

Physical Layer Security over Independent Fluctuating Two-Ray (IFTR) Fading Channels

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ABSTRACT- Underwater acoustic communications (UACs) are vulnerable to eavesdropping because of the broadcast nature of acoustic transmission. In this work, we analyze physical layer security over statistically independent fluctuating two-ray (IFTR) legitimate and eavesdropping links. For the full-CSI benchmark, a closed-form expression for the average secrecy capacity (ASC) is derived as the main analytical contribution. In addition, a closed-form lower bound on the secrecy outage probability (SOP) is obtained. The probability of strictly positive secrecy capacity (SPSC) follows as an exact corollary when the target secrecy rate is zero. The ASC expression is verified through direct numerical integration and independent Monte Carlo simulation using realizations, with a maximum deviation of 0.1336%. Moreover, the SOP lower bound is verified numerically and compared with the exact SOP. Its maximum deviation is 4.25% at a target secrecy rate of 0.1bit/s/Hz over the tested cases; however, larger deviations occur at higher target secrecy rates. A sensitivity analysis further shows the influence of the IFTR parameters on secrecy performance. Finally, three representative IFTR parameter configurations are considered for numerical comparison. Accordingly, these configurations are treated as statistical test cases rather than general representations of measured shallow-water, deep-water, or UWSN environments.

Keywords: Independent Fluctuating Two-Ray Fading, Physical Layer Security, Underwater Acoustic Communication, Average Secrecy Capacity.

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1. INTRODUCTION

Underwater acoustic communications (UACs) have emerged as a practical solution for wireless connectivity in aquatic environments, as acoustic waves enable efficient long-range signal transmission [1]. They support a variety of critical military and civilian applications, including environmental assessment, marine resource surveying, disaster management, and surveillance activities [2]. Owing to the open broadcast characteristics of underwater acoustic wireless channels, UAC links are inherently vulnerable to various security challenges, such as interception and impersonation attempts. In contrast to traditional cryptographic mechanisms implemented at the network's upper layers, physical layer security (PLS) proposes a lightweight solution by exploiting the inherent variability and unpredictability of wireless networks to guarantee the secure transmission of confidential information [3].

Recent studies have shown growing interest in PLS for underwater acoustic communications [4]-[10]. For example, a lightweight attack detection scheme based on route propagation delays was recently introduced in [4]. The authors in [5] proposed a secure transmission framework incorporating an efficient and low-complexity group-based key generation mechanism applied to UWSNs, while [6] showed that fading enables non-zero secrecy in UWA channels with generalized Gaussian noise. Moreover, the security of underwater acoustic OFDM systems employing time-reversal techniques was evaluated in [7]. In addition, [8] investigated secret key generation techniques based on propagation latency in underwater channels, whereas [9] reviewed the existing PLS techniques and the main challenges associated with UAC systems. Furthermore, [10] focused on robust channel parameters for secure key generation.

Most of these works, however, addressed secrecy analysis, authentication, and key generation, and relied on conventional fading models, including Rayleigh, Nakagami-m, and Rician fading. Although these models are widely used, a single conventional distribution may not fully describe propagation conditions in which strong multipath components undergo separate fluctuations. Underwater transmission channels are characterized by time-varying multipath effects, frequency-selective attenuation, motion-induced Doppler shifts, and sparse yet resolvable channel impulse responses [11]. This

motivates the use of independent fluctuating two-ray (IFTR) fading [12] for channels in which more than one strong propagation path is present. The strong components are allowed to vary independently, whereas the aggregate contribution of weaker scattered paths is represented by a diffuse term. This structure offers additional flexibility in describing small-scale fading conditions with independently varying dominant paths.

A tractable representation of IFTR fading was developed in [12] and used to study several communication measures. Its secrecy analysis was formulated in terms of the probability of successful secure transmission. In particular, an analytical expression was obtained when the legitimate link follows IFTR fading and the eavesdropping link is described by a distribution with a known generalized moment-generating

function. The IFTR/IFTR setting was subsequently addressed using the corresponding IFTR expression for the eavesdropping link. A high-SNR secrecy-outage result was also derived, and the probability of strictly positive secrecy capacity was evaluated. The average channel capacity considered in [12], however, pertains to a single IFTR link and does not represent the average secrecy capacity. The latter depends on the positive capacity difference between the legitimate and eavesdropping links and therefore requires the statistics of both links. To the best of the authors' knowledge, a closed-form expression for the ASC when the legitimate and eavesdropping links independently undergo IFTR fading has not been reported. *Table 1* places this result alongside closely related fading-based PLS studies. *Table 1* summarizes the closest fading-based PLS studies and places the present analysis in relation to [12].

Table 1. Comparison with related fading-based pls studies

Ref.	Channel model	ASC	Exact SOP	SOP lower bound	SPSC	CSI assumption	Analytical form	Validation
[19]	Generalized-Gamma main and eavesdropping links	No	No	Yes	Yes	Full CSI of both links at the source	Closed-form SOP lower bound and SPSC	Monte Carlo
[16]	Independent Fisher-Snedecor F composite-fading links	Yes	Yes	No	Yes	Eve CSI known at the source for ASC; no Eve CSI assumed for SOP	Exact and asymptotic expressions	Monte Carlo
[12]	IFTR legitimate link with a general eavesdropping channel, including IFTR	No	Yes	No	Evaluated	Outage formulation; no full-CSI assumption stated	Gamma-mixture/GMGF-based exact and high-SNR secrecy-outage results	Numerical and Monte Carlo
This work	Independent IFTR legitimate and eavesdropping links	Yes	Available in [12]	Yes	Exact corollary of the proposed bound	Full CSI assumed for ASC	Closed-form series expressions	Numerical and simulation verification

Accordingly, the principal analytical contribution of this work is a closed-form expression for the ASC when the legitimate and eavesdropping links independently follow IFTR fading. A closed-form lower bound on the SOP is also derived for the same wiretap setting. The exact SOP available in [12] is not claimed as a new result and is used only as a reference for comparison. The SPSC then follows as an exact corollary of the proposed SOP bound and is therefore not presented as a separate analytical contribution. The derived expressions are evaluated numerically and verified through simulation to examine the effect of the underlying fading conditions on secrecy performance.

The remainder of this paper is organized as follows. *Section 2* describes the system model and the IFTR fading channel. *Section 3* presents the secrecy performance analysis. *Section 4* provides numerical and simulation results the selected IFTR configurations. Finally, *Section 5* concludes the paper.

2. SYSTEM MODEL

In this section, we consider the well-established SISO Wyner's wiretap channel [13], which serves as the cornerstone in physical layer security research, including applications to underwater acoustic communications [4]–[10]. In the considered model, Alice and Bob denote the legitimate transmitter and receiver, respectively, whereas Eve denotes the eavesdropper. The Alice → Bob link represents the main channel, whereas the Alice → Eve link represents the wiretap channel. During transmission, Alice sends a confidential message to Bob, and Eve observes the signal received over the Alice → Eve link and attempts to decode it. Since Eve only listens to the transmitted signal and does not transmit or interfere with the legitimate communication, she is treated as a passive eavesdropper. Both the Alice → Bob and Alice → Eve channels are assumed to undergo independent IFTR fading. For the ASC analysis, Alice is assumed to have perfect instantaneous CSI of both links. This assumption is adopted as

a full-CSI analytical benchmark rather than as a specific CSI-acquisition model. In practical wiretap settings, however, the CSI of the eavesdropping link may be unavailable, imperfect, or outdated. Such CSI uncertainty is not considered here and therefore represents a limitation of the present full-CSI analysis. The present formulation provides a statistical fading representation of the UAC links rather than a complete physical model of underwater propagation. The IFTR model is used to characterize small-scale fading arising from two independently fluctuating dominant components and diffuse scattering. Large-scale attenuation, absorption, Doppler effects, delay spread, frequency selectivity, and interference are not modeled explicitly in the present analysis.

2.1. IFTR Channel Model

The IFTR fading distribution represents a class of fading environments characterized by two independently fluctuating dominant components, along with a scattered component that follows a complex Gaussian distribution [14]. The instantaneous signal-to-noise ratio (SNR) under IFTR fading is statistically characterized through its probability density function (PDF) and cumulative distribution function (CDF), which are given in [12] by:

$$f_i(\gamma_i) = \sum_{j_i=0}^{\infty} \frac{A_{j_i} \gamma_i^{j_i}}{\Gamma(j_i+1) \left(\frac{\gamma_i}{1+K_i}\right)^{j_i+1}} \exp\left(-\frac{(1+K_i)}{\gamma_i} \gamma_i\right) \quad (1)$$

$$F_i(\gamma_i) = \sum_{j_i=0}^{\infty} \frac{A_{j_i}}{\Gamma(j_i+1)} \gamma_{inc}\left(j_i + 1, \frac{(1+K_i)}{\gamma_i} \gamma_i\right) \quad (2)$$

where,

$$\begin{aligned} A_{j_i} &= \sum_{k=0}^{j_i} \binom{j_i}{k} \sum_{p=0}^{j_i-k} \binom{j_i-k}{p} \frac{K_{1_i}^p K_{2_i}^{j_i-k-p}}{j_i!} \sum_{l=0}^k \binom{k}{l} \frac{m_{1_i}^{m_{1_i}} m_{2_i}^{m_{2_i}} (-1)^k}{\Gamma(m_{1_i}) \Gamma(m_{2_i})} \\ &\times \frac{\Gamma(m_{1_i} + p + l)}{(K_{1_i} + m_{1_i})^{m_{1_i}+p+l}} \frac{\Gamma(m_{2_i} + j_i - k - p + l)}{(K_{2_i} + m_{2_i})^{m_{2_i}+j_i-k-p+l}} \\ &\times \left(\frac{K_i \Delta_i}{2}\right)^{2l} {}_2\tilde{F}_1\left(m_{1_i} + p + l, m_{2_i} + j_i - k - p + l, 2l - k + 1; \frac{K_i \Delta_i^2}{4(K_{1_i} + m_{1_i})(K_{2_i} + m_{2_i})}\right) \end{aligned} \quad (3)$$

$$\text{where } K_{1_i} = \frac{K_i(1 + \sqrt{1 - \Delta_i^2})}{2} \text{ and } K_{2_i} = K_i(1 - \sqrt{1 - \Delta_i^2})/2.$$

Here, $i \in \{b, e\}$, where $i = b$ and $i = e$ denote the Alice $\rightarrow$ Bob or Alice $\rightarrow$ Eve channel, respectively. Moreover, the parameters m_{1_i} and m_{2_i} represent the fading severities of the first and second dominant components, respectively, whereas K_i is the Rician factor. In addition, Δ_i quantifies the similarity between the dominant components, and γ_i denotes the average SNR. Furthermore, $\gamma_{inc}(\cdot)$ denotes the lower incomplete gamma function [15], and $\Gamma(\cdot)$ represents the Gamma function [15]. Finally, the function ${}_2\tilde{F}_1(\cdot, \cdot; \cdot; \cdot)$ stands for the regularized Gauss hypergeometric function.

3. PLS PERFORMANCE ANALYSIS UNDER IFTR FADING CHANNELS

3.1. ASC Analysis

Following the full-CSI setting considered in [16] and described in section 2, the ASC is evaluated with the channel conditions of both the legitimate and eavesdropping links available at the transmitter. Accordingly, the instantaneous secrecy capacity is written as [17]

$$C_s(\gamma_b, \gamma_e) = [C_b - C_e]^+, \quad (4)$$

where $[x]^+ = \max\{x, 0\}$. C_b and C_e indicate the channel capacities of the Alice $\rightarrow$ Bob and Alice $\rightarrow$ Eve channels, respectively, and can be expressed as

$$C_b = \log_2(1 + \gamma_b). \quad (5)$$

$$C_e = \log_2(1 + \gamma_e). \quad (6)$$

Accordingly, C_b , C_e , and C_s are expressed in bit/s/Hz.

Since the main and wiretap channels are statistically independent, the average secrecy capacity (ASC), denoted by $\bar{C}_s$, is obtained by averaging the positive instantaneous secrecy capacity over the joint distribution of the two links as,

$$\begin{aligned} \bar{C}_s &= \int_0^\infty \int_0^\infty C_s(\gamma_b, \gamma_e) f(\gamma_b, \gamma_e) d\gamma_e d\gamma_b \\ &= \frac{1}{\ln 2} \left[\underbrace{\int_0^\infty \ln(1 + \gamma_b) f_b(\gamma_b) F_e(\gamma_b) d\gamma_b}_{I_1} \right. \\ &\quad + \underbrace{\int_0^\infty \ln(1 + \gamma_e) f_e(\gamma_e) F_b(\gamma_e) d\gamma_e}_{I_2} \\ &\quad \left. - \underbrace{\int_0^\infty \ln(1 + \gamma_e) f_e(\gamma_e) d\gamma_e}_{I_3} \right], \end{aligned} \quad (7)$$

where $f(\gamma_b, \gamma_e) = f_b(\gamma_b) f_e(\gamma_e)$ indicates the joint pdf of γ_b and γ_e . Inserting eqs. (1) and (2) into eq. (7), the ASC under IFTR fading channels is obtained as stated in the following theorem.

Theorem 1. The ASC for the considered independent IFTR links is given by.

$$\begin{aligned} \text{ASC} = \bar{C}_s &= \frac{1}{\ln 2} \left[\sum_{j_b=0}^{\infty} \sum_{j_e=0}^{\infty} A_{j_b} A_{j_e} \left\{ \frac{s(j_b+1, \frac{1+K_b}{\gamma_b})}{\Gamma(j_b+1) \left(\frac{\gamma_b}{1+K_b}\right)^{j_b+1}} + \right. \right. \\ &\quad \frac{s(j_e+1, \frac{1+K_e}{\gamma_e})}{\Gamma(j_e+1) \left(\frac{\gamma_e}{1+K_e}\right)^{j_e+1}} - \sum_{n=0}^{j_e} \frac{s(j_b+n+1, \frac{\gamma_b(1+K_e)+\gamma_e(1+K_b)}{\gamma_b \gamma_e})}{n! \left(\frac{\gamma_b}{1+K_b}\right)^{j_b+1}} \frac{\left(\frac{1+K_e}{\gamma_e}\right)^n}{\Gamma(j_b+1)} \\ &\quad \left. - \sum_{n=0}^{j_b} \frac{s(j_e+n+1, \frac{\gamma_b(1+K_e)+\gamma_e(1+K_b)}{\gamma_b \gamma_e})}{n! \Gamma(j_e+1) \left(\frac{\gamma_e}{1+K_e}\right)^{j_e+1}} \left(\frac{1+K_b}{\gamma_b}\right)^n \right\} - \\ &\quad \left. \sum_{j_e=0}^{\infty} A_{j_e} \frac{s(j_e+1, \frac{1+K_e}{\gamma_e})}{\Gamma(j_e+1) \left(\frac{\gamma_e}{1+K_e}\right)^{j_e+1}} \right] \end{aligned} \quad (8)$$

Where,

$$S(\alpha, \beta) \triangleq (\alpha - 1)! \exp(\beta) \sum_{k=1}^{\alpha} \frac{\Gamma(k-\alpha, \beta)}{\beta^k} \quad (9)$$

Here, α is a positive integer, $\beta > 0$, and $\Gamma(a, x)$ denotes the upper incomplete gamma function.

Proof: See Appendix A.

For numerical evaluation, the infinite series in eq. (8) are truncated according to a prescribed convergence criterion. The adopted truncation limit, numerical tolerance, convergence behavior, and computational requirements are examined in section 4.

3.2. SOP Analysis

The secrecy outage probability is an essential metric for assessing secrecy performance. It represents the likelihood that the instantaneous secrecy capacity C_s of the considered channels does not satisfy a target rate R_s . Thus, the SOP is given in [18] as

$$\begin{aligned} SOP &= P\{C_s(\gamma_b, \gamma_e) < R_s\} \\ &= P\{\gamma_b < \Psi\gamma_e + \Psi - 1\} \\ &= \int_0^\infty f_e(\gamma_e) F_b(\Psi\gamma_e + \Psi - 1) d\gamma_e, \end{aligned} \quad (10)$$

where $R_s \geq 0$ represents the target secrecy rate in bit/s/Hz, and $\Psi \triangleq 2^{R_s}$. Since $R_s \geq 0$ gives $\Psi \geq 1$, the argument of the CDF in (10) satisfies $\Psi\gamma_e \leq \Psi\gamma_e + \Psi - 1$. Following [19], a lower bound on the SOP can therefore be written as

$$SOP_L = P\{\gamma_b < \Psi\gamma_e\} = \int_0^\infty f_e(\gamma_e) F_b(\Psi\gamma_e) d\gamma_e \leq SOP \quad (11)$$

Substituting the IFTR PDF and CDF in eq. (1) and eq. (2) into eq. (11) leads to the closed-form expression stated in the following theorem.

Theorem 2. The SOP lower bound, SOP_L , for the considered IFTR wiretap channels is given by

$$\begin{aligned} SOP_L &= \sum_{j_b=0}^{\infty} \sum_{j_e=0}^{\infty} \frac{A_{j_b} A_{j_e} \Gamma(j_b + j_e + 2)}{\Gamma(j_b + 1) \Gamma(j_e + 1) \left(\frac{\gamma_e}{(1+K_e)}\right)^{j_e+1} (j_b + 1) \left(\frac{\Psi(1+K_b)}{\gamma_b} + \frac{(1+K_e)}{\gamma_e}\right)^{j_b+j_e+2}} \\ &\quad \times {}_2F_1\left(1, j_b + j_e + 2; j_b + 2; \frac{\frac{\Psi(1+K_b)}{\gamma_b}}{\frac{\Psi(1+K_b)}{\gamma_b} + \frac{(1+K_e)}{\gamma_e}}\right) \end{aligned} \quad (12)$$

where ${}_2F_1(\cdot, \cdot; \cdot; \cdot)$ denotes the Gaussian (or Gauss) hypergeometric function [15].

Proof: See Appendix B

3.3. SPSC Analysis

Positive secrecy is achieved when Bob's instantaneous channel capacity exceeds that of Eve. Accordingly, following [18], the SPSC can be expressed as

$$SPSC = P\{C_s(\gamma_b, \gamma_e) > 0\} = 1 - SOP|_{R_s=0} \quad (13)$$

For $R_s = 0$, we have $\Psi = 2^{R_s} = 1$. In this case, the outage conditions in eqs. (10) and (11) both reduce to $\gamma_b < \gamma_e$, and hence $SOP_L = SOP$. Therefore, $SPSC = 1 - SOP|_{R_s=0}$, and the exact SPSC follows from eq. (12) by setting $\Psi = 1$. Since SPSC over IFTR fading has already been considered in [12], it is treated here as an exact special case of the derived SOP lower bound rather than as a separate contribution.

4. NUMERICAL RESULTS AND DISCUSSION

In this section, we present numerical results that characterize both the ASC and SPSC of underwater acoustic communications under IFTR fading channels. Three representative IFTR parameter configurations, referred to as the shallow-water, deep-water, and UWSN cases, are considered. Their parameter values and selection basis are summarized in table 2. These configurations are used for numerical comparison and are not obtained by fitting a particular underwater measurement campaign. Therefore, the scenario labels are used only to distinguish the selected IFTR parameter sets. In the IFTR model, m_1 and m_2 govern the fluctuations of the two dominant components, K represents their power relative to the diffuse component, and Δ indicates their similarity. For figures 1–6, $\bar{\gamma}_b$ is varied from 0 to 30 dB, whereas $\bar{\gamma}_e = \{3, 6, 9\}$ dB. For numerical evaluation, all SNR values expressed in dB are converted to their corresponding linear values before being substituted into the analytical expressions. The accuracy and convergence of the derived ASC expression are first examined in section 4.1.

Table 2. Representative IFTR configurations used in the numerical analysis

Case	Bob ($m_{1b}, m_{2b}, K_b, \Delta_b$)	Eve ($m_{1e}, m_{2e}, K_e, \Delta_e$)	Selection basis
Shallow-water	(5,7,8,0.4)	(3,4,3,0.5)	Distinct Bob and Eve fading conditions
Deep-water	(25,15,12,0.5)	(10,5,4,0.6)	Larger m_{1b}, m_{2b} , and K for the Bob link
UWSN	(6,6,9,0.5)	(5,3,4,0.5)	Unequal Bob and Eve IFTR conditions

Note: The parameter sets are author-selected representative statistical configurations for numerical comparison and are not obtained from a specific underwater measurement campaign.

4.1. Numerical Validation and Convergence Analysis of the ASC

The ASC expression in eq. (8) was verified by direct numerical integration of eq. (7) and by a Monte Carlo simulation generated independently of the analytical expressions. The simulation generates the two independently fluctuating specular components together with the diffuse

Gaussian component, using 10^7 realizations for each parameter set. The Bob and Eve channels were generated independently from the physical IFTR model using Gamma-distributed specular fluctuations, uniformly distributed phases, and a circular complex Gaussian diffuse component. A fixed pseudorandom sequence was used for reproducibility, and convergence was assessed through the corresponding 95% confidence intervals. Table 3 shows close agreement among the three approaches. The maximum absolute and relative differences between eq. (7) and eq. (8) are 2.216×10^{-9} bit/s/Hz and 2.925×10^{-10} , respectively, whereas the maximum Monte Carlo deviation is 1.336×10^{-3} (0.1336%). The analytical values also lie within the corresponding 95% confidence intervals.

The convergence of eq. (8) was further examined for $J = 40, 50, 60$ and 70 using the criterion $|\bar{C}_s^{(J)} - \bar{C}_s^{(J-10)}| \leq 10^{-8} + 10^{-5} |\bar{C}_s^{(J)}|$. As listed in table 4, the maximum relative change decreases from 6.8815×10^{-3} for $J = 40 \rightarrow 50$ to 1.7894×10^{-4} for $J = 50 \rightarrow 60$, and finally to 3.7721×10^{-6} for $J = 60 \rightarrow 70$. Hence, $J = 70$ is used in the remaining numerical evaluations.

The computations were carried out in Mathematica 13.3.1 using 25-digit working precision and accuracy and precision goals of 8. The IFTR coefficients were computed once and reused, whereas the required incomplete gamma and regularized hypergeometric functions were evaluated at arbitrary precision. The evaluation time of eq. (8) was about 0.044 to 0.058 s per point, compared with 0.085 to 0.117 s for direct numerical integration of eq. (7).

Table 3. Comparison of ASC obtained from numerical integration of (7), closed-form (8), and Monte Carlo simulation for $\gamma_e = 6$ dB

Scenario	Bob SNR (dB)	Eq. (7) Quadrature	Eq. (8) Closed-form	Monte Carlo	MC - Eq. (7)	Relative error
Shallow-water	0	0.08187001	0.08187001	0.08189656	2.6551×10^{-5}	3.2431×10^{-4}
Shallow-water	15	2.70672128	2.70672128	2.70660602	1.1526×10^{-4}	4.2584×10^{-5}
Shallow-water	30	7.57604788	7.57604788	7.57595578	9.2106×10^{-5}	1.2158×10^{-5}
Deep-water	0	0.05965703	0.05965703	0.05970641	4.9378×10^{-5}	8.2770×10^{-4}
Deep-water	15	2.74218443	2.74218443	2.74221742	3.2989×10^{-5}	1.2030×10^{-5}
Deep-water	30	7.65014722	7.65014722	7.65015410	6.8801×10^{-6}	8.9934×10^{-7}
UWSN	0	0.06496457	0.06496457	0.06487777	8.6802×10^{-5}	1.3362×10^{-3}
UWSN	15	2.66512416	2.66512416	2.66579410	6.6994×10^{-4}	2.5137×10^{-4}
UWSN	30	7.53636161	7.53636161	7.53700473	6.4312×10^{-4}	8.5335×10^{-5}

Table 4. Convergence of the ASC in (8) for different series truncation orders

Case	Maximum absolute change (bit/s/Hz)	Maximum relative change
$J = 40$ to 50	7.9791×10^{-4}	6.8815×10^{-3}
$J = 50$ to 60	2.0674×10^{-5}	1.7894×10^{-4}
$J = 60$ to 70	4.3208×10^{-7}	3.7721×10^{-6}

4.2. Numerical Validation and Tightness of the SOP Lower Bound

The closed-form lower bound in eq. (12) was first checked against direct numerical integration of eq. (11) for the three IFTR configurations defined above. The comparison covers $\bar{\gamma}_b = \{0, 15, 30\}$ dB, $\bar{\gamma}_e = 6$ dB, and $R_s = \{0.1, 0.5, 1\}$ bit/s/Hz. Representative results from this comparison are listed in table 5. The two evaluations agree to numerical precision, with a maximum relative difference of 8.89×10^{-13} ; over the complete SNR grid, the difference remains below 1.745×10^{-12} . This independently verifies the evaluation of eq. (12).

The tightness of the bound was then examined against the exact SOP in eq. (10) for $\bar{\gamma}_b = 0$ to 30 dB and $\bar{\gamma}_e = \{3, 6, 9\}$ dB. The maximum percentage deviation is 4.25% for $R_s = 0.1$ bit/s/Hz and increases to 16.90% and 26.95% for $R_s = 0.5$ and 1 bit/s/Hz, respectively. Thus, the bound is particularly accurate at a low target secrecy rate, but becomes less accurate as R_s increases. A smaller deviation is also generally obtained for larger $\bar{\gamma}_e$.

Table 5. Numerical verification of the SOP lower bound in eq. (12) against direct integration of eq. (11)

Case	$\bar{\gamma}_b(\text{dB})$	$R_s(\text{bit/s/Hz})$	Eq. (11)	Eq. (12)	Relative error
Shallow	0	0.1	0.8496378061	0.8496378061	$< 10^{-15}$
Shallow	15	0.5	0.06343333154	0.06343333154	3.0×10^{-15}
Shallow	30	1	0.001257695255	0.001257695255	2.19×10^{-13}
Deep	0	1	0.9420296158	0.9420296158	$< 10^{-15}$
Deep	15	0.1	0.01982827628	0.01982827628	$< 10^{-15}$
Deep	30	0.5	0.0001154473275	0.0001154473275	4.30×10^{-13}
UWSN	0	0.5	0.9093866932	0.9093866932	$< 10^{-15}$
UWSN	15	1	0.1006528043	0.1006528043	$< 10^{-15}$
UWSN	30	0.1	0.0006292761584	0.0006292761584	8.15×10^{-13}

Figure 1. shows the ASC for the selected shallow-water IFTR configuration. The analytical and simulation results agree closely over the entire SNR range. At $\bar{\gamma}_b = 15\text{dB}$, the ASC decreases from 3.3188 to 2.0173 bit/s/Hz when $\bar{\gamma}_e$ increases from 3 to 9dB, which corresponds to a 39.22% loss. This loss is more pronounced at low $\bar{\gamma}_b$; it is 75.22% at 0dB and falls to 16.80% at 30dB. Thus, for the selected IFTR parameters, the influence of the Eve link becomes progressively smaller as the Bob link improves. Likewise, figure 2. presents the corresponding SPSC behavior. At $\bar{\gamma}_b = 15\text{dB}$, the SPSC decreases from 0.9853 to 0.8970 as $\bar{\gamma}_e$ increases from 3 to 9dB. More importantly, an SPSC above 0.9 is achieved at $\bar{\gamma}_b = 10, 13$ and 16dB for $\bar{\gamma}_e = 3, 6$ and 9dB, respectively. Hence, increasing the Eve SNR by 6dB requires about 6dB additional Bob SNR to maintain the same SPSC threshold. Moreover, the SPSC loss caused by the stronger Eve link drops from 74.41% at $\bar{\gamma}_b = 0\text{dB}$ to only 1.67% at 20dB. This further shows that, for the selected IFTR configuration, the effect of the Eve link is mainly pronounced in the low to moderate Bob-SNR region.

Figures 3 and 4 present the ASC and SPSC for the selected deep-water IFTR configuration, and the analytical and simulation results show close agreement. In figure 3, at $\bar{\gamma}_b = 15\text{dB}$, increasing $\bar{\gamma}_e = 3, 6$ and 9dB reduces the ASC from 3.3842 to 2.0096 bit/s/Hz, corresponding to a 40.62% loss. However, this loss falls to 17.06% at $\bar{\gamma}_b = 30\text{dB}$, indicating that the relative effect of the Eve link decreases as the Bob link improves. Likewise, figure 4 shows that at $\bar{\gamma}_b = 15\text{dB}$, the SPSC is 0.9956, 0.9828, and 0.9328 for $\bar{\gamma}_e = 3, 6$ and 9dB, respectively. More importantly, the SPSC threshold of 0.90 is reached at $\bar{\gamma}_b = 9, 12$ and 15dB for the three Eve SNR values, while an SPSC of 0.99 requires 14, 17, and 20dB. Thus, under the selected IFTR parameter configuration, increasing the Eve SNR shifts the required Bob SNR upward, while a sufficiently stronger Bob link substantially reduces its effect on the secrecy performance.

Figures 5 and 6 present the ASC and SPSC for the selected UWSN IFTR configuration, respectively. The analytical and simulation results show close agreement over the considered SNR range. In figure 5, at $\bar{\gamma}_b = 15\text{dB}$, the ASC decreases from 3.2936 to 1.9577 bit/s/Hz when $\bar{\gamma}_e$ increases from 3 to 9dB, corresponding to a 40.56% reduction. This reduction falls to 17.23% at $\bar{\gamma}_b = 30\text{dB}$, indicating that the relative effect of the Eve link becomes smaller as the Bob link improves. Likewise, figure 6 shows that at $\bar{\gamma}_b = 15\text{dB}$, the SPSC is 0.9859, 0.9628, and 0.8997 for $\bar{\gamma}_e = 3, 6$, and 9 dB, respectively. An SPSC of 0.90 is reached at $\bar{\gamma}_b = 10, 13$, and 16dB for the three Eve SNR values, whereas an SPSC of 0.99 requires 17, 20, and 23dB, respectively. Thus, a 3dB increase in Eve SNR shifts the required Bob SNR by approximately 3dB for the same SPSC threshold. These results describe the behavior of the selected statistical IFTR configuration and should not be interpreted as representative of all practical UWSN deployments.

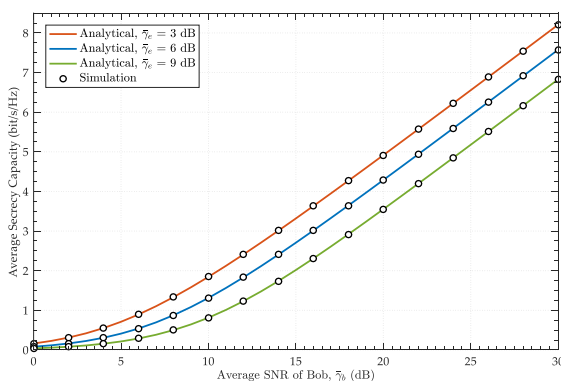


Figure 1. ASC for the selected shallow-water IFTR configuration versus $\bar{\gamma}_b$ for $\bar{\gamma}_e = 3, 6$ and 9dB

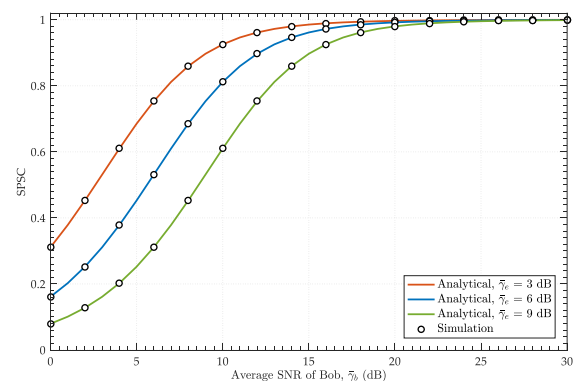


Figure 2. SPSC for the selected shallow-water IFTR configuration versus $\bar{\gamma}_b$ for $\bar{\gamma}_e = 3, 6$ and 9dB

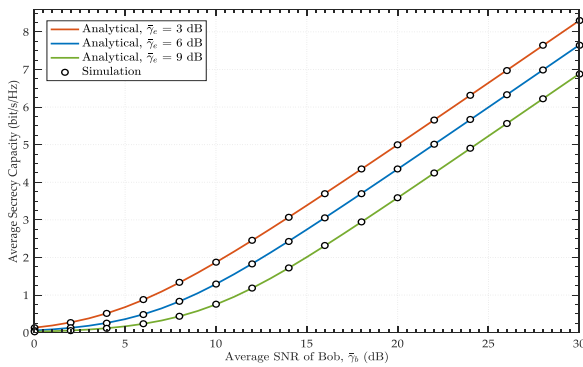


Figure 3. ASC for the selected deep-water IFTR configuration versus γ_b for $\gamma_e = 3, 6$ and 9 dB

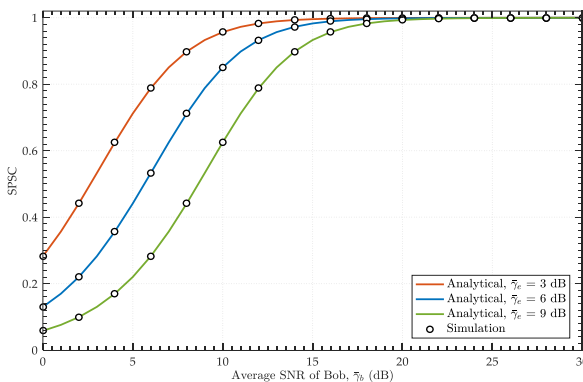


Figure 4. SPSC for the selected deep-water IFTR configuration versus γ_b for $\gamma_e = 3, 6$ and 9 dB

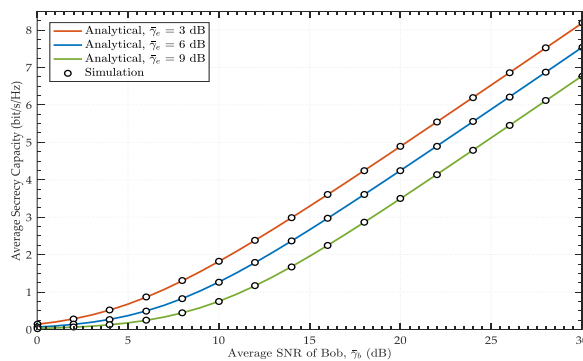


Figure 5. ASC for the selected UWSN IFTR configuration versus γ_b for $\gamma_e = 3, 6$ and 9 dB

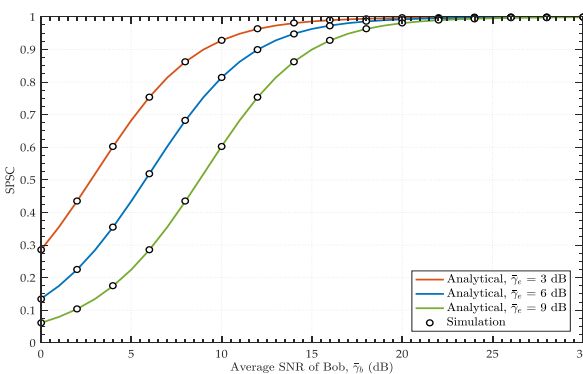


Figure 6. SPSC for the selected UWSN IFTR configuration versus γ_b for $\gamma_e = 3, 6$ and 9 dB

To further examine the influence of the IFTR parameters, a sensitivity analysis was carried out using the shallow-water configuration as the reference, with each Bob parameter varied separately while the remaining parameters were kept fixed.

At $\gamma_b = 15$ dB and $\gamma_e = 6$ dB, increasing m_{1b} from 3 to 10 raises the ASC from 2.6485 to 2.7540 bit/s/Hz and the SPSC from 0.9472 to 0.9723. Likewise, K_b increasing from 3 to 10 raises the ASC from 2.6011 to 2.7250 bit/s/Hz and the SPSC from 0.9325 to 0.9662.

In contrast, increasing Δ_b from 0.1 to 0.5 reduces the ASC from 2.7408 to 2.6858 bit/s/Hz and the SPSC from 0.9702 to 0.9557. The effect of m_{2b} is comparatively small for the selected parameter set. Despite these variations, the secrecy performance continues to improve as γ_b increases.

For comparison with the exact SOP reported in [12], the parameter setting used in [12] is adopted. Thus, both the Bob and Eve links use $(m_{1b} = m_{1e} = 25.5)$, $(m_{2b} = m_{2e} = 7.5)$, $(K_b = K_e = 10)$, and $(\Delta_b = \Delta_e = 0.1)$, with $R_s = 0.1$. Bob's average SNR is varied from -10 to 30 dB, whereas Eve's average SNR is set to the linear values $\gamma_e = \{0.1, 1, 10\}$, as considered in [12]. For the numerical evaluation, Bob's SNR values expressed in dB are converted to linear scale, while the Eve SNR values are used directly.

Figure 7 compares the exact SOP in [12] with the proposed SOP_L and the simulation results. The analytical SOP_L and simulation results agree closely. As summarized in table 6, the maximum deviation is 1.31% for $\gamma_e = 10$, 12.15% for $\gamma_e = 1$, and 67.23% for $\gamma_e = 0.1$. The corresponding maximum absolute differences are 4.561×10^{-3} , 4.446×10^{-2} and 3.631×10^{-1} , respectively.

The sensitivity of the bound to m_{1b} , m_{2b} , K_b , and Δ_b is further examined in table 7 for $R_s = 0.1$ bit/s/Hz and $\gamma_e = 1$, with one Bob parameter varied at a time. Across the tested cases, the maximum absolute difference does not exceed 4.869×10^{-2} and falls below 10^{-2} from about 5 to 7 dB onward. The largest change in relative deviation is observed for K_b , while m_{2b} has little effect. No violation of $SOP_L \leq SOP$ is observed. These results show that the bound accuracy depends on the Eve SNR and the IFTR parameters, while its absolute error becomes small at moderate and high Bob SNRs.

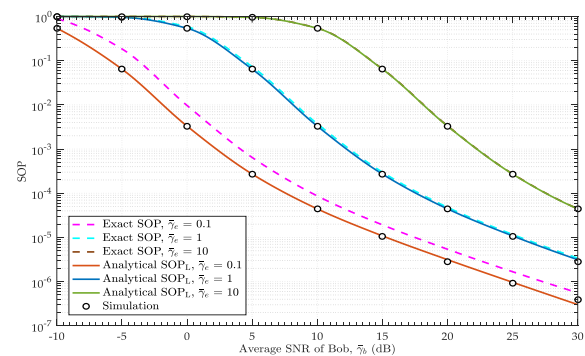


Figure 7. SOP_L under IFTR fading channels versus γ_b for different values of γ_e , compared with the exact SOP

Table 6. Tightness of the proposed SOP_L for the benchmark considered in fig. 7

$\bar{\gamma}_e$ (linear)	Max. abs. diff.	Bob SNR at max. abs. diff. (dB)	Max. dev. (%)	Bob SNR at max. dev. (dB)
0.1	3.631×10^{-1}	-9	67.23	-2
1	4.446×10^{-2}	-1	12.15	7
10	4.561×10^{-3}	9	1.31	17

Table 7. Sensitivity of the proposed SOP_L to the Bob IFTR parameters

Varied parameter	Values tested	Max. abs. diff.	Max. dev. (%)	Bob SNR from which abs. diff. $\leq$ 0.01 (dB)
m_{1b}	5, 15, 25.5	4.446×10^{-2}	12.15	6
m_{2b}	3, 7.5, 15	4.446×10^{-2}	12.15	5
K_b	3, 10, 20	4.869×10^{-2}	30.42	6
Δ_b	0.1, 0.5, 0.9	4.446×10^{-2}	12.15	7

5. CONCLUSION

In this paper, the secrecy performance of independent IFTR legitimate and eavesdropping links was analyzed. A closed-form expression for the ASC was derived, which constitutes the main analytical contribution of this work. A closed-form lower bound on the SOP was also obtained, while the SPSC follows as an exact corollary when the target secrecy rate is zero. The ASC expression was verified through direct numerical integration and independent Monte Carlo simulation, with a maximum simulation deviation of 0.1336%. The convergence of the infinite series was also examined, and $J = 70$ was found sufficient for the numerical evaluations. The proposed SOP lower bound was independently verified against its defining integral and compared with the exact SOP. For the representative IFTR configurations, the results show that the bound is particularly accurate at low target secrecy rates, while its accuracy depends on the Eve SNR and the IFTR parameters. The parameter analysis further shows that m_{1b} , K_b , and Δ_b can noticeably affect the secrecy performance, whereas the influence of m_{2b} is comparatively small for the selected parameter set. The present study considers a SISO wiretap model under a full-CSI benchmark and uses representative statistical IFTR parameter sets. Measurement-based validation and the explicit effects of path loss, Doppler, frequency selectivity, and interference are beyond the scope of this work.

Appendix A. Proof of Theorem 1

The proof follows by evaluating the three terms I_1 , I_2 , and I_3 in eq. (7). Here, j_b and j_e denote the IFTR mixture indices of the Bob and Eve links, respectively, while n denotes the finite-sum index introduced by the incomplete gamma expansion. For a

nonnegative integer j_i , $\Gamma(j_i + 1) = j_i!$ [15]. Since the capacities in eqs. (5) and (6) are written using $\log_2(\cdot)$, we use $\log_2(1+x) = \ln(1+x)/\ln 2$, which gives $\bar{C}_s = (I_1 + I_2 - I_3)/\ln 2$. We then substitute eq. (1) and eq. (2) into I_1 and simplify the resulting integral using the finite-series form of the lower incomplete gamma function.

$$I_1 = \sum_{j_b=0}^{\infty} \sum_{j_e=0}^{\infty} \frac{A_{j_b} A_{j_e}}{\Gamma(j_b+1) \Gamma(j_e+1) \left(\frac{\bar{\gamma}_b}{(1+K_b)}\right)^{j_b+1}} \int_0^{\infty} \ln(1+\gamma_b) \gamma_b^{j_b} e^{-\gamma_b \left(\frac{(1+K_b)}{\bar{\gamma}_b}\right)} \gamma_{inc} \left(j_e+1, \frac{(1+K_e)}{\bar{\gamma}_e} \gamma_b\right) d\gamma_b, \quad (14)$$

Since j_e is a nonnegative integer, the lower incomplete gamma function in eq. (14) can be expanded using [15] as

$$\gamma_{inc} \left(j_e+1, \frac{(1+K_e)}{\bar{\gamma}_e} \gamma_b\right) = j_e! \left(1 - \sum_{n=0}^{j_e} \left(\frac{(1+K_e)}{\bar{\gamma}_e} \gamma_b\right)^n \frac{1}{n!} \exp\left(-\frac{(1+K_e)}{\bar{\gamma}_e} \gamma_b\right)\right). \quad (15)$$

Substituting eq. (15) into I_{inner} and writing the resulting integral as $S(\alpha, \beta) = \int_0^{\infty} \ln(1+u) u^{\alpha-1} \exp(-\beta u) du$, we obtain

$$I_{inner} = j_e! S\left(j_b+1, \frac{(1+K_b)}{\bar{\gamma}_b}\right) - \sum_{n=0}^{j_e} \left(\frac{(1+K_e)}{\bar{\gamma}_e}\right)^n \frac{j_e!}{n!} S\left(j_b+n+1, \frac{\bar{\gamma}_e(1+K_b) + \bar{\gamma}_b(1+K_e)}{\bar{\gamma}_e \bar{\gamma}_b}\right) \quad (16)$$

For the terms appearing in eq. (16), the first argument of $S(\alpha, \beta)$ is a positive integer, for which the finite-sum representation in eq. (9) applies [20]. Substituting eq. (16) into eq. (14) then gives

$$I_1 = \sum_{j_b=0}^{\infty} \sum_{j_e=0}^{\infty} A_{j_b} A_{j_e} \left(\frac{S\left(j_b+1, \frac{(1+K_b)}{\bar{\gamma}_b}\right)}{\Gamma(j_b+1) \left(\frac{\bar{\gamma}_b}{(1+K_b)}\right)^{j_b+1}} - \sum_{n=0}^{j_e} \frac{\left(\frac{(1+K_e)}{\bar{\gamma}_e}\right)^n}{n!} \frac{S\left(j_b+n+1, \frac{\bar{\gamma}_b(1+K_e) + \bar{\gamma}_e(1+K_b)}{\bar{\gamma}_b \bar{\gamma}_e}\right)}{\Gamma(j_b+1) \left(\frac{\bar{\gamma}_b}{(1+K_b)}\right)^{j_b+1}} \right). \quad (17)$$

Applying the same procedure to I_2 gives

$$I_2 = \sum_{j_b=0}^{\infty} \sum_{j_e=0}^{\infty} A_{j_b} A_{j_e} \left(\frac{S\left(j_e+1, \frac{(1+K_e)}{\bar{\gamma}_e}\right)}{\Gamma(j_e+1) \left(\frac{\bar{\gamma}_e}{(1+K_e)}\right)^{j_e+1}} - \sum_{n=0}^{j_b} \frac{\left(\frac{(1+K_b)}{\bar{\gamma}_b}\right)^n}{n!} \frac{S\left(j_e+n+1, \frac{\bar{\gamma}_b(1+K_e) + \bar{\gamma}_e(1+K_b)}{\bar{\gamma}_b \bar{\gamma}_e}\right)}{\Gamma(j_e+1) \left(\frac{\bar{\gamma}_e}{(1+K_e)}\right)^{j_e+1}} \right). \quad (18)$$

The term I_3 contains only the Eve-link PDF and is obtained directly from the definition of $S(\alpha, \beta)$ as

$$I_3 = \sum_{j_e=0}^{\infty} A_{j_e} \frac{S\left(j_e+1, \frac{(1+K_e)}{\bar{\gamma}_e}\right)}{\Gamma(j_e+1) \left(\frac{\bar{\gamma}_e}{(1+K_e)}\right)^{j_e+1}}. \quad (19)$$

Finally, substituting eq. (17), (18) and (19) into $\bar{C}_s = (I_1 + I_2 - I_3)/\ln 2$ gives the ASC expression in eq. (8), which completes the proof. The truncation of the infinite sums is discussed in section 4.1.

Appendix B. Proof of Theorem 2

The proof begins with the integral form of SOP_L in eq. (11). Substituting the IFTR PDF and CDF gives eq. (20), where the remaining integral I_4 is evaluated using [15]. Substituting this result into eq. (20) yields eq. (12). Here, j_b and j_e denote the mixture indices of the Bob and Eve links, respectively, and both take nonnegative integer values. The series truncation and numerical verification are discussed in section 4.2.

On inserting eq. (1) and (2) into (11), the lower bound expression becomes

$$SOP_L = \sum_{j_b=0}^{\infty} \sum_{j_e=0}^{\infty} \frac{A_{j_b} A_{j_e}}{\Gamma(j_b+1) \Gamma(j_e+1)} \left(\frac{\gamma_e}{1+K_e} \right)^{-(j_e+1)} \int_0^{\infty} \underbrace{\gamma_e^{j_e} e^{-\gamma_e \left(\frac{1+K_e}{\gamma_e} \right)} \gamma_{inc} \left(j_b+1, \frac{\psi(1+K_b)}{\gamma_b} \gamma_e \right)}_{I_4} d\gamma_e \quad (20)$$

The remaining integral I_4 is evaluated with the integral identity in [15], leading to

$$I_4 = \frac{\Gamma(j_b+j_e+2) \left(\frac{\psi(1+K_b)}{\gamma_b} \right)^{j_b+1}}{(j_b+1) \left(\frac{\psi \gamma_e(1+K_b) + \gamma_b(1+K_e)}{\gamma_b \gamma_e} \right)^{j_e+j_b+2}} \times {}_2F_1 \left(1, j_b + j_e + 2; j_b + 2; \frac{\psi \gamma_e(1+K_b)}{\psi \gamma_e(1+K_b) + \gamma_b(1+K_e)} \right) \quad (21)$$

Inserting eq. (21) back into eq. (20) results in the closed-form SOP_L expression stated in eq. (12), completing the proof.

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