Physical Layer Security of TAS/MRC Over $\kappa$-$\mu$ Shadowed Fading Channel

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Abstract—This paper investigates the impact on the achievable secrecy performance of multiple-input multiple-output systems by dealing with realistic propagation conditions. Specifically, we focus on the $\kappa$-$\mu$ shadowing fading model, which has proven to be more accurate in characterizing mm-wave scenarios than traditional Rice and Rayleigh ones. By considering transmit antenna selection and maximal ratio combining at the receiver ends, we study two different scenarios, namely: (i) the transmitter has knowledge of the channel state information (CSI) of the eavesdropper link, and (ii) the transmitter does not know eavesdropper’s CSI. Based on these assumptions, we derive novel analytical expressions for the secrecy outage probability (SOP) and the average secrecy capacity (ASC) to assess the secrecy performance in passive and active eavesdropping scenarios, respectively. Moreover, we develop analytical asymptotic expressions of the SOP and ASC at high signal-to-noise ratio regime. Some useful insights on how to obtain noticeable improvements in the secrecy performance are also provided.

Index Terms—$\kappa$-$\mu$ fading model, generalized fading channels, maximal ratio combining, mm-Wave, physical layer security, transmit antenna selection.

I. INTRODUCTION

Traditionally, security systems are based on higher layer cryptographic mechanisms, which contemplate mathematically complex algorithms that demand a high consumption of energy and computational resources. Such methods pose great challenges for their implementation and management for the fifth-generation (5G) networks in practice. Therefore, the cryptography by itself does not constitute an integral solution to the security problems envisioned for future wireless transmissions. In this sense, physical layer security (PLS) arises to provide secure communications in the physical layer by smartly exploiting the impairments (e.g., noise, interference, and fading) of the wireless channel [1]. Shannon introduced the first notions of PLS from the information-theoretical context in his pioneering work in [2]. Later, the so-called wiretap channel was introduced by Wyner in [3]. Subsequently, Wyner’s results were extended for the broadcast channel in [4] and for the Gaussian channel in [5], where it was shown that the secrecy capacity is equal to the difference between the capacities of the main channel and the wiretap channel.

Based on the mentioned results, the keys concepts concerning the generalization of the wiretap channel to multiple-input multiple-output (MIMO) channels were investigated in [6,7]. These works have inspired various research activities to improve the secrecy in different MIMO topologies. For instance, the utilization of artificial noise (AN) for MIMO schemes to enhance the PLS performance was analyzed in [8]. Relevant papers on the impact of cooperative communications on secrecy capacity for MIMO wiretap systems were studied in [10,20]. In [11], the researches focused on the secrecy performance of cognitive MIMO relaying networks. On the other hand, in order to achieve higher secrecy capacities, different beamforming schemes were considered in [12–14]. Nevertheless, due to which the complexity in obtaining the channel state information (CSI) is proportional to the number of antennas in the system, these beamforming methods require the use of advanced signal processing algorithms, resulting in high computational consumption. Alternatively, optimal antenna selection at the transmitter only requires a single radio-frequency (RF) chain compared to the full CSI required in beamforming schemes [15]. From a secrecy perspective, since transmit antenna selection (TAS) provides full transmit diversity, it has been adopted to enhance secrecy performance at low-cost and complexity. Therefore, many research studies have addressed their efforts to investigate TAS in the context of PLS. Among them, in [16,17] and [18,19] the authors investigated the PLS metrics of TAS in maximal ratio combining (MRC) receivers undergo Rayleigh and Nakagami-$m$ fading channels, respectively. Readers can refer to [20,21] (and references therein) for guidance about secrecy performance in TAS/MRC systems. Very recently, in [22,23], the researchers examined the secrecy performance in MIMO wiretap channels over generalized fading conditions (i.e., $\kappa$-$\mu$, and $\eta$-$\mu$ fading models).

However, the fading channels considered in the aforementioned works have proven to be inaccurate to characterize the propagation medium of the 5G scenarios in practice. To circumvent this issue, generalized and versatile channel models such as Fluctuating Two-Ray (FTR) [25], and the $\kappa$-$\mu$ shadowed [26] have been proposed in the last years. Such models rely on the assumption in that dominant components are subject to random fluctuations (also known as shadowing). Based on this channel feature, the $\kappa$-$\mu$ shadowing fading model finds great applicability in a range of real-world applications such as device-to-device (D2D) communications, underwater
acoustic communications (UAC), body-centric fading channels, unmanned aerial vehicle (UAV) systems, land mobile satellite (LMS), etc [27]. In the context of PLS, in [28, 29], the authors investigated the secrecy metrics over the two fading models above referenced in single-input single-output (SISO) wiretap channels. Nevertheless, the secrecy performance over $\kappa$-$\mu$ shadowed channel model in MIMO systems is still unexplored. Our goal is to investigate the impact of multiple antennas on the secrecy performance over $\kappa$-$\mu$ shadowed fading channels. In light of the above considerations, the main takeaways of our work are as follows:

- Novel closed-form expressions for the probability density function (PDF) and the cumulative distribution function (CDF) of the maximum of independent and identically distributed (i.i.d.) $\kappa$-$\mu$ shadowed random variables (RVs) associated with the legitimate links are derived.
- Assuming that the transmitter is not aware of the CSI of the wiretap path, we derive exact closed-form expressions for the secrecy outage probability (SOP). We also provide closed-form expressions for the average secrecy rate (ASC) by assuming that the CSI of the eavesdropper path is available at the transmitter. Both secrecy metrics are developed in TAS/MRC systems under $\kappa$-$\mu$ shadowed fading channels.
- Simple asymptotic expressions for the SOP in the high signal-to-noise ratio (SNR) regime are obtained. Based on these formulations, we provide some useful insights of the impact of the system parameters (i.e., numbers of antennas and fading parameters) on the PLS performance. In addition, asymptotic expressions for the ASC are derived.

The remainder of this manuscript is organized as follows. Section II introduces the system and channel models and a framework that addresses the PDF and CDF of the maximum of i.i.d. $\kappa$-$\mu$ shadowed RVs. Section III derives closed-form expressions for the SOP and the asymptotic behaviour of the SOP over i.i.d. $\kappa$-$\mu$ shadowed fading channels. Section IV presents analytical expressions for the ASC, based on which formulations for the asymptotic ASC are also obtained. Section V shows illustrative numerical results and discussions. Finally, concluding remarks are provided in Section VI.

**Notation:** Throughout this paper, $f_X(z)$ and $F_X(z)$ denote the probability density function (PDF) and the cumulative distribution function (CDF) of a RV $Z$: $E[\cdot]$, expectation; $\Pr\{\cdot\}$, probability; $|\cdot|$, the absolute value; $\simeq$, “asymptotically equal to”; $\approx$, “approximately equal to”. In addition, $\Gamma(\cdot)$, denotes the gamma function [36, Eq. (6.1.1)]; $\zeta$, represents the Euler’s constant [35, Eq. (8,367.1)]; $e$, the exponential constant [35, Eq. (0,245.1)]; $\gamma(\cdot, \cdot)$, the lower incomplete gamma function [36, Eq. (6.5.2)]; $\Gamma(\cdot, \cdot)$, the upper incomplete gamma function [36, Eq. (6.5.3)]; $F_2(\cdot; \cdot; \cdot)$, the hypergeometric function [36, Eq. (15.1.1)]; and $F_1(\cdot; \cdot; \cdot)$, the confluent hypergeometric function [36, Eq. (13.1.3)].

## II. System and Channel Model

### A. System Model

We consider the classic three-node model, where a source node Alice (A) sends confidential information to a legitimate destination node Bob (B), while an eavesdropper Eve (E) attempts to intercept this information through the eavesdropper channel, as illustrated in Fig. 1. All the nodes i.e., the transmitter, the receiver and the eavesdropper, are equipped with multiple antennas denoted by $N_A$, $N_B$, and $N_E$, respectively. Also, it is assumed that both the main and eavesdropper channels are subject i.i.d. quasi-static $\kappa$-$\mu$ shadowed fading. The PDF and CDF of the instantaneous SNR of the RV $\gamma$ following $\kappa$-$\mu$ shadowed fading can be expressed as a finite mixture of gamma distributions as given in [30] by

- **If** $m < \mu$

$$f_\gamma(\gamma) = \sum_{j=1}^{\mu-m} A_{1,j} F_{\gamma j}^G (\omega_{A1}; \mu - m - j + 1; \gamma) + \sum_{j=1}^{m} A_{2,j} F_{\gamma j}^G (\omega_{A2}; m - j + 1; \gamma), \quad (1a)$$

$$F_{\gamma}(\gamma) = 1 - \sum_{j=1}^{\mu-m} A_{1,j} \exp\left(\frac{-\gamma}{\Delta_1}\right) \sum_{r=0}^{\mu-m-j} \frac{1}{r!} \left(\frac{\gamma}{\Delta_1}\right)^r - \sum_{j=1}^{m} A_{2,j} \exp\left(\frac{-\gamma}{\Delta_2}\right) \sum_{r=0}^{m-j} \frac{1}{r!} \left(\frac{\gamma}{\Delta_2}\right)^r, \quad (1b)$$

- **If** $m \geq \mu$

$$f_\gamma(\gamma) = \sum_{j=0}^{m-\mu} B_j F_{\gamma j}^G (\omega_B; m - j; \gamma), \quad (2a)$$

$$F_{\gamma}(\gamma) = 1 - \sum_{j=0}^{m-\mu} B_j \exp\left(-\frac{\gamma}{\Delta_2}\right) \sum_{r=0}^{m-j-1} \frac{1}{r!} \left(\frac{\gamma}{\Delta_2}\right)^r, \quad (2b)$$

where $f_X^G(\tau; \tilde{m}; x)$ denotes the PDF of a RV $x$ following a gamma distribution, defined as

$$f_X^G(\tau; \tilde{m}; x) = \left(\frac{\tau}{\tilde{m}}\right)\tilde{m}^{x-1} \exp\left(-\frac{x}{\tilde{m}}\right) \left(\frac{\tau}{\tilde{m}}\right), \quad (3)$$

1Currently, the PDF and CDF of the $\kappa$-$\mu$ shadowed distribution can be represented by (i) hypergeometric functions as proposed in its original formats [30]; (ii) a series in terms of Laguerre polynomials [27], and (iii) an infinite [30] and finite [35] mixture of gamma distributions. In this work, we chose the last one because of its mathematically treatable expressions in dealing with TAS/MRC systems.
In our MIMO wiretap system, the optimum TAS protocol selects the strongest antenna which maximizes the instantaneous SNR between Alice and Bob for transmission. From a secrecy perspective, this fact is beneficial as it maximizes channel capacity and fully exploits the multi-antenna diversity at the transmitter. Nevertheless, on the eavesdropper’s channel side, the optimum TAS for Bob corresponds to a random transmit antenna for Eve. Also, in order to maximize the instantaneous SNRs at the receiver ends as well, we consider the MRC diversity combining technique to be employed at both Bob and Eve. The index of the selected antenna at the transmitter, denoted by $k^*$, is determined by

$$k^* = \arg \max_{1 \leq k \leq N_A} \sum_{l=1}^{N_B} |h_{k,l}|^2,$$

(7)

where $h_{k,l}$ is the channel coefficient of the link between $k$-th transmitting antenna at Alice and $l$-th receiving antenna at Bob. Also, through a feedback channel, the value of $k^*$ is available to the transmitter. Under TAS/MRC setup, the received signals at the $l$-th antenna of Bob and at the $r$-th ($1 \leq r \leq N_E$) antenna of Eve can be formulated as

$$y_{B,l} = \sqrt{P}h_{k^*,l}x + n_l,$$

(8a)

$$y_{E,r} = \sqrt{P}g_{k^*,r}x + n_r,$$

(8b)

where $P$ is the transmit power per antenna, $x$ denotes the secret message to be transmitted, $h_{k^*,l}$ is the channel coefficients of the link between the selected antenna, $k^*$, at Alice and the $l$-th receiving antenna at Bob. Likewise, $g_{k^*,r}$ is the channel coefficient of the link between the selected antenna, $k^*$, at Alice and the $r$-th receiving antenna at Eve. Also, $n_l$ and $n_r$ are additive white complex Gaussian noise at the receivers of the $l$-th antenna of Bob and at the $r$-th antenna of Eve with zero mean and variance $\sigma^2_{n_l}, w \in \{B, E\}$, respectively. Based on (8), the corresponding instantaneous SNRs at the receivers can be expressed as

$$\gamma_B = \frac{P \sum_{l=1}^{N_B} |h_{k^*,l}|^2}{\sigma^2_B},$$

(9a)

$$\gamma_E = \frac{P \sum_{r=1}^{N_E} |g_{k^*,r}|^2}{\sigma^2_E}.$$ 

(9b)

**B. Channel Statistics**

In this section, we present the theoretical background concerning the statistics of the main and eavesdropper channels to facilitate the secrecy analysis in the next sections.

Let $\gamma_{k^*,r} = \frac{|g_{k^*,r}|^2}{\sigma^2_{n_r}}$ be the instantaneous received SNR of the $r$-th diversity branch of the MRC receiver at Eve. Now, by considering $N_E$ i.i.d. $\kappa - \mu$ shadowed RVs, i.e., $\gamma_{k^*,r} \sim (\gamma_{E}, \kappa_{E}, \mu_{E}, m_{E})$ for $r = \{1, \ldots, N_E\}$, the sum of the RV $\gamma_E$ is another $\kappa - \mu$ shadowed RV with scaled parameters, i.e., $\gamma_E \sim (N_{E\gamma}, \kappa_E, \mu_{E\gamma}, m_{E\gamma})$ [26, Proposition 1]. Therefore, from (9b) the corresponding PDF and CDF at Eve are given by

- **If** $m_{E} < \mu_{E}$

$$f_{\gamma_{E}}(\gamma_{E}) = \sum_{j=1}^{\nu_{E}} A_{1,j}^{E} f_{G}\left(\omega_{A_1}; \nu_{E} - j + 1; \gamma_{E}\right)$$

$$+ \sum_{j=1}^{\nu_{E}} A_{2,j}^{E} f_{G}\left(\omega_{A_2}; \nu_{E} - j + 1; \gamma_{E}\right),$$

(10a)
\[ F_{\gamma_E}(\gamma_E) = 1 - \sum_{j=0}^{\eta_E} A^E_j \exp \left( -\frac{\gamma_E}{\Delta^E} \right) \sum_{r=0}^{\eta_E-j} \frac{1}{r!} \left( \frac{\gamma_E}{\Delta^E} \right)^r, \]

\[ F_{\gamma_E}(\gamma_E) = 1 - \sum_{j=0}^{\eta_E} B^E_j \exp \left( -\frac{\gamma_E}{\Delta^E} \right) \sum_{r=0}^{\eta_E-j} \frac{1}{r!} \left( \frac{\gamma_E}{\Delta^E} \right)^r, \]

(10b)

where \( \eta_E = N_E(\mu_E - m_E) \), and \( \nu_E = N_E m_E \).

- If \( m_E \geq \mu_E \)

\[ f_{\gamma_E}(\gamma_E) = \frac{\beta_E}{\Delta^E} \sum_{j=0}^{\eta_E} A^E_j \exp \left( -\frac{\gamma_E}{\Delta^E} \right) \sum_{r=0}^{\eta_E-j} \frac{1}{r!} \left( \frac{\gamma_E}{\Delta^E} \right)^r, \]

(11a)

\[ f_{\gamma_E}(\gamma_E) = \frac{\beta_E}{\Delta^E} \sum_{j=0}^{\eta_E} B^E_j \exp \left( -\frac{\gamma_E}{\Delta^E} \right) \sum_{r=0}^{\eta_E-j} \frac{1}{r!} \left( \frac{\gamma_E}{\Delta^E} \right)^r, \]

(11b)

where \( \beta_E = N_E(\mu_E - m_E) \). For notational convenience, all the coefficients marked with superscripts \( E \) (e.g., \( \Delta^E \)) refer to the fading parameters at Eve, which can be obtained from \( A \) to \( B \) by substituting \( \gamma \rightarrow N_E \gamma_E, \mu \rightarrow N_E \mu_E, m \rightarrow N_E m_E, \) and \( \kappa \rightarrow \kappa_E \).

Now, let \( \gamma_{k,t} = \frac{E|h_{k,t}^2|}{s_B^t} \) be the instantaneous received SNR of the \( l \)-th diversity branch of the MRC receiver at Bob, the CDF and PDF of \( \gamma_B = \sum_{t=1}^{N_B} \gamma_{k,t} \) are given in the following propositions.

**Proposition 1.** The CDF of \( \gamma_B \) is given by

- If \( m_B < \mu_B \)

\[ F_{\gamma_B}(\gamma_B) = 1 + \sum_{h=1}^{N_B} (-1)^h \left( \frac{N_B}{h} \right) \sum_{k=0}^{h} \left( \frac{k!}{\rho(h-k)} \right) \sum_{h_q \in \rho(h-k)} p(h-k, q), \]

\[ \times \left[ \prod_{q=1}^{h} \frac{1}{\left( \frac{\Delta_B}{\Delta^E} \right)} \frac{\eta_{B-q}}{\left( \eta_B - q \right)!} \sum_{z=\eta_{B+q}}^{\eta_B+1} \frac{A^B_{\eta_{B+q}+1}}{z} \right]^{p(h-k)}, \]

\[ \times \exp \left( -\frac{\Delta_B k}{\Delta^E} \right) \sum_{h_q \in \rho(h-k)} p(h-k, q), \]

\[ \times \frac{1}{\left( \frac{\Delta_B}{\Delta^E} \right)} \frac{\eta_{B-t}}{\left( \eta_B - t \right)!} \sum_{z=\eta_{B+q}}^{\eta_B+1} \frac{A^B_{\eta_{B+q}+1}}{z} \right]^{s(t)}, \]

\[ \times \exp \left( -\frac{\Delta_B k}{\Delta^E} \right) \sum_{h_q \in \rho(h-k)} p(h-k, q), \]

(12)

where \( \eta_B = N_B(\mu_B - m_B), \nu_B = N_B m_B \). Likewise as in the previous case, all the coefficients marked with superscripts \( B \) (e.g., \( \Delta^B \)) refer to the fading parameters at Bob, which can be obtained from \( A \) to \( B \) by substituting \( \gamma \rightarrow N_B \gamma_B, \mu \rightarrow N_B \mu_B, m \rightarrow N_B m_B, \) and \( \kappa \rightarrow \kappa_B \). Also, based on the multinomial theorem [42], Eq. (24.1.2), \( \rho(h-k, q) = \{(s_1, s_2, \ldots, s_{\nu_B}) : s_t \in \mathbb{N}, \sum_{t=1}^{\nu_B} s_t = h-k\} \), and \( \rho(h-k, q) = \{(p_1, p_2, \ldots, p_{\nu_B}) : p_q \in \mathbb{N}, \sum_{q=1}^{\nu_B} p_q = h\} \).

- If \( m_B \geq \mu_B \)

\[ F_{\gamma_B}(\gamma_B) = 1 + \sum_{h=1}^{N_B} (-1)^h \left( \frac{N_B}{h} \right) \sum_{k=0}^{h} \left( \frac{k!}{\rho(h-k, q)} \right) \sum_{p(h-k, q)} p(h-k, q), \]

\[ \times \left[ \prod_{q=1}^{h} \frac{1}{\left( \frac{\Delta_B}{\Delta^E} \right)} \frac{\eta_{B-q}}{\left( \eta_B - q \right)!} \sum_{z=\eta_{B+q}}^{\eta_B+1} \frac{A^B_{\eta_{B+q}+1}}{z} \right]^{p(h-k)}, \]

\[ \times \exp \left( -\frac{\Delta_B k}{\Delta^E} \right) \sum_{h_q \in \rho(h-k, q)} p(h-k, q), \]

\[ \times \frac{1}{\left( \frac{\Delta_B}{\Delta^E} \right)} \frac{\eta_{B-t}}{\left( \eta_B - t \right)!} \sum_{z=\eta_{B+q}}^{\eta_B+1} \frac{A^B_{\eta_{B+q}+1}}{z} \right]^{s(t)}, \]

\[ \times \exp \left( -\frac{\Delta_B k}{\Delta^E} \right) \sum_{h_q \in \rho(h-k, q)} p(h-k, q), \]

(13)

where \( \beta_B = N_B(m_B - \mu_B) \), and \( \rho(h, \nu_B) = \{(s_1, s_2, \ldots, s_{\nu_B}) : s_t \in \mathbb{N}, \sum_{t=1}^{\nu_B} s_t = h\} \).

**Proof.** See Appendix A.

**Proposition 2.** From (12) and (13), the PDFs of \( \gamma_B \) can be obtained as

- If \( m_B < \mu_B \)

\[ f_{\gamma_B}(\gamma_B) = \sum_{h=1}^{N_B} (-1)^h \left( \frac{N_B}{h} \right) \sum_{k=0}^{h} \left( \frac{k!}{\rho(h-k, q)} \right) \sum_{p(h-k, q)} p(h-k, q), \]

\[ \times \left[ \prod_{q=1}^{h} \frac{1}{\left( \frac{\Delta_B}{\Delta^E} \right)} \frac{\eta_{B-q}}{\left( \eta_B - q \right)!} \sum_{z=\eta_{B+q}}^{\eta_B+1} \frac{A^B_{\eta_{B+q}+1}}{z} \right]^{p(h-k)}, \]

\[ \times \exp \left( -\frac{\Delta_B k}{\Delta^E} \right) \sum_{h_q \in \rho(h-k, q)} p(h-k, q), \]

\[ \times \frac{1}{\left( \frac{\Delta_B}{\Delta^E} \right)} \frac{\eta_{B-t}}{\left( \eta_B - t \right)!} \sum_{z=\eta_{B+q}}^{\eta_B+1} \frac{A^B_{\eta_{B+q}+1}}{z} \right]^{s(t)}, \]

\[ \times \exp \left( -\frac{\Delta_B k}{\Delta^E} \right) \sum_{h_q \in \rho(h-k, q)} p(h-k, q), \]

(14)

- If \( m_B \geq \mu_B \)

\[ f_{\gamma_B}(\gamma_B) = \sum_{h=1}^{N_B} (-1)^h \left( \frac{N_B}{h} \right) \sum_{k=0}^{h} \left( \frac{k!}{\rho(h-k, q)} \right) \sum_{p(h-k, q)} p(h-k, q), \]

\[ \times \left[ \prod_{q=1}^{h} \frac{1}{\left( \frac{\Delta_B}{\Delta^E} \right)} \frac{\eta_{B-q}}{\left( \eta_B - q \right)!} \sum_{z=\eta_{B+q}}^{\eta_B+1} \frac{A^B_{\eta_{B+q}+1}}{z} \right]^{p(h-k)}, \]

\[ \times \exp \left( -\frac{\Delta_B k}{\Delta^E} \right) \sum_{h_q \in \rho(h-k, q)} p(h-k, q), \]

\[ \times \frac{1}{\left( \frac{\Delta_B}{\Delta^E} \right)} \frac{\eta_{B-t}}{\left( \eta_B - t \right)!} \sum_{z=\eta_{B+q}}^{\eta_B+1} \frac{A^B_{\eta_{B+q}+1}}{z} \right]^{s(t)}, \]

\[ \times \exp \left( -\frac{\Delta_B k}{\Delta^E} \right) \sum_{h_q \in \rho(h-k, q)} p(h-k, q), \]

(15)

**III. Secrecy Outage Probability Analysis**

**A. Exact SOP Analysis**

Here, we consider a silent eavesdropper, in which its channel state information (CSI) is not available at Alice. Therefore,
Alice selects a constant secrecy rate $R_S$ to transmit messages to Bob. In practical networks, this setup is well known as a passive eavesdropping scenario. The secrecy capacity $C_S$ is defined as

$$C_S = \max \{ C_B - C_E, 0 \},$$

in which $C_B = \log_2(1 + \gamma_B)$ and $C_E = \log_2(1 + \gamma_E)$ are the capacities of the main and eavesdropper channels, respectively. Note that secrecy can be guaranteed, only if $R_S \leq C_S$, and is compromised otherwise. Thus, in this scenario, the SOP is a useful performance metric for measuring information leakage. The SOP is defined as the probability that the instantaneous $C_S$ falls below a predefined target secrecy rate $R_S$. The SOP can be formulated as \[32\]

$$\text{SOP} = \Pr \{ C_S (\gamma_B, \gamma_E) < R_S \} = \Pr \{ \gamma_B < \tau \gamma_E + \tau - 1 \} = \int_{0}^{\infty} F_{\gamma_B} (\tau \gamma_E + \tau - 1) f_{\gamma_E} (\gamma_E) d\gamma_E. \quad (17)$$

where $\tau \Delta \rightarrow \frac{R_S}{2}$. \[32\]

**Proposition 3.** The SOP for $m_i < \mu_i$ and $m_i \geq \mu_i$ with $i \in \{ B, E \}$ over i.i.d. $\kappa$-$\mu$ shadowed fading channels can be obtained as \[19\] and \[20\], respectively, at the top of the next page.

**Proof.** See Appendix \[32\] \[32\].

From (17), a high SNR approximation of the SOP, defined as $\text{SOP}_A$, can be expressed as

$$\text{SOP}_A = \Pr \{ \gamma_B < \tau \gamma_E \} \leq \text{SOP}. \quad (18)$$

**B. Asymptotic SOP**

In this section, we focus in developing asymptotic SOP closed-form expressions in the high-SNR regime to gain more insights into the behavior of the fading parameters in the system performance. Here, we consider the scenario where $\gamma_B \rightarrow \infty$ while $\gamma_E$ is kept fixed, i.e., the case in which A is very close to B and E is located far away. Our aim is to express the asymptotic SOP expression in the form $\text{SOP} \approx G_c \gamma_B^{-G_d}$, where $G_c$ and $G_d$ represent the secrecy array gain and the secrecy diversity gain, respectively. Next, the asymptotic SOP expression over $\kappa$-$\mu$ shadowed fading channels is given in the following Proposition.

**Proposition 4.** The asymptotic closed-form expression of the SOP over i.i.d. $\kappa$-$\mu$ shadowed can be obtained as \[21\], at the top of the next page.

**Proof.** See Appendix \[32\].

From (21), note that the secrecy diversity gain is given by $G_c = N_A N_T / N_B$, which only depends on both the antenna settings and the fading parameter related to the legitimate channel. In other words, this means that the secrecy diversity gain is directly affected by varying either the number of antennas (i.e., $N_A$ and/or $N_B$) or the number of wave clusters arriving at Bob. This fact plays a pivotal role in the secrecy performance of the system (as will be discussed in Section \[5\]). On the other hand, notice that fading parameter $\mu_E$ corresponding to the eavesdropper channel does not affect the secrecy diversity gain of the underlying system (vide Fig. \[5\]).

**IV. AVERAGE SECRECY CAPACITY**

In this section, we consider the active eavesdropping scenario, where the CSI of both the main channel and the eavesdropper channel are known at Alice. In such a case, unlike the passive eavesdropping scenario, Alice can adapt the achievable secrecy rate $R_S$ such that $R_S \leq C_S$. Here, the maximum achievable secrecy rate occurs when $R_S = C_S$. Since the CSI of the eavesdropper channel is available at Alice, the average secrecy capacity is an essential performance metric to assess the secrecy performance.

**A. Exact ASC**

According to \[32\], the ASC, $\bar{C}_S$, is defined as the average of the secrecy rate over the instantaneous SNR of the main channel and eavesdropper channels. Therefore, $\bar{C}_S$ can be formulated as \[23\] Proposition 3.

$$\bar{C}_S = \bar{C}_B - \mathcal{L}(\bar{\tau}_B, \bar{\tau}_E), \quad (27)$$

where $\bar{C}_B$ is the average capacity of the main link, given by

$$\bar{C}_B = \frac{1}{\ln 2} \int_{0}^{\infty} \frac{1 - F_{\gamma_B} (\gamma_E)}{1 + \gamma_E} d\gamma_E, \quad (28)$$

and $\mathcal{L}(\bar{\tau}_B, \bar{\tau}_E)$ can be interpreted as ASC loss, defined as

$$\mathcal{L}(\bar{\tau}_B, \bar{\tau}_E) = \frac{1}{\ln 2} \int_{0}^{\infty} \frac{\bar{F}_{\gamma_B} (\gamma_E) \bar{F}_{\gamma_E} (\gamma_E)}{1 + \gamma_E} d\gamma_E, \quad (29)$$

in which $\bar{F}_{\gamma_B}$ and $\bar{F}_{\gamma_E}$ denote the complementary CDF (CCDF) of the RV $\gamma_B$ and $\gamma_E$, respectively. Then, the ASC expressions over i.i.d. $\kappa$-$\mu$ shadowed fading channels in a TAS/MRC system are given as follows.

**Proposition 5.** The ASC closed-form expressions for $m_i \geq \mu_i$ and $m_i < \mu_i$ with $i \in \{ B, E \}$ over i.i.d. $\kappa$-$\mu$ shadowed fading channels can be formulated as \[22\] and \[23\] respectively.

**Proof.** See Appendix \[32\].

**B. Asymptotic ASC**

In this section, we concentrate our attention on deriving closed-form asymptotic ASC expressions to assess the system performance in the high SNR regime. Here, as in the asymptotic SOP analysis, we consider that $\bar{\gamma}_B$ goes to infinity, while $\bar{\gamma}_E$ is kept unchanged. Based on this, the asymptotic expression of the ASC can be expressed as \[23\]

$$\bar{C}_S \approx \bar{C}_B \gamma_B^{-\infty} - \bar{C}_E, \quad (30)$$

where the average capacity of the eavesdropper channel, $\bar{C}_E$, is given by \[22\]

$$\bar{C}_E = \frac{1}{\ln 2} \int_{0}^{\infty} \frac{1 - F_{\gamma_E} (\gamma_E)}{1 + \gamma_E} d\gamma_E, \quad (31)$$

**Proposition 6.** The asymptotic expressions of ASC for $m_i < \mu_i$ and $m_i \geq \mu_i$ with $i \in \{ B, E \}$ over i.i.d. $\kappa$-$\mu$ shadowed
\[
SOP = \sum_{h=0}^{N_A} (-1)^h \left( \begin{array}{c} N_A \\ h \end{array} \right) \sum_{k=0}^{h} \left( \begin{array}{c} k \\ h \end{array} \right) \sum_{\rho(h,k,q)} (h-k)! \sum_{s_1 \cdots s_m} \left[ \prod_{t=1}^{\eta_B} \left( \frac{\eta_B-t}{(\eta_B)!} \right) \sum_{z=\eta_B+1-t}^{\eta_B} A^{B}_{1,\eta_B+1-z} \right]^{s_t} \prod_{\rho(k,v)} \frac{k!}{p_1! \cdots p_{m!}} \right] 
\]

\[
\times \left[ \prod_{q=1}^{\eta_B} \left( \frac{\eta_B-q}{(\eta_B)!} \right) \sum_{z=\eta_B+1-q}^{\eta_B} A^{B}_{2,\eta_B+1-z} \right]^{p_q} \exp \left[ -\left( \tau - 1 \right) \left( \frac{h-k}{\Delta^B} + \frac{k}{\Delta^B} \right) \right] \sum_{b=0}^{\eta_B} \left( \eta_B-j + 1 \right) \frac{A^E_{b,j}}{\left( \frac{\eta_B-j + 1}{\Delta^E} \right)^{\eta_B-j + 1}} 
\]

\[
\times \left( \frac{\tau (h-k)+1}{\Delta^B} + \frac{\tau k}{\Delta^B} + \frac{\nu_E-j + 1}{\omega_A^B} \right)^{-1-b+j-\nu_E} \Gamma \left( 1 + b - j + \nu_E + \frac{\eta_E-j + 1}{\Delta^E} \right) \sum_{b=0}^{\eta_E} \left( \frac{\eta_E-j + 1}{\Delta^E} \right)^{\eta_E-j + 1} 
\]

\[
\times \left( \frac{\tau (h-k)+1}{\Delta^B} + \frac{\tau k}{\Delta^B} + \frac{\nu_E-j + 1}{\omega_A^B} \right)^{-1-b+j-\nu_E} \Gamma \left( 1 + b - j + \nu_E + \frac{\eta_E-j + 1}{\Delta^E} \right) \sum_{b=0}^{\eta_E} \left( \frac{\eta_E-j + 1}{\Delta^E} \right)^{\eta_E-j + 1} 
\]

\[
SOP = \sum_{h=0}^{N_A} (-1)^h \left( \begin{array}{c} N_A \\ h \end{array} \right) \exp \left[ -h \left( \frac{\tau - 1}{\Delta^B} \right) \right] \sum_{\rho(h,v)} \frac{h!}{s_1! \cdots s_m!} \left[ \prod_{t=1}^{\eta_B} \left( \frac{\eta_B-t}{(\eta_B)!} \right) \sum_{z=\eta_B+1-T}^{\eta_B} B^{B}_{\eta_B+1-z} \right]^{s_t} \prod_{\rho(h,v)} \frac{h!}{p_1! \cdots p_{m!}} \right] 
\]

\[
\times \left[ \prod_{t=1}^{\eta_B} \left( \frac{\eta_B-t}{(\eta_B)!} \right) \sum_{z=\eta_B+1-T}^{\eta_B} B^{B}_{\eta_B+1-z} \right]^{p_q} \exp \left[ -\left( \tau - 1 \right) \left( \frac{h-k}{\Delta^B} + \frac{k}{\Delta^B} \right) \right] \sum_{b=0}^{\eta_B} \left( \eta_B-j + 1 \right) \frac{A^E_{b,j}}{\left( \frac{\eta_B-j + 1}{\Delta^E} \right)^{\eta_B-j + 1}} 
\]

\[
\times \left( \frac{\tau (h-k)+1}{\Delta^B} + \frac{\tau k}{\Delta^B} + \frac{\nu_E-j + 1}{\omega_A^B} \right)^{-1-b+j-\nu_E} \Gamma \left( 1 + b - j + \nu_E + \frac{\eta_E-j + 1}{\Delta^E} \right) \sum_{b=0}^{\eta_E} \left( \frac{\eta_E-j + 1}{\Delta^E} \right)^{\eta_E-j + 1} 
\]

\[
SO \approx \left( \frac{m_B^{N_B\eta_B} (1 + \kappa_B)^{N_B\eta_B} m_B^{N_B\eta_B-1} \tau^{N_B\eta_B}}{N_B^T m_B^{N_B\eta_B} (m_B + \kappa_B m_B)^{N_B\eta_B} \Gamma (N_B\eta_B)} \right)^{-N_A \eta_B m_B} 
\]

\[
\times \Gamma (N_A \eta_B m_B + \eta_B \mu_E) \frac{N_A \eta_B m_E}{m_E^{N_B\eta_B} \Gamma (N_B \eta_B \mu_E + m_E \eta_B)} \frac{\kappa E \mu E}{m_E + \kappa \mu E} 
\]

\[
C_S = \frac{1}{\ln 2} \sum_{h=1}^{N_A} (-1)^{h+1} \left( \begin{array}{c} N_A \\ h \end{array} \right) \sum_{\rho(h,v)} \frac{h!}{s_1! \cdots s_m!} \left[ \prod_{t=1}^{\eta_B} \left( \frac{\eta_B-t}{(\eta_B)!} \right) \sum_{z=\eta_B+1-T}^{\eta_B} B^{B}_{\eta_B+1-z} \right]^{s_t} \exp \left( \frac{h}{\Delta^B} \right) 
\]

\[
\times \Gamma \left( 1 + r \sum_{t=1}^{\eta_B} (\eta_B-t) s_t \right) \Gamma \left( -r \sum_{t=1}^{\eta_B} (\eta_B-t) s_t, \frac{h}{\Delta^B} \right) - \Gamma \left( 1 + \eta_B, \frac{h}{\Delta^B} \right) \sum_{\rho(h,v)} \frac{h!}{s_1! \cdots s_m!} \right] 
\]

\[
\times \left[ \prod_{t=1}^{\eta_B} \left( \frac{\eta_B-t}{(\eta_B)!} \right) \sum_{z=\eta_B+1-T}^{\eta_B} B^{B}_{\eta_B+1-z} \right]^{p_q} \exp \left[ -\left( \tau - 1 \right) \left( \frac{h-k}{\Delta^B} + \frac{k}{\Delta^B} \right) \right] \sum_{b=0}^{\eta_B} \left( \eta_B-j + 1 \right) \frac{A^E_{b,j}}{\left( \frac{\eta_B-j + 1}{\Delta^E} \right)^{\eta_B-j + 1}} 
\]

\[
\times \left( \frac{\tau (h-k)+1}{\Delta^B} + \frac{\tau k}{\Delta^B} + \frac{\nu_E-j + 1}{\omega_A^B} \right)^{-1-b+j-\nu_E} \Gamma \left( 1 + b - j + \nu_E + \frac{\eta_E-j + 1}{\Delta^E} \right) \sum_{b=0}^{\eta_E} \left( \frac{\eta_E-j + 1}{\Delta^E} \right)^{\eta_E-j + 1} 
\]

V. Numerical results and discussions

In this section, we provide some numerical results along with Monte Carlo simulation to assess the proposed analytical derivations. In all plots, it is considered that the fading severity parameters (i.e., \( \mu_i \) and \( m_i \) for \( i \in \{B,E\} \)) take integer

Proof. See Appendix E
\[ C_S = \frac{1}{\ln 2} \sum_{h=1}^{N_A} (-1)^{h+1} \left( \frac{N_A}{h} \right) \sum_{k=0}^{h} \frac{k!}{\prod_{\rho(k,v_p)}} p_1^{v_0} \cdots p_{v_n}^{v_n} \left[ \prod_{q=1}^{v_p} \left( \frac{\Delta^Q}{(\nu_B - q)!} \sum_{z = v_B + 1 - q}^{v_B} A_{2^v, \nu_B + 1 - z} \right) \right] \sum_{\rho(h,k,\eta_B)} \frac{(h-k)!}{s_1! \cdots s_{\eta_B}!} \]

\[ \times \left[ \prod_{t=1}^{\eta_B} \left( \frac{\Delta^Q}{(\eta_B - t)!} \sum_{z = \eta_B + 1 - t}^{\eta_B} A_{1^t, \eta_B + 1 - t} \right) \right] \exp \left( \frac{h-k}{\Delta^Q} \right) + \frac{k}{\Delta^Q} \right) \Gamma \left( 1 + \sum_{t=1}^{\eta_B} (\eta_B - t) s_t + \sum_{q=1}^{v_B} (\nu_B - q) p_q \right) \]

\[ \times \Gamma \left( 1 + r + \sum_{t=1}^{\eta_B} (\eta_B - t) s_t + \sum_{q=1}^{v_B} (\nu_B - q) p_q \right) + \sum_{t=1}^{\eta_B} \left( \frac{\Delta^Q}{(\nu_B - q)!} \sum_{z = \eta_B + 1 - t}^{\eta_B} A_{1^t, \eta_B + 1 - t} \right) \left( \frac{h-k}{\Delta^Q} \right) + \frac{k}{\Delta^Q} \right) \Gamma \left( 1 + r + \sum_{t=1}^{\eta_B} (\eta_B - t) s_t + \sum_{q=1}^{v_B} (\nu_B - q) p_q \right) \]

\[ \times \exp \left( \frac{1}{\Delta^Q} \right) \left( \frac{\eta_B}{(\eta_B - t)!} \sum_{r=0}^{\eta_B} \left( \frac{1}{\Delta^Q} \right)^r \Gamma (1 + r) \right) \left( \frac{1}{\Delta^Q} \right)^r \Gamma (1 + r) \right). \]

\[ C_S^\infty \simeq \log_2 (N_B \bar{\gamma}_B) + \log_2 (e) \left( \sum_{h=1}^{N_A} (-1)^{h+1} \left( \frac{N_A}{h} \right) \sum_{k=0}^{h} \frac{k!}{\prod_{\rho(k,v_p)}} p_1^{v_0} \cdots p_{v_n}^{v_n} \left[ \prod_{q=1}^{v_p} \left( \frac{\Delta^Q}{(\nu_B - q)!} \sum_{z = v_B + 1 - q}^{v_B} A_{2^v, \nu_B + 1 - z} \right) \right] \sum_{\rho(h,k,\eta_B)} \frac{(h-k)!}{s_1! \cdots s_{\eta_B}!} \right] \]

\[ \times \left[ \prod_{t=1}^{\eta_B} \left( \frac{\Delta^Q}{(\eta_B - t)!} \sum_{z = \eta_B + 1 - t}^{\eta_B} A_{1^t, \eta_B + 1 - t} \right) \right] \exp \left( \frac{h-k}{\Delta^Q} \right) + \frac{k}{\Delta^Q} \right) \Gamma \left( 1 + \sum_{t=1}^{\eta_B} (\eta_B - t) s_t + \sum_{q=1}^{v_B} (\nu_B - q) p_q \right) \]

\[ \times \Gamma \left( 1 + r + \sum_{t=1}^{\eta_B} (\eta_B - t) s_t + \sum_{q=1}^{v_B} (\nu_B - q) p_q \right) + \sum_{t=1}^{\eta_B} \left( \frac{\Delta^Q}{(\nu_B - q)!} \sum_{z = \eta_B + 1 - t}^{\eta_B} A_{1^t, \eta_B + 1 - t} \right) \left( \frac{h-k}{\Delta^Q} \right) + \frac{k}{\Delta^Q} \right) \Gamma \left( 1 + r + \sum_{t=1}^{\eta_B} (\eta_B - t) s_t + \sum_{q=1}^{v_B} (\nu_B - q) p_q \right) \]

\[ \times \exp \left( \frac{1}{\Delta^Q} \right) \left( \frac{\eta_B}{(\eta_B - t)!} \sum_{r=0}^{\eta_B} \left( \frac{1}{\Delta^Q} \right)^r \Gamma (1 + r) \right) \left( \frac{1}{\Delta^Q} \right)^r \Gamma (1 + r) \right). \]
goals is to analyze the secrecy diversity gain of the legitimate channels for the considered cases. So, based on the asymptotic plots, we see that the antenna configuration at Alice is one of the factors that clearly contributes in the slope of the SOP in a proportional way. On one hand, this means that the drop of the SOP is more steep (i.e., better secrecy performance) as the number of transmit antennas increases. On the other hand, as the transmit antennas decreases the SOP is impaired and the drop is not so pronounced. These facts are in coherence with the results obtained in the $G_d$ expression.

Fig. 3 presents the SOP vs. $\gamma_B$, for various numbers of receiving antennas, $N_E$, and fixed number antennas, $N_A = N_B = 2$. For all curves, the setting parameter values are: $R_S = 1$ bps/Hz, $\gamma_E = 8$ dB, $\mu_i = 2$, $\kappa_i = 2$, and $m_i = 3$ for $i \in \{B, E\}$. The markers denote Monte Carlo simulations.

In Fig. 4 we evaluate the SOP as a function of $\gamma_B$, considering different numbers of receiving antennas, $N_E$, and fixed number antennas $N_A = N_E = 2$. For all instances, the configuration parameters are as follows: $R_S = 2$ bps/Hz, $\gamma_E = 8$ dB, $\mu_i = 1$, and $m_i = 2$ for $i \in \{B, E\}$. In this scenario, we consider small $(\kappa_B = \kappa_E = 1.5)$ and large $(\kappa_B = \kappa_E = 10)$ LOS components in the received wave clusters for a different number of antennas at Bob. It can be observed that, if the increase in the number of Bob’s antennas is accompanied by strong LOS components $(\kappa_B = \kappa_E = 10)$, the secrecy diversity gain increases, resulting in a noticeable improvement in the secrecy performance. This result is linked to the fact that $N_B$ directly influences the slope of the SOP, as shown in $G_d$ formulation. However, in the opposite scenario (wherein both $N_B$ and $\kappa_i$ for $i \in \{B, E\}$ decrease), we note that the SOP performance deteriorates.

Fig. 5 shows the SOP vs. $\gamma_B$, for $N_A = N_B = 2$, $N_E = 3$, and different received wave clusters, $\mu_B$, and $\mu_E$. The remainder parameters are set to: $R_S = 2$ bps/Hz, $\gamma_E = 8$ dB, $\kappa_i = 4$, and $m_i = 5$ for $i \in \{B, E\}$. In the proposed scenarios, we investigate the influence of the number of wave clusters at the receiver ends on the secrecy performance. We consider the following two cases: (i) $\mu_E$ is kept fixed, whereas $\mu_B$ goes from 2 to 5; (ii) $\mu_B$ is kept unchanged, whereas $\mu_E$
K = 25 dB = 15 dB

networks.

not affected by the number of received wave clusters at Eve.

expression) that the secrecy diversity gain of the system is
remains identical. This fact corroborates our finding (vide

unchanged number of:

case, it is observed that as

µ increases, the secrecy performance improves. In the latter

increases, the slope of the SOP
.

behavior changes when

m ≤ µi or m < µi (for i ∈ {B, E}). In addition, in Fig. 6 and Fig. 7 it can be noted that the
asymptotic ASC curves tightly approximate the Monte Carlo
simulations in the high SNR regime.

VI. CONCLUSIONS

We have analyzed the impact on the PLS performance of
MIMO wiretap systems by assuming a versatile channel model
ranging from strong LOS to weak LOS, from light to heavy
shadowing for the LOS components, and from homogeneous
diffuse scattering to scenarios which foster the clustering
of scattered multipath waves. We have provided numerical
results that reveal that large LOS components (κi) for), weak
shadowing environment (mi for i ∈ {B, E}), rich scattering
condition at the intended receiver (µB), and multiple antennas
at the legitimate users collectively lead to improve the secrecy
performance. Furthermore, it has been shown that impact in

m = 1, and LOS environments κi = 5 for i ∈ {B, E}.

From all figures, it is straightforward to see that increasing
NA implies increasing ĈS. However, for these cases, having
more number of antennas at the transmitter does not reflect
a noticeable improvement in terms of ĈS, because the LOS
fluctuation is severe.

Next, Fig. 7 shows the ASC as a function of τB, considering
different numbers of receiving antennas, N̄E, and fixed number
of antennas, NA = NE = 2. The remainder parameters are set
to: τE = 8 dB, and µi = m i = 2 for i ∈ {B, E}.

The inference does not apply in the
previous cases, where an increase in the power of the LOS
is obviously favorable for the SOP and consequently for the
ĈS. We can explain this observation because if µi = mi (for
i ∈ {B, E}) implies that both the scattering and the shadowed
LOS components in each cluster experience the same fading.

Therefore, ĈS is independent of κi. However, this channel
behavior changes when mi ≥ µi or mi < µi (for i ∈ {B, E}).

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NA implies increasing ĈS. However, for these cases, having
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fluctuation is severe.

Next, Fig. 7 shows the ASC as a function of τB, considering
different numbers of receiving antennas, N̄E, and fixed number
of antennas, NA = NE = 2. The remainder parameters are set
to: τE = 8 dB, and µi = m i = 2 for i ∈ {B, E}.

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i ∈ {B, E}) implies that both the scattering and the shadowed
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Therefore, ĈS is independent of κi. However, this channel
behavior changes when mi ≥ µi or mi < µi (for i ∈ {B, E}).

In addition, in Fig. 6 and Fig. 7 it can be noted that the
asymptotic ASC curves tightly approximate the Monte Carlo
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VI. CONCLUSIONS

We have analyzed the impact on the PLS performance of
MIMO wiretap systems by assuming a versatile channel model
ranging from strong LOS to weak LOS, from light to heavy
shadowing for the LOS components, and from homogeneous
diffuse scattering to scenarios which foster the clustering
the increase on the number of wave clusters arriving at Eve is negligible from a secrecy perspective.

Appendix A

Proof of Proposition 11

Using (33) into \( \gamma_{B} = \sum_{l=1}^{N_{B}} \gamma_{k,l} \), the CDF of \( \gamma_{B} \) can be formulated as

\[
F_{\gamma_{B}}(\gamma_{B}) = \left( F_{\gamma_{1}}(\gamma_{B}) \right)^{N_{A}},
\]

(32)

where \( \gamma_{1} = \sum_{l=1}^{N_{B}} \gamma_{k,l} \) with \( \gamma_{k,l} \) denoting the instantaneous received SNR of the link between a single transmitting \( k \) antenna at Alice and \( l \)-th receiving antenna at Bob.

In dealing with i.i.d. channels, the CDF of \( \gamma_{1} \) can be obtained by following the same methodology used for (10), and (11), i.e., \( \gamma_{1} \sim (N_{B}, \kappa_{B}, N_{B}\mu_{B}, N_{B}\beta_{B}) \). However, the resulting CDFs of \( \gamma_{1} \) become intractable in developing (32), if not impossible. Therefore, we propose to reformulate such CDFs of \( \gamma_{1} \) from its original forms to equivalent expressions by changing the indices of the sums and rearranging some of the terms, so we obtain

- If \( m_{B} < \mu_{B} \)

\[
F_{\gamma_{1}}(\gamma_{B}) = 1 - \sum_{j=0}^{\nu_{B}-1} \left( \frac{\eta_{B}}{\nu_{B}-j} \right)^{\nu_{B}-j} \sum_{z=\nu_{B}+1-j}^{\eta_{B}} A_{1,\nu_{B}+1-z}^{B} \cdot \exp \left\{ -\frac{\eta_{B}}{\nu_{B}-j} \right\} \sum_{j=1}^{\nu_{B}} \left( \frac{\nu_{B}}{\nu_{B}-j+1} \right)^{\nu_{B}-j} \sum_{z=\nu_{B}+1-j}^{\nu_{B}+1-z} A_{1,\nu_{B}+1-z}^{B},
\]

(33)

where \( \eta_{B} = N_{B}(\mu_{B} - m_{B}) \), and \( \nu_{B} = N_{B}m_{B} \).

The resulting CDFs of \( \gamma_{1} \) refer to (10b) and (11b) by changing all the subscripts E by B.

\[ \text{If } m_{B} \geq \mu_{B} \]

\[
F_{\gamma_{1}}(\gamma_{B}) = 1 - \sum_{j=0}^{\nu_{B}-1} \left( \frac{\eta_{B}}{\nu_{B}-j} \right)^{\nu_{B}-j} \exp \left\{ -\frac{\eta_{B}}{\nu_{B}-j} \right\} \sum_{z=\nu_{B}+1-j}^{\eta_{B}} A_{1,\nu_{B}+1-z}^{B} \cdot \sum_{j=1}^{\nu_{B}} \left( \frac{\nu_{B}}{\nu_{B}-j+1} \right)^{\nu_{B}-j} \sum_{z=\nu_{B}+1-j}^{\nu_{B}+1-z} A_{1,\nu_{B}+1-z}^{B},
\]

(34)

where \( \beta_{B} = N_{B}(m_{B} - \mu_{B}) \), and the coefficients marked with superscripts B (e.g., \( \Delta^{B} \)) are associated to the fading parameters at Bob,

\[
T(j) = \begin{cases} 
\nu_{B} + 1, & \text{for } 0 \leq j \leq \beta_{B} \\
\beta_{B} + 1, & \text{otherwise}.
\end{cases}
\]

In both (33) and (34), the respective coefficients can be obtained from (34) to (32) by substituting \( \gamma \to N_{B}\gamma_{B}, \mu \to N_{B}\mu_{B}, m \to N_{B}m_{B}, \) and \( \kappa \to \kappa_{B} \).

In what follows, we derive the CDF of \( \gamma_{B} \) for \( m_{B} < \mu_{B} \) and \( m_{B} \geq \mu_{B} \).

- If \( m_{B} < \mu_{B} \)

Substituting (33) into (32) and by applying the binomial expansion twice [35, Eq. (1.111)], we get

\[
F_{\gamma_{B}}(\gamma_{B}) = \sum_{h=0}^{N_{A}} (-1)^{h} \left( \frac{N_{A}}{h} \right) \sum_{k=0}^{h} \left( \sum_{j=1}^{\nu_{B}} \left( \frac{\nu_{B}}{\nu_{B}-j+1} \right)^{\nu_{B}-j} \sum_{z=\nu_{B}+1-j}^{\nu_{B}+1-z} A_{1,\nu_{B}+1-z}^{B} \right)^{k} \cdot \exp \left\{ -\frac{\eta_{B}}{\nu_{B}-j} \right\} \sum_{z=\nu_{B}+1-j}^{\nu_{B}+1-z} A_{1,\nu_{B}+1-z}^{B},
\]

(35)

Next, by invoking the multinomial theorem [36, Eq. (24.1.2)] for both terms \( T_{1} \) and \( T_{2} \), and after some mathematical manipulations, the CDF of \( \gamma_{B} \) can be formulated as in (12), which concludes the proof.

- If \( m_{B} \geq \mu_{B} \)

Replacing (34) into (32) and by applying the binomial expansion [35, Eq. (1.111)], it follows that

\[
F_{\gamma_{B}}(\gamma_{B}) = \sum_{h=0}^{N_{A}} (-1)^{h} \left( \frac{N_{A}}{h} \right) \sum_{j=1}^{\nu_{B}} \left( \frac{\nu_{B}}{\nu_{B}-j+1} \right)^{\nu_{B}-j} \sum_{z=\nu_{B}+1-j}^{\nu_{B}+1-z} A_{1,\nu_{B}+1-z}^{B} \cdot \exp \left\{ -\frac{\eta_{B}}{\nu_{B}-j} \right\} \sum_{z=\nu_{B}+1-j}^{\nu_{B}+1-z} A_{1,\nu_{B}+1-z}^{B},
\]

(36)

Again, by using the multinomial expansion [36, Eq. (24.1.2)] into \( T_{3} \), and after some algebraic manipulations, the CDF of \( \gamma_{B} \) can be expressed as in (13). This completes the proof.
APPENDIX B

PROOFS OF PROPOSITION

A. SOP

• If \( m_i < \mu_i \) for \( i \in \{B, E\} \)

Substituting (12) and (10a) into (17), we can obtain

\[
\begin{align*}
\text{SOP} &= \sum_{h=0}^{N_A} (-1)^h \binom{N_A}{h} \sum_{k=0}^{h} \binom{h}{\rho(h-k,\eta_B)} \sum_{s_1! \cdots s_{\eta_B}} (h-k)! \\
&\times \prod_{t=1}^{\eta_B} \left( \frac{1}{(\eta_B-t)!} \sum_{z=\eta_B+1-t}^{\eta_B} A_{1,\eta_B+1-t} \right) s_t \\
&\times \sum_{\rho(k,\eta_B)} \frac{k!}{p_1! \cdots p_{\eta_B}!} \left[ \prod_{q=1}^{\eta_B} \exp \left( \frac{(\tau-1)k}{\Delta^2} \right) \right] \\
&\times \exp \left( -\frac{(\tau-1)k}{\Delta^2} \right) \left[ \sum_{j=1}^{\eta_B} A_{1,j} \right] \left( \gamma E \right) \\
&\times \int_{I_3}^{\infty} \frac{\gamma^\eta_B-1 \exp (-\gamma E - \tau + \frac{\tau(k-1)}{\Delta^2} + \frac{\tau(k-1)\eta_B+1}{\Delta^2} \gamma E)}{I_3} d\gamma E \\
&\times \gamma^\eta_B-1 \exp \left( -\gamma E \left( \frac{\tau(k-1)}{\Delta^2} + \frac{\tau(k-1)\eta_B+1}{\Delta^2} \right) \right) d\gamma E \\
&\times \exp \left( -\gamma E \left( \frac{\tau(k-1)}{\Delta^2} + \frac{\tau(k-1)\eta_B+1}{\Delta^2} \right) \right). \\
\end{align*}
\]

Again, by using [35] Eq. (1.111) - Eq. (3.35.12) to solve \( I_3 \), the SOP can be formulated as in (20). This concludes the proof.

APPENDIX C

PROOF OF PROPOSITION

A. SOP\( ^\infty \)

1) Keeping \( \tau_E \) Fixed and \( \tau_B \rightarrow \infty \) : Firstly, by using the asymptotic-matching method proposed in [37], the CDF of a \( \kappa-\mu \) shadowed RV given in (1b) and (25) can be approximated by a gamma distribution with CDF

\[
F^{\infty}_E(x) \approx \frac{\gamma \left( \alpha, \frac{x}{\lambda} \right)}{\Gamma(\alpha)},
\]

where the shape parameters \( \alpha \) and \( \lambda \) are given in terms of the \( \kappa-\mu \) shadowed fading parameters as

\[
\alpha = \mu, \quad \lambda = \frac{\tau}{(1+\kappa)\mu} \left( \frac{m+\kappa\mu^\mu}{m^m} \right) \frac{1}{\mu}. \tag{40b}
\]

Now, in order to asymptotically approximate \( F_{\tau_1}(\tau_B) \), we use the following relationship \( \gamma (a, x) \simeq x^a / s \) as \( x \rightarrow 0 \) in (39), and then replacing \( \gamma \rightarrow N_B, \mu \rightarrow N_B \mu_B, m \rightarrow N_B m_B, \) and \( \kappa \rightarrow \kappa_B \). Next, by plugging the resulting asymptotic \( F_{\tau_1}(\tau_B) \) in (32), this yields

\[
F_B(\tau_B) \simeq \frac{m_B^N B_B N_B - 1}{m_B N_B^N B_B (m_B + \kappa_B \mu_B)^{N_B m_B} \Gamma(N_B \mu_B)} \frac{N_A}{(m_B + \kappa_B \mu_B)^{N_B m_B} \Gamma(N_B \mu_B)}. \tag{41}
\]
Substituting (41) with \([26, \text{Eq. (4)}]\) with the respective substitutions into \((18)\), it follows that

\[
\text{SOP}^\infty \sim \left( \frac{m_B^{N_{mB}} (1 + \kappa_B) N_{nB} m_B^{N_{nB} - 1} \tau_{N_{nB} \mu_B}}{N_B^{\gamma_E} \Gamma(N_{E}\mu_E) \gamma_E^{N_{E} \mu_E}} \right)_{E\mu_E} \times \int_0^\infty \gamma_E^{N_{E} \mu_E + N_{nB} \gamma_E (1 + \kappa_E)} \exp \left( -\frac{\gamma_E \mu_E (1 + \kappa_E)}{\gamma_E} \right) \, d\gamma_E. 
\]

\[\times 1_F \left( \frac{\gamma_E \kappa_E \mu_E N_{nB} (1 + \kappa_E)}{\gamma_E (\mu_E + \kappa_E \mu_E)} \right) \frac{d\gamma_E}{I_4} \tag{42}\]

Finally, \([35, \text{Eq. (7.522.9)}]\)

\[\text{APPENDIX D} \]
\[\text{PROOF OF PROPOSITION 8}\]

- If \(m_i < \mu_i\) for \(i \in \{B, E\}\)

Inserting \((12)\) in \((28)\), the result is

\[
\bar{C}_B = \frac{1}{\ln 2} \sum_{h=1}^{N_A} (-1)^{h+1} \binom{N_A}{h} \sum_{k=0}^{h} \binom{k}{\nu_n} \frac{k!}{p_{\nu_n}!} \times \left[ \prod_{q=1}^{\nu_n} \left( \frac{1}{\gamma_E} \right)^{\nu_n - q} \sum_{z=\nu_n + 1 - q}^{\nu_n} \frac{A_{2n-1}^B (z-\nu_n)}{\gamma_E^{(1 + \nu_n)}} \right] \\
\times \sum_{\rho(h-k, \nu_n)} \frac{(h-k)!}{s_1! \cdots s_{\nu_n}!} \binom{\nu_n}{\rho(h-k, \nu_n)} \sum_{l=1}^{\nu_n} \left( \frac{1}{\gamma_E} \right)^{\nu_n - l} \prod_{l=1}^{\nu_n} \left( \frac{1}{\gamma_E} \right)^{\nu_n - q} \sum_{z=\nu_n + 1 - q}^{\nu_n} \frac{A_{2n-1}^B (z-\nu_n)}{\gamma_E^{(1 + \nu_n)}} \\
\times \exp \left( -\gamma_E \left( \frac{h-k}{\gamma_E} \right) \right) \frac{\gamma_E^2}{\gamma_E^{(1 + \nu_n)}} \int_0^\infty \frac{1}{\gamma_E} \exp \left( -\gamma_E \left( \frac{h-k}{\gamma_E} \right) \right) \frac{\gamma_E^2}{\gamma_E^{(1 + \nu_n)}} \frac{d\gamma_E}{I_5} \tag{43}\]

Again, by using \([35, \text{Eq. (3.353.5)}]\), both \(I_6\) and \(I_7\) can be evaluated en closed-form. Then, by combining \((43)\) and \((44)\), the \(C_B\) can be expressed as in \((23)\). This completes the proof.

- If \(m_i \geq \mu_i\) for \(i \in \{B, E\}\)

Plugging \((13)\) in \((28)\), we have

\[
\bar{C}_B = \frac{1}{\ln 2} \sum_{h=1}^{N_A} (-1)^{h+1} \binom{N_A}{h} \sum_{s_1 = \nu_n + 1 - q}^{\nu_n} \frac{s_1!}{s_1! \cdots s_{\nu_n}!} \binom{\nu_n}{s_1} \frac{B_{s_1}^B (s_1-\nu_n)}{\gamma_E^{(1 + \nu_n)}} \\
\times \exp \left( -\gamma_E \left( \frac{h-k}{\gamma_E} \right) \right) \frac{\gamma_E^2}{\gamma_E^{(1 + \nu_n)}} \int_0^\infty \frac{1}{\gamma_E} \exp \left( -\gamma_E \left( \frac{h-k}{\gamma_E} \right) \right) \frac{\gamma_E^2}{\gamma_E^{(1 + \nu_n)}} \frac{d\gamma_E}{I_5} \tag{45}\]

Employing \([35, \text{Eq. (3.353.5)}]\), the integral in \(I_5\) can be expressed in simple exact closed-form. Then, by substituting \((12)\) with the aid of \([35, \text{Eq. (3.353.5)}]\), \(I_7\) can be evaluated in exact closed-form expression. Next, by inserting \((11b)\) and \((13)\)
into (29), this yields

\[
\mathcal{L}(\gamma_B, \gamma_E) = \frac{1}{\ln 2} \sum_{h=1}^{N_A} (-1)^{h+1} \binom{N_A}{h} \sum_{\rho(h,v_B)} \frac{h!}{s_1! \cdots s_{v_B}!} \times \left[ \prod_{t=1}^{\nu_B} \left( \frac{1}{\Delta^t} \right)^{v_B - t} \int_0^{\beta_B} \exp \left( -\frac{\gamma_E}{\Delta^t} \right) \right] \times \sum_{j=0}^{\beta_B} B_j^B \sum_{r=0}^{\nu_B - j - 1} \frac{1}{r!} \left( \frac{1}{\Delta^t} \right)^r \int_0^{\infty} \exp \left( -\frac{\gamma_E}{\Delta^t} \right) \times \frac{1}{1 + \gamma_E} \exp \left( -\frac{\gamma_E h}{\Delta^t} \right) \int_0^\infty \exp \left( -\frac{\gamma_E}{\Delta^t} \right) \int_0^\infty \exp \left( -\frac{\gamma_E}{\Delta^t} \right) \int_0^\infty \exp \left( -\frac{\gamma_E}{\Delta^t} \right)
\]

where \( \Delta^t \) are discriminants.

Similar to evaluate \( I_7 \), the identity [35, Eq. (3.353.5)] is used to calculate \( I_8 \). Finally, by combining (45) and (46), the \( C_S \) can be formulated as in (22), which concludes the proof.

\section*{Appendix E}
\section*{Proof of Proposition 6}

\begin{itemize}
  \item If \( m_i < \mu_i \) for \( i \in \{B, E\} \)
  \item If \( m_i \geq \mu_i \) for \( i \in \{B, E\} \)
\end{itemize}

Inserting (10b) in (31), this yields

\[
\tilde{C}_E = \frac{1}{\ln 2} \left( \sum_{j=1}^{\nu_B} A_{E,j} \sum_{r=0}^{\nu_B - j} \frac{1}{r!} \left( \frac{1}{\Delta^t} \right)^r \int_0^\infty \exp \left( -\frac{\gamma_E}{\Delta^t} \right) \right) \times \frac{\gamma_E}{1 + \gamma_E} d\gamma_E + \sum_{j=1}^{\nu_B} A_{E,j} \sum_{r=0}^{\nu_B - j} \frac{1}{r!} \left( \frac{1}{\Delta^t} \right)^r \times \int_0^\infty \exp \left( -\frac{\gamma_E}{\Delta^t} \right) \frac{\gamma_E}{1 + \gamma_E} d\gamma_E.
\]

Expanding the integral term in (49) and making use of [38, Eq. (3.351.3)], \( I_{11} \) can be evaluated in a simple form. Next, taking the derivative of the the resulting expression with respect to \( n \), and setting \( n = \frac{1}{2} \), \( C_{T \rightarrow \infty} \) can be formulated in closed-form fashion. Finally, by replacing \( C_{T \rightarrow \infty} \) and (47) into (40), and after some manipulations, \( C_{S \rightarrow \infty} \) is attained as in (23). This completes the proof.

Substituting (11b) into (31), we obtain

\[
\tilde{C}_E = \frac{1}{\ln 2} \left( \sum_{j=0}^{\beta_B} B_j^E \sum_{r=0}^{\nu_B - j - 1} \frac{1}{r!} \left( \frac{1}{\Delta^t} \right)^r \int_0^\infty \exp \left( -\frac{\gamma_E}{\Delta^t} \right) \times \frac{\gamma_E}{1 + \gamma_E} d\gamma_E. \right)
\]

Again, making use of [38, Eq. (3.353.5)], \( I_{12} \) is computed in a closed-form solution. Here, following similar steps to obtain \( C_{T \rightarrow \infty} \) as in the previous case, we substitute (15) into \( \mathcal{M}(n) \),
we get
\[
M(n) = \frac{1}{\mathcal{B}} \sum_{h=1}^{N_A} (-1)^h \binom{N_A}{h} \left( \sum_{\nu(h,\nu_n)} s_{\nu_n,1} \cdots s_{\nu_n,1} \right) f(\mathcal{B} h, \nu) \sum_{\nu=1}^{\mathcal{B}} \exp \left( \frac{h_{\mathcal{B}}}{\mathcal{B}} \right) \\
 \times \int_0^{\infty} \Delta h \exp \left( -\frac{h_{\mathcal{B}}}{\mathcal{B}} \right) \int_1^{\infty} d\gamma \frac{d\gamma_{\mathcal{B}}}{\gamma_{\mathcal{B}}} \int_{\gamma_{\mathcal{B}}}^{\infty} d\gamma_{\mathcal{B}}
\]

Performing the integral term in (51) and recalling the identity \( \frac{1}{n} \text{Eq. (3.351.3)} \), \( I_{13} \) is obtained in closed-form expression. Next, by plugging (51) in (48), then taking the derivative with respect to \( n \), and setting \( n = 0 \), \( C_{\mathcal{B}}^{\infty} \) is attained in closed-from formulation. Finally, by substituting the \( C_{\mathcal{B}}^{\infty} \) together with (50), and after some algebra, \( C_{\mathcal{B}}^{\infty} \) is expressed as in (25). This completes the proof.

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