

Secure hybrid power-frequency multiple access in satellite terrestrial communication systems: a performance study

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Article Info

Article history:

Received Jan 3, 2025

Revised Oct 29, 2025

Accepted Dec 8, 2025

Keywords:

Hybrid power-frequency multiple access

Intercept probability

Outage probability

Satellite-terrestrial systems

Shadowed-Rician fading

ABSTRACT

This paper investigates a secure hybrid power-frequency multiple access (PFMA) framework for satellite-terrestrial communications. By integrating power- and frequency-domain multiplexing, PFMA achieves approximately 4 dB lower transmit signal-to-noise ratio (SNR) than non-orthogonal multiple access (NOMA) for the same connection outage probability (COP) at $\text{SNR} > 0$ dB, and it reduces the COP by up to 30% at low-to-medium SNRs. It further decreases the intercept probability (IP) by 20–25% at $P_S = 10$ dBm. Closed-form COP and IP expressions are derived under shadowed-Rician fading with both internal and external eavesdroppers and validated via Monte Carlo simulations. Parameter analysis indicates that PFMA's SNR gain can either extend coverage by 60% or save 37% energy, providing design guidelines for 6G, satellite IoT, and emergency communication systems. The single-cell assumption points to future work on multi-cell and mobility scenarios.

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1. INTRODUCTION

Satellite-terrestrial communication systems are a foundation for next-generation networks, enabling reliable and ubiquitous connectivity. Among multiple access techniques, hybrid power-frequency multiple access (HPFMA) combines power- and frequency-domain multiplexing to enhance spectral efficiency. However, its security and performance can be hindered by shared channels and the complexities of hybrid architectures [1], [2]. Existing studies have explored improvements via relay protocols, energy harvesting, intelligent reflecting surfaces (IRS), and spectrum sharing [3]–[10]. Secure HPFMA performance under realistic fading and dual eavesdropping scenarios is still underexplored. This work fills that gap via a comprehensive performance analysis of secure HPFMA in satellite-terrestrial systems, focusing on reliability-security trade-offs and design insights for 6G and satellite IoT.

Table 1 contrasts our work with prior studies. Unlike [11]–[13], which focus on non-orthogonal multiple access (NOMA) or simplified fading, we derive closed-form connection outage probability (COP) and intercept probability (IP) for power-factor multiple access (PFMA) under shadowed-Rician fading with both internal and external eavesdroppers. Contributions: (i) closed-form COP, IP, their asymptotics, and diversity order for PFMA under shadowed-Rician fading with both internal and external eavesdroppers; PFMA requires

≈ 4 dB lower SNR than NOMA for the same COP at $\text{SNR} > 0$ dB; (ii) Monte Carlo validation across diverse parameters, showing superior COP over NOMA at low-to-medium signal-to-noise ratio (SNR); and (iii) parameter study (power, antennas, shadowed-Rician parameters, bandwidth) revealing up to 60% coverage gain or 37% energy saving.

Table 1. Comparison with related works

Ref.	Model	Metrics	Channel	Eavesdropping	Limitations	Our contribution
[3]	NOMA	Secrecy rate	Rayleigh	External	No closed-form COP/IP	Closed-form COP and IP for PFMA
[4]	NOMA	Outage, ergodic capacity (EC)	Nakagami- m	None	Simplified fading	Shadowed-Rician, dual eavesdroppers
[13]	NOMA	COP	Rician	Internal	No external case	Dual eavesdroppers with PFMA
[14]	Partial-NOMA	Secrecy rate	Rayleigh	Internal	No frequency-domain analysis	Hybrid power-frequency, closed-form metrics
[15]	NOMA	IP	Rayleigh	Internal	Simplified channel	Shadowed-Rician with asymptotics
Ours	PFMA	COP, IP, diversity order (DO)	Shadowed-Rician	Internal and external	–	First closed-form COP/IP for PFMA; ~ 4 dB SNR gain over NOMA

2. SYSTEM MODEL

Consider Figure 1, where a satellite (S) employs three subcarriers (s_B, s_R, s_{RB}) to transmit the confidential signal x_R to Roy (R) and the secure signal x_B to Bob (B). Subcarriers s_B and s_R occupy bandwidth portions (BPs) α_B and α_R , respectively, and carry x_B and x_R using orthogonal multiple access (OMA). Meanwhile, a superposition signal $x_{RB} = \sqrt{\beta_R} x_R + \sqrt{\beta_B} x_B$ with power-allocation (PA) factors β_R, β_B corresponds to NOMA on s_{RB} with BP α_{RB} . Bob and Roy combine their received signals after baseband recovery without successive interference cancellation (SIC). The BP/PA rules are $\alpha_R + \alpha_B + \alpha_{RB} = 1$, $\beta_B + \beta_R = 1$, and $\alpha_{RB} \leq \alpha_B, \alpha_R$. Here, α_Q ($Q \in \{B, R\}$) denotes the OMA BPs, while α_{RB} is the PFMA superposition BP; β_B and β_R are NOMA PA factors. Unless stated otherwise, receivers are assumed to have perfect SIC when required by a scheme definition.

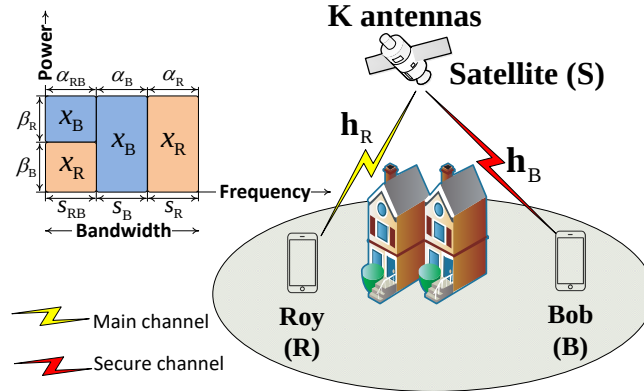


Figure 1. System model of hybrid PFMA in satellite-terrestrial communication

2.1. Propagation and beamforming

Roy acts as an internal eavesdropper and may use SIC to recover Bob's message. All channels $\mathbf{h}_Q$ are quasi-static shadowed-Rician with $Q \in \{R, B\}$. channel estimation errors (CEEs) render perfect channel state information (CSI) difficult; CSI is estimated via minimum mean square error (MMSE). The effective channel is:

$$\mathbf{h}_Q = \mathbf{g}_Q^\dagger \mathbf{w}_Q \sqrt{L_{SQ} \vartheta_S \vartheta(\theta_Q)} \quad (1)$$

Here, $\mathbf{g}_Q \in \mathbb{C}^{K \times 1}$ is the shadowed-Rician vector (S→Q), $\mathbf{w}_Q \in \mathbb{C}^{K \times 1}$ is maximum ratio transmission (MRT):

$$\mathbf{w}_Q = \frac{\mathbf{g}_Q}{\|\mathbf{g}_Q\|_F} \quad (2)$$

The free-space loss is:

$$L_{SQ} = \frac{1}{\mathcal{K}_B T W} \left(\frac{c}{4\pi f_c d_{SQ}} \right)^2 \quad (3)$$

with $\mathcal{K}_B = 1.38 \times 10^{-23}$ J/K, T the noise temperature, W the bandwidth, c the speed of light, f_c the carrier, and d_{SQ} the S–Q distance [16]. The satellite beam gain is:

$$\vartheta(\theta_Q) = \vartheta_Q \left(\frac{I_1(\bar{\rho}_Q)}{2\bar{\rho}_Q} + 36 \frac{I_3(\bar{\rho}_Q)}{\bar{\rho}_Q^3} \right) \quad (4)$$

where $I_i(\cdot)$ is the i th-order Bessel function (first kind), $\bar{\rho}_Q = 2.07123 \frac{\sin \theta_Q}{\sin \theta_{Q,3dB}}$, and $\theta_{Q,3dB}$ is the 3 dB beamwidth.

2.2. Signal processing at Q

The received baseband signal at $Q \in \{R, B\}$ is:

$$\bar{y}_Q = \begin{cases} \sqrt{\alpha_Q P_S L_{SQ} \vartheta_S \vartheta(\theta_Q)} x_Q \mathbf{g}_Q^\dagger \mathbf{w}_Q + n_Q, & s_Q \\ \sqrt{\alpha_{RB} P_S L_{SQ} \vartheta_S \vartheta(\theta_Q)} x_{RB} \mathbf{g}_Q^\dagger \mathbf{w}_Q + n_Q, & s_{RB} \end{cases} \quad (5)$$

where P_S is the satellite transmit power and $n_Q \sim \mathcal{CN}(0, \sigma_Q^2)$. Define $\nu_Q = \alpha_Q + \alpha_{RB} \beta_Q$ and $\mu_Q = \alpha_Q + \alpha_{RB}$. The aggregate SINR for decoding x_Q at Q is [17].

$$\bar{\gamma}_Q = \frac{\nu_Q \delta_Q \|\mathbf{g}_Q\|_F^2}{\nu_Q \delta_Q \|\mathbf{g}_Q\|_F^2 + \mu_Q} = \frac{\nu_Q \mathcal{A}_Q}{\nu_Q \mathcal{A}_Q + \mu_Q} \quad (6)$$

where $\varrho_S = P_S / \sigma_Q^2$ is the SNR, $\mathcal{A}_Q = \delta_Q \|\mathbf{g}_Q\|_F^2$, and $\delta_Q = \varrho_S L_{SQ} \vartheta_S \vartheta(\theta_Q)$. After canceling its own data via SIC, Roy tries to intercept x_B with:

$$\hat{\gamma}_R = \frac{\alpha_{RB} \beta_B \delta_R \|\mathbf{g}_R\|_F^2}{\mu_R} = \frac{\nu_R \mathcal{A}_R}{\mu_R} \quad (7)$$

2.3. Terrestrial channel model

Assuming i.i.d. coefficients, the probability density function (PDF) of $|g_Q^{(k)}|^2$ (S→Q, k th antenna) under shadowed-Rician fading is:

$$f_{|g_Q^{(k)}|^2}(x) = \alpha_Q e^{-\beta_Q x} {}_1F_1(m_Q; 1; \varpi_Q x), \quad x \geq 0 \quad (8)$$

with,

$$\alpha_Q = \left[\frac{2b_Q m_Q}{2b_Q m_Q + \Omega_Q} \right]^{m_Q} / (2b_Q), \quad \beta_Q = \frac{1}{2b_Q}, \quad \varpi_Q = \frac{\Omega_Q(2b_Q m_Q + \Omega_Q)}{2b_Q}$$

Here, Ω_Q (LOS power), $2b_Q$ (diffuse power), and m_Q (fading severity) follow [18]. For integer m_Q ,

$$f_{|g_Q^{(k)}|^2}(x) = \alpha_Q e^{-(\beta_Q - \varpi_Q)x} \sum_{t=0}^{m_Q-1} \zeta_Q(t) x^t, \quad \zeta_Q(t) = \frac{(-1)^t (1 - m_Q)_t \varpi_Q^t}{(t!)^2} \quad (9)$$

Using Bankey *et al.* [19], the PDF of $\mathcal{A}_Q$ is:

$$f_{\mathcal{A}_Q}(x) = \sum_{j_1=0}^{m_Q-1} \cdots \sum_{j_K=0}^{m_Q-1} \frac{\Lambda_Q(K)}{\delta_Q^{\Delta_Q}} x^{\Delta_Q-1} \exp\left(-\frac{\psi_Q}{\delta_Q} x\right) \quad (10)$$

where,

$$\Lambda_Q(K) = \alpha_Q^K \prod_{l=1}^K \zeta_Q(j_l) \prod_{u=1}^{K-1} \mathcal{B}\left(\sum_{p=1}^u j_p + u, j_{u+1} + 1\right), \Delta_Q = \sum_{l=1}^K j_l + K, \psi_Q = \beta_Q - \delta_Q \quad (11)$$

The cumulative distribution function (CDF) follows from ([18] (8.352.6)):

$$F_{\mathcal{A}_Q}(x) = 1 - \sum_{j_1=0}^{m_Q-1} \cdots \sum_{j_K=0}^{m_Q-1} \sum_{p=0}^{\Delta_Q-1} \frac{\Lambda_Q(K) \Gamma(\Delta_Q)}{p! \psi_Q^{\Delta_Q-p} \delta_Q^p} \exp\left(-\frac{\psi_Q x}{\delta_Q}\right) x^p \quad (12)$$

3. CONNECTION OUTAGE PERFORMANCE

Let R_B and R_R be the target rates. The capacity is $\mathcal{C}(\bar{\gamma}_Q) = \log_2(1 + \bar{\gamma}_Q)$. The COP is:

$$\begin{aligned} \text{COP} &= 1 - \Pr(\mathcal{C}(\bar{\gamma}_R) > R_R, \mathcal{C}(\bar{\gamma}_B) > R_B) \\ &= 1 - [1 - F_{\bar{\gamma}_R}(u_R)] [1 - F_{\bar{\gamma}_B}(u_B)] \end{aligned} \quad (13)$$

where $u_Q = 2^{R_Q} - 1$. We need $F_{\bar{\gamma}_Q}(x)$:

Theorem 1 Under uncorrelated shadowed-Rician fading, the CDF of $\bar{\gamma}_Q$ is:

$$F_{\bar{\gamma}_Q}(x) = 1 - \sum_{j_1=0}^{m_Q-1} \cdots \sum_{j_K=0}^{m_Q-1} \sum_{p=0}^{\Delta_Q-1} \frac{\Lambda_Q(K) \Gamma(\Delta_Q)}{p! \psi_Q^{\Delta_Q-p} \delta_Q^p} \exp\left(-\frac{\psi_Q \varsigma_Q x}{\delta_Q(\varepsilon_Q - x)}\right) \left(\frac{\varsigma_Q x}{\varepsilon_Q - x}\right)^p \quad (14)$$

valid for $0 \leq x < \varepsilon_Q$, where $\varepsilon_Q = \nu_Q/(\alpha_{RB}\beta_T)$ for $T \in \{R, B\}$, $T \neq Q$, and $\varsigma_Q = \mu_Q/(\alpha_{RB}\beta_T)$

Proof 1 Use $F_{\bar{\gamma}_Q}(x) = \Pr(\bar{\gamma}_Q < x)$ and (12)

Substituting (14) into (13) gives the exact COP:

$$\text{COP} = 1 - \prod_{Q \in \{R, B\}} [1 - F_{\bar{\gamma}_Q}(u_Q)] \quad (15)$$

Diversity order (high SNR). Following the high-SNR asymptotic expansion approach in [20], from (12), for $\rho_S \rightarrow \infty$, a Maclaurin expansion yields ([21], (51)).

$$F_{\mathcal{A}_Q}^\infty(x) \simeq \frac{\alpha_Q^K x^K}{K! \delta_Q^K} \quad (16)$$

Combining with (15), the asymptotic COP is:

$$\text{COP}^\infty = \frac{\alpha_Q^K}{K! \delta_Q^K} \left[\left(\frac{\varsigma_R u_R}{\varepsilon_R - u_R}\right)^K + \left(\frac{\varsigma_B u_B}{\varepsilon_B - u_B}\right)^K \right] \quad (17)$$

$$\text{IP} = \sum_{j_1=0}^{m_B-1} \cdots \sum_{j_K=0}^{m_B-1} \sum_{p=0}^{\Delta_B-1} \frac{\Lambda_B(K) \Gamma(\Delta_B)}{p! \psi_B^{\Delta_B-p} \delta_B^p} \exp\left(-\frac{\psi_B \varsigma_B u_B}{\delta_B(\varepsilon_B - u_B)}\right) \left(\frac{\varsigma_B u_B}{\varepsilon_B - u_B}\right)^p \quad (18)$$

Remark 1 The closed-form COP and IP depend on long-term channel statistics (not instantaneous coefficients), enabling low-cost evaluation and design for integrated satellite-terrestrial networks with perfect-CSI baselines.

Remark 2 The framework aligns with practical deployments where satellites offer backhaul and gap-filler aided access for indoor handhelds, supporting streaming and broadband connectivity.

4. RESULTS AND DISCUSSIONS

This section provides numerical simulations to verify the analytical expressions. Shadowed-Rician parameters for the S-Q link follow [22]: heavy shadowing (HS) (m_Q, b_Q, Ω_Q) = (1, 0.063, 0.0007) and average shadowing (AS) (5, 0.251, 0.279). Unless otherwise stated [16], parameters are $K \in \{1, 2, 3\}$, $R_R = 1$ bits per channel use (BPCU), $R_B = 0.5$ BPCU, $\beta_B = 0.7$, $\beta_R = 0.3$, $\alpha_B = \alpha_R = (1 - \alpha_{RB})/2$, $f_c = 2$ GHz, $W = 15$ MHz, $T = 300$ K, $c = 3 \times 10^8$ m/s, $d_{SQ} = 35786$ km, $\vartheta_S = 53.45$ dB, $\vartheta_Q = 4.8$ dB, $\theta_Q = 0.8^\circ$, $\theta_{Q,3dB} = 0.3^\circ$, bandwidth (BW) = 10 MHz, $\text{noise figure (NF)} = 10$ dB, $N_0 = -174$ dBm/Hz. The noise power is $\sigma_Q^2[\text{dBm}] = N_0 + 10 \log_{10}(\text{BW}) + \text{NF}$ [23]. Table 2 summarizes key settings.

Table 2. Simulation parameters

Parameter	Value	Description
K	1, 2, 3	Number of satellite antennas
P_S	$[-10, 30]$ dBm	Satellite transmit power
α_{RB}	0.1, 0.2, 0.3	BP for superposition signal
m_Q	1 (HS), 5 (AS)	Fading severity
β_B	0.7	Power allocation for Bob

Figure 2 shows COP vs. P_S (dBm). Increasing K reduces COP via spatial diversity. PFMA with $\alpha_{RB} \in \{0.1, 0.2, 0.3\}$ consistently outperforms NOMA. At higher P_S (> 10 dBm), COP saturates. Agreement between exact and asymptotic curves validates the analysis. Smaller α_{RB} further improves COP by reducing inter-user interference in the combined SINRs. The observed ≈ 4 dB SNR gain (see Figure 3) translates to $\sim 60\%$ coverage extension or up to 37% power saving via the free-space loss with traceability in [15].

$$L_{SQ} = \left(\frac{4\pi f d_{SQ}}{c} \right)^2 \quad (19)$$

Figure 3 presents COP vs. P_S for HS and AS, comparing PFMA and NOMA. Exact (solid) and asymptotic (dashed) curves match closely. PFMA consistently outperforms NOMA, with larger gains under HS. Under HS ($m_Q=1$, $b_Q=0.063$, $\Omega_Q=0.0007$), COP increases by up to 20% at low P_S relative to AS ($m_Q=5$, $b_Q=0.251$, $\Omega_Q=0.279$). Imperfect CSI (MMSE with estimation errors) further degrades COP: a 10% error-variance rise adds ≈ 5 –10% COP, highlighting PFMA's reliance on accurate CSI and its vulnerability to severe shadowing.

Figure 4 shows COP vs. β_B for $K \in \{1, 2, 3\}$ and $\alpha_{RB} = 0.4$. Larger K reduces COP for both schemes, with PFMA dominating across all β_B . The curves demonstrate the reliability trade-off as β_B varies. In Figure 5, IP is plotted vs. P_S for PFMA and NOMA. Varying $\alpha_{RB} \in \{0.1, 0.2, 0.3\}$ shows PFMA achieves lower IP for the same P_S . As P_S increases, IP approaches 1 for all schemes, while smaller α_{RB} benefits low- P_S security. Exact curves validate the analysis. Future research may consider additional practical aspects, e.g., hardware RF impairments such as I/Q imbalance [24], security-reliability trade-off with non-ideal untrusted relaying [25], and simultaneous secure-and-covert transmission under practical assumptions [26].

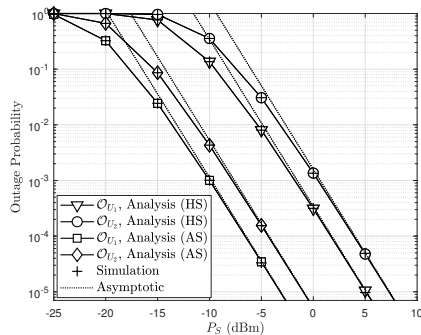


Figure 2. COP comparison: PFMA vs. NOMA

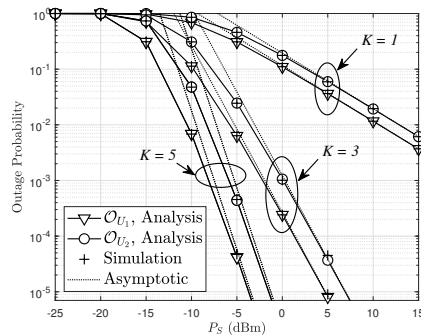
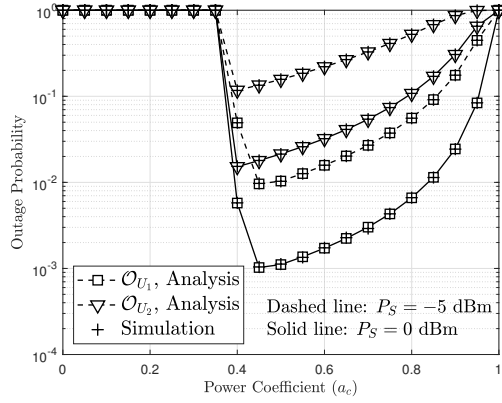
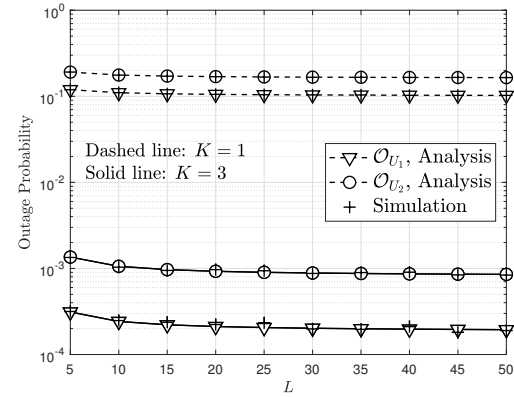


Figure 3. COP vs. P_S under different shadowing; $K = 3$, $\alpha_{RB} = 0.2$

Figure 4. COP vs. β_B , $\alpha_{RB} = 0.4$ Figure 5. IP vs. P_S (dBm); $K=2$, $R_R=R_B=1$

5. CONCLUSION

We proposed and analyzed a PFMA-based hybrid multiple access framework for secure satellite-terrestrial networks. Closed-form COP and IP expressions (with asymptotics and diversity) under shadowed-Rician fading and dual eavesdroppers reveal ~ 4 dB SNR gain over NOMA, up to 30% COP reduction, and 20–25% IP reduction at $P_S=10$ dBm. Simulations confirm potential $\sim 60\%$ coverage increase or up to 37% energy saving. Future work will consider multi-cell and mobility scenarios, imperfect self-interference mitigation, optimized BP/PA, multi-antenna transceivers, colluding eavesdroppers, and broader fading models.

ACKNOWLEDGMENT

Authors would like to thank Industrial University of Ho Chi Minh City (IUH) for the support of time and facilities for this study.

FUNDING INFORMATION

This study was self-funded by the authors.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Huu Q. Tran	✓	✓		✓	✓	✓		✓	✓	✓				
Viet-Thanh Pham		✓				✓		✓		✓				

C : **C**onceptualization
M : **M**ethodology
So : **S**oftware
Va : **V**alidation
Fo : **F**ormal Analysis

I : **I**nterpretation
R : **R**esources
D : **D**ata Curation
O : **O**riginal Draft
E : **E**diting

Vi : **V**isualization
Su : **S**upervision
P : **P**roject Administration
Fu : **F**unding Acquisition

CONFLICTS OF INTEREST

Authors state no conflict of interest.

DATA AVAILABILITY

No new data were generated or analyzed.

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