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 implementation of the physical-layer security (PLS) transmission of 5G and beyond communication system. In order to meet the tremendous increase in mobile data traffic, a new design consuming less memory 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, which differs 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 memory consumption of FDA-DM systems significantly compared with the conventional zero-forcing (ZF) and singular value decomposition (SVD) approaches. Moreover, the PLS performance of the proposed low-memory-consumption FDA-DM scheme is analyzed in fluctuating two-ray (FTR) fading channels for the first time, including bit error rate (BER), secrecy rate (SR), and secrecy outage probability (SOP). More importantly, the closed-form expressions for the lower bound of the average SR and the upper bound of the 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 the DM-based PLS transmission of 5G and beyond communication system.

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

I. INTRODUCTION

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PHYSICAL-LAYER security (PLS) is one of the most important aspects of 5G and beyond wireless communications [1]. 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 [2], 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 [3],[4]. Traditionally, DM technology is implemented using phased arrays (PA) [5], 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 [6][7], has been applied into DM implementations to realize two-dimension security in both range and angle.

Specifically, the FDA was first utilized in [8] to achieve range-angle dependent secure DM transmissions with fixed linear frequency increments. The work in [9] utilized the FDA with non-linear frequency increments to decouple range-angle-dependent transmit beam patterns for DM transmissions. The FDAs with random and time-modulated frequency increments were exploited for secure DM transmissions in [10] and [11], respectively. FDA was also used in [12][13] to establish secure DM transmissions for proximal legitimate user and eavesdropper. In addition to the single-user FDA-DM schemes [8]-[13], multi-user FDA-DM schemes were also investigated intensively by means of the spread spectrum technology [14], optimization algorithms [15], singular value decomposition (SVD) [16], weighted-type fractional Fourier transform (WFRFT) [17], respectively.

In the DM transmission schemes, artificial noise (AN) plays an important role. 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 [10], [12], [15], [18]-[20]. The SVD method provided another way to redesign the orthogonal precoding matrix [16]. 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 secure DM transmission scheme with low memory consumption for 5G and beyond communication system. Moreover, the aforementioned DM-related works only considered the line-of-sight (LoS) channels in free space. Regarding the FDA-DM transmission in multipath fading channels, the authors in [21] and [22] 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 [21], [23] about FDA-DM transmissions in fading channels utilized ZF-based AN method, which demand 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 [24]. Recently, the fluctuating two-ray (FTR) fading model was proposed in [24], which can provide a better fit for small-scale fading measurements in mmWave communications. The authors in [26], [27] and [28] generalized the FTR fading model into arbitrary fading parameter case, cascaded case, and squared case, respectively. More recently, the secrecy rate (SR), secrecy outage probability (SOP) and symbol error rate (SER) of FTR fading channels were analyzed in [29], [30] and [31] without AN (NoAN), respectively. The power adaption algorithm and wireless-powered UAV relay communication in FTR fading channels were investigated in [32] and [33], 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 low-memory-consumption 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) Based on the proposed FDA model, a low-memory-consumption FDA-DM scheme is further proposed with the assistance of single-point AN, which significantly outperforms the conventional ZF method [10], [12], [15], [18] and the SVD method [16]. The proposed low-memory-consumption FDA-DM scheme provides an efficient strategy to lower the memory requirements for the PLS transmissions of 5G and beyond communications.

3) The bit error rate (BER), SR and SOP performances 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 of average SR and the upper bound of SOP. Numerical experiments are conducted to compare the PLS performances of the proposed SP and the conventional ZF [10], [12], [15], [18]-[23], SVD [16] and NoAN [29]-[31] 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 low-memory-consumption multi-carrier FDA 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 BER, average SR and 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. $N(0, \sigma^2)$ and $CN(0, \sigma^2)$ refer to the real and complex Gaussian distributions with zero mean and variance $\sigma^2$, respectively. $\mathcal{U}\{\cdot, \cdot\}$ is the uniform distribution. Finally, the probability function is denoted by $\Pr (\cdot)$.

II. FDA MODEL IN THREE DIMENSIONS

Most of the state-of-the-art analyzes the FDA only in two dimensions [6]-[17], 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.

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 ($l = 0, \cdots, L - 1$) subcarrier of the $n$-th ($n = -N, \cdots, 0, \cdots, N$) element is designed as

$$f_{n,l} = f_0 + \Delta f_{n,l}$$

where $f_0$ is the central radiated frequency, $\Delta f$ 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 $|\Delta f_{n,l}| \ll f_0$.

![Fig. 1. The proposed FDA-DM scheme in FTR fading channels.](image-url)
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

\[
x_{n,l}(t) = e^{j2\pi f_{n,l} t}
\]

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

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

where \( c \) denotes light speed and \( r_n \) refers to the path length from the \( n \)-th element to the observation point. With the far field approximation, \( r_n \) can be calculated as

\[
r_n \approx r - nd \sin \theta \cos \psi
\]

Taking (1) and (4) into (5) yields

\[
y(r, \theta, \psi) \approx \sum_{n=-N}^{N} \sum_{l=0}^{L-1} \exp \left\{ j2\pi f_{0} \left( t - \frac{r_n}{c} \right) \right\} \sum_{n=-N}^{N} \sum_{l=0}^{L-1} \exp \left\{ j2\pi \left( \Delta f_{n,l} \left( t - \frac{r_n}{c} \right) + \frac{1}{c} f_0 nd \sin \theta \cos \psi + \frac{1}{c} \Delta f_{n,l nd} \sin \theta \cos \psi \right) \right\}
\]

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 (7) can be further approximated as

\[
y(r, \theta, \psi) \approx \sum_{n=-N}^{N} \sum_{l=0}^{L-1} \exp \left\{ j2\pi f_0 \left( t - \frac{r_n}{c} \right) \right\} \sum_{n=-N}^{N} \sum_{l=0}^{L-1} \exp \left\{ j2\pi \left( \Delta f_{n,l} \left( t - \frac{r_n}{c} \right) + \frac{1}{c} f_0 nd \sin \theta \cos \psi \right) \right\}
\]

The terms inside the summation of (8) 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 \( \Delta a_{n,l} \)

\[
a_{n}(r, \theta, \psi) = \begin{bmatrix} e^{j2\pi \left( \Delta f_{n,l} \left( t - \frac{r_n}{c} \right) + \frac{1}{c} f_0 nd \sin \theta \cos \psi \right)} \\
e^{j2\pi \left( \Delta f_{n,l} \left( t - \frac{r_n}{c} \right) + \frac{1}{c} f_0 nd \sin \theta \cos \psi \right)} \\
e^{j2\pi \left( \Delta f_{n,l} \left( t - \frac{r_n}{c} \right) + \frac{1}{c} f_0 nd \sin \theta \cos \psi \right)} \end{bmatrix}^T
\]

which is an \( L \times 1 \) vector.

Therefore, the overall normalized steering vector of the symmetrical multi-carrier FDA can be calculated as

\[
\mathbf{h}(r, \theta, \psi) = \frac{1}{\sqrt{(2N+1)L}} \begin{bmatrix} a_{n}^T(r, \theta, \psi) \cdots a_{n}^T(r, \theta, \psi) \cdots a_{n}^T(r, \theta, \psi) \end{bmatrix}^T
\]
TABLE I
COMPARISON FOR MEMORY REQUIREMENTS OF DIFFERENT FDA-DM METHODS

| Items                                      | ZF [10], [13], [15], [18, 23] | SVD [16] | Proposed SP |
|--------------------------------------------|---------------------------------|----------|-------------|
| Orthogonal matrix/vector                   | $P_{ZF}^P = I_{(2N+1)L} - h_B h_B^H$ | $h_B^H = U \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} V_1 \ V_0 \end{bmatrix}^H$, $P_{SVD}^P = V_0$ | $P_{SP}^P = \text{Any orthogonal vector of } h_B^H$ |
| Size of orthogonal matrix/vector           | $(2N + 1)L \times (2N + 1)L$    | $(2N + 1)L \times 2N$ | $(2N + 1)L \times 1$ |
| Artificial noise                           | $z_{ZF} \in \mathbb{C}^{(2N+1)L \times 1}$ | $z_{SVD} \in \mathbb{C}^{2N \times 1}$ | $z_{SP} \in \mathbb{C}$ |
| Size of artificial noise                   | $(2N + 1)L \times 1$            | $2N \times 1$ | $1$ |
| Total size                                 | $(2N + 1)^2L^2 + (2N + 1)L$     | $2N(2N + 1)L + 2N$ | $(2N + 1)L + 1$ |
| Memory complexity                          | $O(N^2L^2)$                    | $O(N^2L)$ | $O(NL)$ |

The normalization vector in this paper is designed as $p_2^{SP} = h_B$ 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 $p_2^{SP}$ can be designed as an arbitrary orthogonal vector of $h_B^H$ rather than a matrix. Comparatively, $p_2^{ZF}$ can be an arbitrary column vector of $P_{ZF}^2$ or $P_{SVD}^2$. In the following analysis, $p_2$ specifically refers to the proposed $p_2^{SP}$.

3) Proposed SP method: The normalization vector in this paper is designed as $p_2^{SP} = h_B$ 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 $p_2^{SP}$ can be designed as an arbitrary orthogonal vector of $h_B^H$ rather than a matrix. Comparatively, $p_2^{ZF}$ can be an arbitrary column vector of $P_{ZF}^2$ or $P_{SVD}^2$. In the following analysis, $p_2$ specifically refers to the proposed $p_2^{SP}$.

4) Comparison for the ZF, SVD and SP methods: In order to illustrate the advantage of 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 $O(N^2L^2)$ and $O(N^2L)$ to $O(NL)$, which significantly outperforms the ZF and SVD methods.

In addition, Fig. 2 and Fig. 3 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 0.68% total memory of the ZF method or 5% total memory of the SVD method. Fig. 4 and Fig. 5 further show the total memory consumptions and the corresponding ratios versus $N$ and $L$, respectively, from which it demonstrates that the proposed SP method can save much more memory than the conventional ZF and SVD methods as well.

B. Bob’s and Eve’s Signals
After Alice transmits the signal, the received signal of Bob located at $(r_B, \theta_B, \psi_B)$ can be written as

$$y(\tau_B, \theta_B, \psi_B) = \epsilon_B h_B^H x + \xi_B \tag{15}$$

$$= \epsilon_B \beta_1 \sqrt{P_s} h_B^H p_1 s + \epsilon_B \alpha \beta_2 \sqrt{P_s} h_B^H p_2 z + \xi_B$$

$$= \epsilon_B \beta_1 \sqrt{P_s} s + \xi_B \tag{16}$$

where $\xi_B$ is the complex additive white Gaussian noise (AWGN) with zero mean and variance $\delta_{\xi_B}^2$, i.e., $\xi_B \sim \mathcal{CN}(0, \delta_{\xi_B}^2)$. In addition, $\epsilon_B$ represents the FTR fading coefficient which is defined as $\epsilon_B$,
where $\zeta_B$ is a Gamma distributed random variable with zero mean and probability density function given by

$$f_{\zeta_B}(\zeta_B) = \frac{m_B^r e^{-m_B \zeta_B}}{\Gamma(m_B)} e^{-m_B \zeta_B} \quad (19)$$

Moreover, $U_B$ and $V_B$ are constant amplitudes with specular components modulated by a Nakagami-$m_B$ random variable. $\varphi_B$ and $\psi_B$ are statistically independent and uniformly distributed random phases, i.e., $\varphi_B, \psi_B \sim U(0, \pi)$. $X_B + iY_B$ refers to the diffuse component with $X_B$ and $Y_B$ following a Gaussian distribution, i.e., $X_B, Y_B \sim N(0, \sigma_B^2)$. The FTR fading parameters can be calculated by $K_B = \frac{U_B^2 + V_B^2}{2\sigma_B^2}$ and $\Delta_B = \frac{2U_B V_B}{U^2 + V^2}$. It can be observed from (17) 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.

Similarly, the received signal of Eve located at $(r_E, \theta_E, \psi_E)$ can be expressed as

$$y(r_E, \theta_E, \psi_E) = \epsilon_E h_E^H x + \zeta_E$$

$$= \epsilon_E \beta_1 \sqrt{P_s} h_E^H p_1 s + \epsilon_E \alpha_2 \beta_2 \sqrt{P_s} h_E^H p_2 z + \zeta_E \quad (20)$$

$$= \epsilon_E \beta_1 \sqrt{P_s} p_1 s + \epsilon_E \alpha_2 \beta_2 \sqrt{P_s} p_2 z + \epsilon_E^N \quad (21)$$

$$= \epsilon_E \beta_1 \sqrt{P_s} p_1 s + \epsilon_E \alpha_2 \beta_2 \sqrt{P_s} p_2 z + \epsilon_E^N \quad (22)$$

where $\zeta_E \sim CN(0, \sigma_E^2)$ indicates the complex AWGN, $h_E = h(r_E, \theta_E, \psi_E)$ refers to Eve’s normalized steering vector, $\rho_1 = h_E^H p_1$, and $\rho_2 = h_E^H p_2$. Additionally, the fading coefficient $\epsilon_E$ is defined as

$$\epsilon_E = \sqrt{\varepsilon_E} u_{E} e^{i\psi_E} + \sqrt{\varepsilon_E} v_{E} e^{i\theta_E} + X_E + iY_E \quad (23)$$

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 (22) consists of three items. The first is the useful signal distorted by $\rho_1$ and the second is the inserted AN. Both can be regarded as interference for Eve, thereby guaranteeing the PLS transmission between Alice and Bob.

**Fig. 4.** Total memory required to store the orthogonal matrix/vector and the AN of the proposed SP method and the conventional ZF and SVD methods versus $N$.

**Fig. 5.** The ratio of total memory of the SP method to that of the ZF or SVD methods versus $N$ and $L$.

### IV. Physical-Layer Security Analysis

In this section, we will analyze the PLS performances of the proposed FDA-DM model including BER, SP and SOP, which are important metrics to measure the performances of DM transmission systems [35].

**A. Bit Error Rate**

To acquire the BER formula, we consider the case of no fading, which means $\epsilon_E = \epsilon_E = 1$. As a matter of fact, when the fading is considered, the derived BER formula can refer to [31] as long as the channel state information (CSI) [36] [37] is fully estimated at Bob.

According to (17), the received signal of Bob is simply the summation of the useful signal and AWGN, and the average signal-to-noise ratio (SNR) of Bob can be written as

$$\gamma_B = \frac{\beta_1^2 P_s E(|s|^2)}{\delta_B^2} \quad (24)$$

For an $M$-ary baseband modulation, the SNR per bit can be calculated by

$$\gamma_{bit} = \frac{\beta_1^2 P_s E(|s|^2)}{\delta_B^2 \log_2 M} = \frac{\gamma_B}{\log_2 M} \quad (25)$$

Therefore, if PSK modulation is adapted, the BER formula for the proposed FDA-DM system can be calculated by [38]

$$P_e \approx \frac{2}{\log_2 M} Q \left( \sqrt{2\gamma_B \log_2 M \sin \frac{\pi}{M}} \right) \quad (26)$$

where $Q(u) = \frac{1}{\sqrt{2\pi}} \int_u^{\infty} \exp{-u^2/2} du$ is the tail distribution function of the standard normal distribution.

**B. Secrecy Rate**

When the FTR fading is considered, we can rewrite the SNR of Bob as

$$\gamma_B = \frac{|\epsilon_B|^2 \beta_1^2 P_s E(|s|^2)}{\delta_B^2} = \beta_1^2 \lambda_B \quad (27)$$
where \( \lambda_B = |\epsilon_B|^2 P_s \mathbb{E}(|s|^2)/\sigma_B^2 \) is Bob’s SNR of the FTR fading channel without splitting AN, the average of which can be calculated by \( \lambda_B = \mathbb{E}(|\epsilon_B|^2) P_s \mathbb{E}(|s|^2)/\delta_B^2 = 2\sigma_B^2(1 + K_B)P_s/\delta_B^2 \) \cite{22}.

According to (22), we can write the signal to interference-noise-SNR (SINR) of Eve as

\[
\gamma_E = \frac{|\epsilon_E|^2 \beta_2^2 |\rho|_2^2 P_s \mathbb{E}(|s|^2)/\delta_E^2}{|\epsilon_E|^2 \beta_2^2 |\rho|_2^2 P_s \mathbb{E}(|s|^2)/\delta_E^2 + 1} \tag{28}
\]

Let \( \lambda_E = |\epsilon_E|^2 P_s \mathbb{E}(|s|^2)/\delta_E^2 \), which indicates Eve’s SNR of FTR fading channels without splitting AN, the average of which can be calculated by \( \lambda_E = \mathbb{E}(|\epsilon_E|^2) P_s \mathbb{E}(|s|^2)/\delta_E^2 = 2\sigma_E^2(1 + K_E)P_s/\delta_E^2 \). Moreover, taking the assumption \( \mathbb{E}(|s|^2) = \mathbb{E}(|z|^2) = 1 \) into (28) yields

\[
\gamma_E = \frac{\beta_2^2 |\rho|_2^2 \lambda_E}{\alpha^2 \beta_2^2 |\rho|_2^2 2\lambda_E + 1} = \frac{\eta \lambda_E}{\mu \lambda_E + 1} \tag{29}
\]

where \( \eta = \beta_2^2 |\rho|_2^2 \) and \( \mu = \alpha^2 \beta_2^2 |\rho|_2^2 \).

According to [26], the probability density function (PDF) and cumulative distribution function (CDF) of \( \lambda_i \) (\( i \in \{ B, E \} \)) can be written as

\[
f_{\lambda_i}(x) = \frac{m_i^{m_i}}{\Gamma(m_i)} \sum_{j_i=0}^{\infty} K_{j_i}^{m_i} \frac{d_{j_i}}{j_i!j_i!} \frac{x^{j_i}}{(2\sigma_i^2)^{j_i+1}} \exp \left( -\frac{x}{2\sigma_i^2} \right) \tag{30}
\]

and

\[
F_{\lambda_i}(x) = \frac{m_i^{m_i}}{\Gamma(m_i)} \sum_{j_i=0}^{\infty} K_{j_i}^{m_i} \Gamma \left( j_i + 1, \frac{x}{2\sigma_i^2} \right) \tag{31}
\]

where \( j_i! \) denotes the factorial of the integer \( j_i \); \( \Gamma(\cdot) \) and \( \Gamma(\cdot,\cdot) \) refer to the ordinary Gamma function [39, Eq. (8.310.1)] and the lower incomplete Gamma function [39, Eq. (8.350.1)], respectively. In addition, the term \( d_{j_i} \) in (30) and (31) is expressed as

\[
d_{j_i} \triangleq \sum_{k=0}^{j_i} \binom{j_i}{k} \left( \frac{\Delta_i}{2} \right)^k \sum_{l=0}^{k} \binom{k}{l} \Gamma(j_i + m_i + 2l - k) \cdot e^{(2l-k)x/2} \left[ (m_i + K_i)^2 - (K_i\Delta_i)^2 \right]^{-\frac{j_i + m_i}{2}} \cdot L_{j_i+2m_i-1}^{k-2l} \left( \frac{m_i + K_i}{\sqrt{(m_i + K_i)^2 - (K_i\Delta_i)^2}} \right) \tag{32}
\]

Before deriving the PDF and CDF of \( \gamma_E \), we first point out a fact that the lower and upper bounds of \( \gamma_E \) are 0 and \( \tau = \eta/\mu \), respectively, which can be directly obtained by replacing \( \lambda_E \rightarrow 0 \) and \( \lambda_E \rightarrow \infty \) into (29). Therefore, the CDF of \( \gamma_E \) can be acquired by

\[
F_{\gamma_E}(x) = \Pr \left( \gamma_E \leq x \right) \tag{35}
\]

\[
= \Pr \left( \frac{\eta \lambda_E}{\mu \lambda_E + 1} \leq x \right) \tag{36}
\]

\[
= \Pr \left( \lambda_E \leq \frac{x}{\eta - \mu \lambda_E} \right) \tag{37}
\]

\[
= \left\{ \begin{array}{ll}
F_{\lambda_E} \left( \frac{x}{\eta - \mu \lambda_E} \right), & 0 < x < \tau \\
1, & x \geq \tau
\end{array} \right. \tag{38}
\]

Consequently, the PDF of \( \gamma_E \) can be calculated by

\[
f_{\gamma_E}(x) = \frac{dF_{\gamma_E}(x)}{dx} \tag{39}
\]

\[
= \left\{ \begin{array}{ll}
\frac{\eta}{(\eta - \mu \lambda_E)^2} f_{\lambda_E} \left( \frac{x}{\eta - \mu \lambda_E} \right), & 0 < x < \tau \\
0, & x \geq \tau
\end{array} \right. \tag{40}
\]

Using the PDFs and CDFs of Bob’s and Eve’s SINRs, the instantaneous secrecy rate can be defined as

\[
R_s(\gamma_B, \gamma_E) = \left[ \log_2(1 + \gamma_B) - \log_2(1 + \gamma_E) \right]^+ \tag{41}
\]

where \([\cdot]^+ = \max\{\cdot, 0\} \). If we further assume Bob’s and Eve’s channels experience independent fading, the average secrecy
Then, the average secrecy rate can be obtained in Lemma 1 of which a special case is [29, Eq. (10)]

\[
\bar{R}_s(\gamma_B, \gamma_E) = \int_0^\infty \int_0^\infty R_s(\gamma_B, \gamma_E) f(\gamma_B, \gamma_E) d\gamma_B d\gamma_E
\]

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

Before deriving the secrecy rate, we define

\[
\Psi(v_1, v_2, v_3, v_4, v_5, \tau) = \int_0^\infty \ln(1 + t) \frac{t^{v_3}}{(\tau - t)^{v_5}} \exp \left\{ -v_4 t - \frac{v_5 t}{\tau - t} \right\} dt
\]

of which a special case is [29, Eq. (10)]

\[
S(u, v) = \Psi(1, 1, 0, 0, 0, \infty)
\]

where \( S(u, v) = \Psi(1, 1, 0, 0, 0, \infty) \). Please see Appendix B.

**Lemma 1**: The average secrecy rate of the proposed FDA-DM system in FTR fading is given by

\[
\bar{R}_s(\gamma_B, \gamma_E) = I_1 + I_2 - I_3
\]

where the expressions of \( I_1, I_2 \) and \( I_3 \) are listed in (48), (49) and (50), respectively. Moreover, the term \( \chi \) in the expression of \( I_1 \) is defined as

\[
\Psi(1, j_B, 0, 1, 2\beta_1^2\sigma_B^2, 0, \tau)
\]

\[
= \int_0^\tau \ln(1 + \gamma_B) \gamma_B^{j_B} \exp \left( -\frac{\gamma_B}{2\beta_1^2\sigma_B^2} \right) d\gamma_B
\]

\[
= \int_0^\tau \ln(1 + \gamma_B) \gamma_B^{j_B} \exp \left( -\frac{\gamma_B}{2\beta_1^2\sigma_B^2} \right) d\gamma_B
\]

\[
= \int_0^\tau \ln(1 + \gamma_B) \gamma_B^{j_B} \exp \left( -\frac{\gamma_B}{2\beta_1^2\sigma_B^2} \right) d\gamma_B
\]

\[
= \int_0^\tau \ln(1 + \gamma_B) \gamma_B^{j_B} \exp \left( -\frac{\gamma_B}{2\beta_1^2\sigma_B^2} \right) d\gamma_B
\]

\[
= \int_0^\tau \ln(1 + \gamma_B) \gamma_B^{j_B} \exp \left( -\frac{\gamma_B}{2\beta_1^2\sigma_B^2} \right) d\gamma_B
\]

Therefore, the SOP of the proposed FDA-DM system in FTR fading can be obtained by

\[
P_{out} = \Pr \left\{ \log_2 \frac{1 + \gamma_B}{1 + \gamma_E} < R_0 \right\}
\]

\[
= \Pr \left\{ \gamma_B < 2R_0(1 + \tau) - 1 \right\}
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]

\[
= \sum_{j_B=0}^{\infty} \frac{K_B^j d_{j_B} K_E^j d_{j_E}}{\Gamma(m_B) j_B! j_E! (2\beta_1^2\sigma_B^2)^{j_B+1}} \left( 1 + \frac{1}{2\beta_1^2\sigma_B^2} \right) \Psi(1, j_B, 0, + n, 1, 1, \tau)
\]
TABLE II
SIMULATION PARAMETERS

| Parameter                          | Value            |
|-----------------------------------|------------------|
| Central frequency, $f_0$          | 30 GHz           |
| Fixed frequency increment, $\Delta f$ | 20 kHz           |
| Number of FDA elements, $2N+1$    | 21               |
| Number of subcarriers for each element, $L$ | 7               |
| Total signal power, $P_s$         | 1                |
| Power splitting factor, $\beta_1$ | 0.9, 0.7         |
| AWGN variance, $\delta_E^2$, $\delta_B^2$ | 1                |
| FTR parameters, $(m_B, R_B, \Delta_B)$ | (2.3, 10, 0.5)  |
| FTR parameters, $(m_E, K_E, \Delta_E)$ | (5.3, 15, 0.35) |
| Location of Bob, $(r_B, \theta_B, \psi_B)$ | (1 km, 20°, 30°) |
| Location of Eve, $(r_E, \theta_E, \psi_E)$ | (1.5 km, -20°, 25°) |
| Number of Monte Carlo experiments | 10^5             |
| Modulation mode                   | PSK, QAM         |

V. NUMERICAL RESULTS

In this section, Monte Carlo experiments are conducted to verify the theoretical analysis, where the ZF method [10, 12], [15, 18]-[23], the SVD method [16], and the NoAN method [29]-[31] are included. The detailed simulation parameters are listed in Table II.

A. Bit Error Rate

Fig. 6 describes the BER performances with $\beta_1 = 0.9$ versus range, azimuth angle, and elevation angle, respectively, where QPSK modulation and SNR = 10 dB are adopted. It can be clearly observed from Fig. 6 that only the receiver along the desired range, azimuth angle and elevation angle can achieve good BER performance, while the receivers at other locations cannot receive the confidential signal. In addition, compared with conventional FDA models [6]-[17], Fig. 6(c) also verifies that an extra dimension, i.e., elevation angle, is realized via the analytical model as analyzed in Section II.

Fig. 7 and Fig. 8 show the BER performances versus SNR (dB) with PSK and QAM modulations, respectively. It is observed that the proposed SP method can achieve almost the same BER performance as the conventional ZF and SVD methods. In addition, Bob exhibits a better BER performance while Eve’s BER is much worse, which verifies the physical-layer security of the proposed FDA-DM model. Moreover, the BER of Bob becomes better with larger $\beta_1$, which is because a larger $\beta_1$ allocates more power to the useful signal.

\[
I_3 = \frac{m_B m_E}{2 \Gamma(m_E)} \sum_{j_B=0}^{\infty} \sum_{j_E=0}^{\infty} \frac{K_E^{j_E} d_B^{j_B}}{j_E! j_E! (2 \mu \sigma_E^2)^{j_E+1}} \Psi(1, j_E, j_E+2, 0, \frac{1}{2 \mu \sigma_E^2}, \tau) (50) 
\]

\[
P_{out} = \frac{m_B m_E}{\Gamma(m_B) \Gamma(m_E)} \sum_{j_B=0}^{\infty} \sum_{j_E=0}^{\infty} K_E^{j_E} d_B^{j_B} \left[ \Psi(0, j_E, j_E+2, 0, \frac{1}{2 \mu \sigma_E^2}, \tau) - \sum_{n=0}^{j_B} \frac{1}{n!} \exp \left( -\frac{2 R_B}{2 \beta_I^2 \sigma_B^2} \right) \sum_{k=0}^{n} \binom{n}{k} \frac{2^k R_B (2 R_B - 1)^{n-k}}{(2 \beta_I^2 \sigma_B^2)^n} \Psi(0, j_E+k, j_E+2, \frac{2 R_B}{2 \beta_I^2 \sigma_B^2}, \frac{1}{2 \mu \sigma_E^2}, \tau) \right] (55) 
\]
B. Secrecy Rate

In the simulations of the average SR, \( \beta_1 = 0.9 \) is adopted. Fig. 9 depicts the average SR of the proposed FDA-DM scheme versus \( \lambda_B \) 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 average SR climbs with increasing \( \lambda_B \) when \( \lambda_E \) is fixed. Second, compared with ZF and SVD approaches, the proposed SP method can achieve almost the same average SR. Although there is actually a very small penalty on average SR when \( \lambda_E \) is fixed. Differently, the average SRs of the proposed SP and the conventional ZF and SVD methods 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.

C. Secrecy Outage Probability

\( \beta_1 = 0.9 \) is adopted in the simulations of the SOP as well. Fig. 11 and Fig. 12 present the SOP of the proposed FDA-DM scheme versus \( \lambda_B \) in FTR fading channels with \( R_0 = 0 \) and \( R_0 = 0.5 \) bits/s/Hz, respectively. Comparing Fig. 11 and Fig.
12, it holds for all four PLS methods that the SOP decreases with smaller $R_0$. Given a specific $R_0$ and $\lambda_E$, as expected, the SOP drops as $\lambda_E$ increases. Compared with the conventional NoAN method, the proposed SP method can achieve much lower SOP. More importantly, there exists an upper bound of SOP when $\lambda_E \to \infty$ 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.

Fig. 13 and Fig. 14 illustrate the SOP of the proposed FDA-DM scheme versus $\lambda_E$ in FTR fading channels with $R_0 = 0$ and $R_0 = 0.5$ bits/s/Hz, respectively. Analogous to Fig. 11 and Fig. 12, 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 $\lambda_E$. But for the conventional NoAN method, it roars rapidly to $1$ when $\lambda_E$ 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.

VI. Conclusion

In this paper, we presented a low-memory-consumption 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 rate and secrecy outage probability. In the proposed FDA-DM scheme, the FDA was analyzed in three dimensions, i.e., range, azimuth angle, and elevation angle. Moreover, the secrecy rate and secrecy outage probability 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 SR bound and upper SOP bound were derived and numerical demonstrations by Monte Carlo experiments were provided as well. One future work is to investigate the PLS performance of the proposed low-memory-consumption FDA-DM scheme with multiple legitimate users.

APPENDIX

A. Proof of Lemma 1

Here, we derive the expression of $I_1$. Substituting (33) and (38) into (42), we can obtain (60)–(62), where

$$\Upsilon \left( j_E + 1, \frac{\gamma_B}{2\sigma_E^2(\eta - \mu_B)} \right)$$

can be written as [39, Eq. (8.354.1)]

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

Substituting (63) into (61) and using (43), we can acquire

$$I_{1,1} = j_E! \psi(1, j_E + 0, \frac{1}{2\beta_1^2\sigma_B^2}, 0, \tau) = j_E! \sum_{n=0}^{j_E} \frac{1}{n!(2\mu\sigma_E^2)^n} \psi(1, j_E + n, n, \frac{1}{2\beta_1^2\sigma_B^2}, \frac{1}{2\mu\sigma_E^2}, \tau)$$

Similarly, $I_{1,2}$ can be calculated by

$$I_{1,2} = \psi(1, j_E + 0, \frac{1}{2\beta_1^2\sigma_B^2}, 0, \infty) - \psi(1, j_E + 0, \frac{1}{2\beta_1^2\sigma_B^2}, 0, \tau)$$

Substituting (64) and (65) into (61) and (62), we can get the expression of $I_1$ in (48). $I_2$ and $I_3$ can be derived in the same way, which ends the proof of Lemma 1.
B. Proof of Lemma 2

Observing (29), when $\sigma^2 \rightarrow \infty$, we can subsequently obtain $\lambda \rightarrow \infty$ and $\gamma_{E} \rightarrow \tau$. Therefore, $R_{s}^{\text{Low}}$ can be written as

$$R_{s}^{\text{Low}}(\gamma_B, \gamma_E) = \frac{1}{\ln 2} \int_{0}^{\infty} \left[ \ln(1 + \gamma_B) - \ln(1 + \gamma_E) \right]^+ f_{\gamma_B}(\gamma_B) d\gamma_B$$

Then, the binomial theorem yields

$$f(\gamma_B) = \frac{\gamma_B}{\gamma_E (\gamma_E + \gamma_B)}$$

Replacing (30) and (33) into (66) yields (67) and (68), and substituting (43) into (68) ends the proof of Lemma 2.

C. Proof of Lemma 3

Given a fixed secrecy rate $R_0$, the SOP in (54) can be further written as

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

Then, replacing (30), (33) and (40) into (70) yields (71)-(73). Using [39, Eq. (8.354.1)], (73) can be calculated by (74)-(77). According to the binomial theorem [39, Eq. (1.111)], we can write

$$\left( \frac{2^{R_0}(1 + \gamma_E) - 1}{2\beta^2/\sigma_B^2} \right)^n = \frac{\gamma_B}{\gamma_E (\gamma_E + \gamma_B)}$$

Therefore, $B$ can be acquired in (80)-(82) by replacing (79) into (76). Finally, substituting (77) and (82) into (73) ends the proof of Lemma 3.
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