{Distorted Signal}} + \underbrace{\epsilon_E \alpha \beta_2 \sqrt{P_s} \rho_2 z}_{\text{Artificial Noise}} + \underbrace{\boldsymbol{\xi}_E}_{\text{AWGN}}, \quad (44c)$$

where $\boldsymbol{\xi}_E = [\xi_{E,1} \cdots \xi_{E,j} \cdots \xi_{E,J}]^T \sim \mathcal{CN}(\mathbf{0}, \delta_E^2 \mathbf{I}_J)$ indicates Eve's complex AWGN vector. According to (44c), the SINR of the multi-antenna Eve can be rewritten as

$$\gamma_E^{MA} = \frac{||\epsilon_E||^2 \beta_1^2 |\rho_1|^2 P_s \mathbb{E}(|s|^2) / \delta_E^2}{||\epsilon_E||^2 \alpha^2 \beta_2^2 |\rho_2|^2 P_s \mathbb{E}(|z|^2) / \delta_E^2 + 1} \quad (45a)$$

$$= \frac{\eta \lambda_E^{MA}}{\mu \lambda_E^{MA} + 1}, \quad (45b)$$

where $\lambda_E^{MA} = ||\epsilon_E||^2 P_s \mathbb{E}(|s|^2) / \delta_E^2$ represents the multi-antenna Eve's SNR. It is easy to observe that λ_E^{MA} is a sum of squared FTR random variables, of which the PDF and CDF can be calculated by [37, Eqs.(5) and (6)].

According to above analysis, the simulated ASCs with single-antenna ($J = 1$) and multi-antenna ($J = 7, 100, \infty$) Eves are shown in Fig. 8. It can be observed from Fig. 8 that 1) no matter Eve has single or multiple antenna(s), the proposed SP method can achieve almost the same ASC as the conventional ZF and SVD methods; 2) compared with the conventional NoAN method, only a slight ASC reduction occurs for the proposed SP method when Eve has multiple antennas, while the ASC of the NoAN method reduces dramatically with a multi-antenna Eve; 3) the ASC has a lower bound when

Fig. 8. ASC $\bar{C}_s$ versus (a) Bob's average SNR $\bar{\lambda}_B$ ($\bar{\lambda}_E = 10$ dB) and (b) Eve's average SNR $\bar{\lambda}_E$ ($\bar{\lambda}_B = 10$ dB) in FTR fading channels with a multi-antenna Eve. ($f_0 = 30$ GHz, $\Delta f = 20$ kHz, $N = 10$, $L = 7$, $\beta_1 = 0.9$)

Fig. 9. Gap ASCs between single-antenna Eve ($J = 1$) and multi-antenna Eve ($J = 7, 100$). ($f_0 = 30$ GHz, $\Delta f = 20$ kHz, $N = 10$, $L = 7$, $\beta_1 = 0.9$)

Eve's antenna number J goes to ∞ , which is the same as the single-antenna case. As a matter of fact, $J \rightarrow \infty$ implies $\lambda_E^{\text{MA}} \rightarrow \infty$ and further $\gamma_E^{\text{MA}} \rightarrow \tau = \eta/\mu$, which accounts for the lower bound on ASC.

In order to further illustrate the secrecy degradation, we depict the gap ASC between the single-antenna ($J = 1$) and multi-antenna ($J = 7, 100$) Eves in Fig. 9. It shows that along with the increase of Eve's average SNR, the gap ASC (secrecy degradation) climbs from zero to a peak value before reducing to zero again. This means that a) the multi-antenna ($J > 1$) Eve cannot degrade the secrecy performance when its average SNR $\bar{\lambda}_E$ is sufficiently small or large; b) the secrecy performance will be slightly degraded only when $\bar{\lambda}_E$ falls into a "middle" range (for example, between 0 dB and 40 dB with the given simulation parameters). As a matter of fact, this phenomenon can be explained by (22) and (45). On the one hand, from (22), the lower and upper bounds on $\bar{\gamma}_E$ (single-antenna) are $\bar{\gamma}_E^{\text{Low}} = 0$ and $\bar{\gamma}_E^{\text{UP}} = \tau = \eta/\mu$. On the other hand, it can be obtained from (45) that $\lambda_E^{\text{MA}} \rightarrow 0$ and ∞ correspond to the lower and upper bounds on $\bar{\gamma}_E^{\text{MA}}$ (multi-

antenna), i.e., $\bar{\gamma}_E^{\text{MA,Low}} = 0$ and $\bar{\gamma}_E^{\text{MA,UP}} = \tau = \eta/\mu$, which are the same as the case with a single-antenna Eve. Therefore, when the average SNR $\bar{\lambda}_E$ is sufficiently small or large, the secrecy performance will not be noticeably degraded even with a multi-antenna Eve.

E. Discussions on the Time-Variance of FDA

Owing to the small frequency increments between adjacent antennas, the far-field beampattern radiated by FDA is time-variant, which is a common problem for nearly all types of FDA including the multi-carrier FDA utilized in this paper. The time-variant problem may result in short-time secure transmissions via the proposed FDA-DM scheme, which may be possibly used for secure signaling control from a base station to legitimate users.

To achieve long-time secure transmissions via the proposed FDA-DM scheme, the time-variant problem of FDA should be properly addressed, which, however, is not the focus of this paper. As a matter of fact, the key purposes of this paper are to present a memory-efficient SP method and to analyze the PLS performances of DM systems in FTR fading channels. Although only the multi-carrier FDA model is adopted in this paper, the proposed SP method and the PLS analysis on ASC and SOP in FTR fading channels do not depend on some specific antenna array, which are flexible and applicable to other antenna arrays (like PA)-based DM schemes as well.

VI. CONCLUSION

In this paper, we presented a memory-efficient single-point AN-aided secure DM transmission scheme for 5G and beyond communications based on symmetrical multi-carrier FDA, which significantly outperforms the conventional ZF and SVD approaches with only a very small penalty on secrecy. In the proposed FDA-DM scheme, the FDA was analyzed in three dimensions, i.e., range, azimuth angle, and elevation angle. Moreover, the ASC and SOP of the proposed FDA-DM scheme were analyzed, for the first time, in FTR fading channels, which provide a better fit for small-scale fading

measurements in mmWave communications. The closed-form expressions of lower ASC bound and upper SOP bound were derived and numerical demonstrations with Monte Carlo trials were provided as well. This work opens a way to lower the memory requirements for DM-based PLS transmission of 5G and beyond communications. Some challenges and future works are to investigate the PLS performance of the proposed FDA-DM scheme with multiple multi-antenna users and to solve the time-variant problem of FDA.

APPENDIX

A. Proof of Lemma 1

Here, we derive the expression of $\mathcal{I}_1$. Substituting (26) and (28d) into (31), we can obtain (46), where $\Upsilon\left(j_E + 1, \frac{\gamma_B}{2\sigma_E^2(\eta - \mu\gamma_B)}\right)$ can be written as 47 [51, Eq. (8.354.1)]. Substituting (47) into (46b) and using (32), we can acquire

$$\begin{aligned} \mathcal{I}_{1,1} &= j_E! \Psi(1, j_B, 0, \frac{1}{2\beta_1^2 \sigma_B^2}, 0, \tau) \\ &\quad - j_E! \sum_{n=0}^{j_E} \frac{1}{n! (2\mu\sigma_E^2)^n} \Psi(1, j_B + n, n, \frac{1}{2\beta_1^2 \sigma_B^2}, \frac{1}{2\mu\sigma_E^2}, \tau). \end{aligned} \quad (48)$$

Similarly, $\mathcal{I}_{1,2}$ can be calculated by

$$\mathcal{I}_{1,2} = \Psi(1, j_B, 0, \frac{1}{2\beta_1^2 \sigma_B^2}, 0, \infty) - \Psi(1, j_B, 0, \frac{1}{2\beta_1^2 \sigma_B^2}, 0, \tau). \quad (49)$$

Substituting (48) and (49) into (46b), we can get the expression of $\mathcal{I}_1$ in (37). $\mathcal{I}_2$ and $\mathcal{I}_3$ can be derived in the same way, which ends the proof of Lemma 1.

B. Proof of Lemma 2

Observing (22), when $\sigma_E^2 \rightarrow \infty$, we can subsequently obtain $\lambda_E \rightarrow \infty$ and $\gamma_E \rightarrow \tau$. Therefore, $\bar{C}_s^{\text{Low}}$ can be written as

$$\begin{aligned} \bar{C}_s^{\text{Low}}(\gamma_B, \gamma_E) &= \frac{1}{\ln 2} \int_0^\infty [\ln(1 + \gamma_B) - \ln(1 + \tau)]^+ f_{\gamma_B}(\gamma_B) d\gamma_B \quad (50a) \\ &= \frac{1}{\ln 2} \int_\tau^\infty \ln(1 + \gamma_B) f_{\gamma_B}(\gamma_B) d\gamma_B \\ &\quad - \frac{1}{\ln 2} \int_\tau^\infty \ln(1 + \tau) f_{\gamma_B}(\gamma_B) d\gamma_B. \end{aligned} \quad (50b)$$

Replacing (23) and (26) into (50) yields (51), and substituting (32) into (51b) ends the proof of Lemma 2.

C. Proof of Lemma 3

Given a fixed secrecy capacity R_0 , the SOP in (41b) can be further written as

$$P_{\text{out}} = \Pr\{\gamma_B < 2^{R_0}(1 + \gamma_E) - 1\} \quad (52a)$$

$$= \int_0^\infty F_{\gamma_B}(2^{R_0}(1 + \gamma_E) - 1) f_{\gamma_E}(\gamma_E) d\gamma_E. \quad (52b)$$

Then, replacing (23), (26) and (29b) into (52b) yields (53). Using [51, Eq. (8.354.1)], the term $\mathcal{A}$ in (53b) can be calculated by (54), where

$$\begin{aligned} \mathcal{B} &= \int_0^\tau \frac{\gamma_E^{j_E}}{(\tau - \gamma_E)^{j_E+2}} \left(\frac{2^{R_0}(1 + \gamma_E) - 1}{2\beta_1^2 \sigma_B^2} \right)^n \\ &\quad \times \exp\left(-\frac{\gamma_E}{2\mu\sigma_E^2(\tau - \gamma_E)} - \frac{2^{R_0}(1 + \gamma_E) - 1}{2\beta_1^2 \sigma_B^2}\right) d\gamma_E. \end{aligned} \quad (55)$$

According to the binomial theorem [51, Eq. (1.111)], we can write

$$\left(\frac{2^{R_0}(1 + \gamma_E) - 1}{2\beta_1^2 \sigma_B^2} \right)^n = \left(\frac{2^{R_0}}{2\beta_1^2 \sigma_B^2} \gamma_E + \frac{2^{R_0} - 1}{2\beta_1^2 \sigma_B^2} \right)^n \quad (56a)$$

$$= \frac{2^{nR_0}}{(2\beta_1^2 \sigma_B^2)^n} \sum_{k=0}^n \binom{n}{k} \gamma_E^k \left(\frac{2^{R_0} - 1}{2^{R_0}} \right)^{n-k}. \quad (56b)$$

$$\mathcal{I}_1 = \frac{1}{\ln 2} \int_0^\tau \ln(1 + \gamma_B) f_{\gamma_B}(\gamma_B) F_{\gamma_E}(\gamma_B) d\gamma_B + \frac{1}{\ln 2} \int_\tau^\infty \ln(1 + \gamma_B) f_{\gamma_B}(\gamma_B) F_{\gamma_E}(\gamma_B) d\gamma_B \quad (46a)$$

$$\begin{aligned} &= \frac{m_B^{m_B} m_E^{m_E}}{\ln 2 \Gamma(m_B) \Gamma(m_E)} \sum_{j_B=0}^\infty \sum_{j_E=0}^\infty \frac{K_B^{j_B} d_{j_B} K_E^{j_E} d_{j_E}}{j_B! j_B! j_E! j_E! (2\beta_1^2 \sigma_B^2)^{j_B+1}} \\ &\quad \times \underbrace{\int_0^\tau \ln(1 + \gamma_B) \gamma_B^{j_B} \exp\left(-\frac{\gamma_B}{2\beta_1^2 \sigma_B^2}\right) \Upsilon\left(j_E + 1, \frac{\gamma_B}{2\sigma_E^2(\eta - \mu\gamma_B)}\right) d\gamma_B}_{\mathcal{I}_{1,1}} \\ &\quad + \frac{m_B^{m_B}}{\ln 2 \Gamma(m_B)} \sum_{j_B=0}^\infty \frac{K_B^{j_B} d_{j_B}}{j_B! j_B! (2\beta_1^2 \sigma_B^2)^{j_B+1}} \underbrace{\int_\tau^\infty \ln(1 + \gamma_B) \gamma_B^{j_B} \exp\left(-\frac{\gamma_B}{2\beta_1^2 \sigma_B^2}\right) d\gamma_B}_{\mathcal{I}_{1,2}}. \end{aligned} \quad (46b)$$

$$\Upsilon\left(j_E + 1, \frac{\gamma_B}{2\sigma_E^2(\eta - \mu\gamma_B)}\right) = j_E! \left(1 - \exp\left(-\frac{\gamma_B}{2\sigma_E^2(\eta - \mu\gamma_B)}\right) \sum_{n=0}^{j_E} \frac{1}{n!} \left(\frac{\gamma_B}{2\sigma_E^2(\eta - \mu\gamma_B)} \right)^n \right). \quad (47)$$

Therefore, $\mathcal{B}$ can be further rewritten in (57) by replacing (56b) into (55). Finally, substituting (54c) and (57c) into (53b) ends the proof of Lemma 3.

D. Proof of Lemma 4

According to the definition of SOP, the upper bound on SOP when $\sigma_E^2 \rightarrow \infty$ can be written as

$$P_{\text{out}}^{\text{UP}} = \Pr \left\{ \log_2 \frac{1 + \gamma_B}{1 + \gamma_E} < R_0 \right\} \Big|_{\sigma_E^2 \rightarrow \infty} \quad (58a)$$

$$= \Pr \left\{ \gamma_B < 2^{R_0}(1 + \tau) - 1 \right\} \quad (58b)$$

$$= F_{\gamma_B} \left(2^{R_0}(1 + \tau) - 1 \right). \quad (58c)$$

Then applying (27) into (58c), we can obtain

$$P_{\text{out}}^{\text{UP}} = \frac{m_B^{m_B}}{\Gamma(m_B)} \sum_{j_B=0}^{\infty} \frac{K_B^{j_B} d_{j_B}}{j_B! j_B!} \Upsilon \left(j_B + 1, \frac{2^{R_0}(1 + \tau) - 1}{2\beta_1^2 \sigma_B^2} \right), \quad (59)$$

which ends the proof of Lemma 4.

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$$\bar{C}_s^{\text{Low}}(\gamma_B, \gamma_E) = \frac{1}{\ln 2} \int_{\tau}^{\infty} \ln(1 + \gamma_B) \frac{m_B^{m_B}}{\Gamma(m_B)} \sum_{j_B=0}^{\infty} \frac{K_B^{j_B} d_{j_B}}{j_B! j_B!} \frac{\gamma_B^{j_B}}{(2\beta_1^2 \sigma_B^2)^{j_B+1}} \exp \left(-\frac{\gamma_B}{2\beta_1^2 \sigma_B^2} \right) d\gamma_B - \frac{\ln(1 + \tau)}{\ln 2} [1 - F_{\gamma_B}(\tau)] \quad (51a)$$

$$= \frac{m_B^{m_B}}{\ln 2 \Gamma(m_B)} \sum_{j_B=0}^{\infty} \frac{K_B^{j_B} d_{j_B}}{j_B! j_B! (2\beta_1^2 \sigma_B^2)^{j_B+1}} \int_{\tau}^{\infty} \ln(1 + \gamma_B) \gamma_B^{j_B} \exp \left(-\frac{\gamma_B}{2\beta_1^2 \sigma_B^2} \right) d\gamma_B - \frac{\ln(1 + \tau)}{\ln 2} [1 - F_{\gamma_B}(\tau)]. \quad (51b)$$

$$P_{\text{out}} = \int_0^{\tau} \frac{m_B^{m_B}}{\Gamma(m_B)} \sum_{j_B=0}^{\infty} \frac{K_B^{j_B} d_{j_B}}{j_B! j_B!} \Upsilon \left(j_B + 1, \frac{2^{R_0}(1 + \gamma_E) - 1}{2\beta_1^2 \sigma_B^2} \right) \frac{\eta}{(\eta - \mu\gamma_E)^2} \frac{m_E^{m_E}}{\Gamma(m_E)} \times \sum_{j_E=0}^{\infty} \frac{K_E^{j_E} d_{j_E}}{j_E! j_E!} \frac{(\frac{\gamma_E}{\eta - \mu\gamma_E})^{j_E}}{(2\sigma_E^2)^{j_E+1}} \exp \left(-\frac{\gamma_E}{2\sigma_E^2} \right) d\gamma_E \quad (53a)$$

$$= \frac{m_B^{m_B}}{\Gamma(m_B)} \frac{m_E^{m_E}}{\Gamma(m_E)} \sum_{j_B=0}^{\infty} \sum_{j_E=0}^{\infty} \frac{K_B^{j_B} d_{j_B} K_E^{j_E} d_{j_E} \tau}{j_B! j_B! j_E! j_E! (2\mu\sigma_E^2)^{j_E+1}} \times \underbrace{\int_0^{\tau} \Upsilon \left(j_B + 1, \frac{2^{R_0}(1 + \gamma_E) - 1}{2\beta_1^2 \sigma_B^2} \right) \frac{\gamma_E^{j_E}}{(\tau - \gamma_E)^{j_E+2}} \exp \left(-\frac{\gamma_E}{2\mu\sigma_E^2(\tau - \gamma_E)} \right) d\gamma_E}_{\mathcal{A}}. \quad (53b)$$

$$\mathcal{A} = \int_0^{\tau} j_B! \left(1 - \exp \left(-\frac{2^{R_0}(1 + \gamma_E) - 1}{2\beta_1^2 \sigma_B^2} \right) \sum_{n=0}^{j_B} \frac{1}{n!} \left(\frac{2^{R_0}(1 + \gamma_E) - 1}{2\beta_1^2 \sigma_B^2} \right)^n \right) \times \frac{\gamma_E^{j_E}}{(\tau - \gamma_E)^{j_E+2}} \exp \left(-\frac{\gamma_E}{2\mu\sigma_E^2(\tau - \gamma_E)} \right) d\gamma_E \quad (54a)$$

$$= j_B! \int_0^{\tau} \frac{\gamma_E^{j_E}}{(\tau - \gamma_E)^{j_E+2}} \exp \left(-\frac{\gamma_E}{2\mu\sigma_E^2(\tau - \gamma_E)} \right) d\gamma_E - \sum_{n=0}^{j_B} \frac{j_B!}{n!} \mathcal{B} \quad (54b)$$

$$= j_B! \Psi(0, j_E, j_E + 2, 0, \frac{1}{2\mu\sigma_E^2}, \tau) - \sum_{n=0}^{j_B} \frac{j_B!}{n!} \mathcal{B}. \quad (54c)$$

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$$\mathcal{B} = \int_0^\tau \frac{\gamma_E^{j_E}}{(\tau - \gamma_E)^{j_E+2}} \frac{2^{nR_0}}{(2\beta_1^2\sigma_B^2)^n} \sum_{k=0}^n \binom{n}{k} \gamma_E^k \left(\frac{2^{R_0} - 1}{2^{R_0}} \right)^{n-k} \exp \left(-\frac{\gamma_E}{2\mu\sigma_E^2(\tau - \gamma_E)} - \frac{2^{R_0}(1 + \gamma_E) - 1}{2\beta_1^2\sigma_B^2} \right) d\gamma_E \quad (57a)$$

$$= \exp \left(-\frac{2^{R_0} - 1}{2\beta_1^2\sigma_B^2} \right) \sum_{k=0}^n \binom{n}{k} \frac{2^{kR_0}(2^{R_0} - 1)^{n-k}}{(2\beta_1^2\sigma_B^2)^n} \int_0^\tau \frac{\gamma_E^{j_E+k}}{(\tau - \gamma_E)^{j_E+2}} \exp \left(-\frac{\gamma_E}{2\mu\sigma_E^2(\tau - \gamma_E)} - \frac{2^{R_0}\gamma_E}{2\beta_1^2\sigma_B^2} \right) d\gamma_E \quad (57b)$$

$$= \exp \left(-\frac{2^{R_0} - 1}{2\beta_1^2\sigma_B^2} \right) \sum_{k=0}^n \binom{n}{k} \frac{2^{kR_0}(2^{R_0} - 1)^{n-k}}{(2\beta_1^2\sigma_B^2)^n} \Psi(0, j_E + k, j_E + 2, \frac{2^{R_0}}{2\beta_1^2\sigma_B^2}, \frac{1}{2\mu\sigma_E^2}, \tau). \quad (57c)$$

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