THE PUBLISHING HOUSE
OF THE ROMANIAN ACADEMY

*PROCEEDINGS OF THE ROMANIAN ACADEMY, Series A,*
*Volume 25, Number 3/2024, pp. 253–260*
DOI: 10.59277/PRA-SER.A.25.3.10

# END-TO-END PERFORMANCE OF MIXED RF/UWOC SYSTEM WITH AF PROTOCOL BASED ON MELLIN TRANSFORM

Qian PEI[1], Yanjun ZHANG[1,*], Shuxin SUN[1], Wei LIAN[2], Ziang XUAN[1]

[1] Yanshan University, School of Information Science and Engineering, The Key Laboratory for Special Fiber and Fiber Sensor of Hebei Province, Qinhuangdao 066004, China
[2] Yanshan University, National Engineering Research Center for Equipment and Technology of Cold Strip Rolling, Qinhuangdao 066004, Hebei, China
Corresponding author: Yanjun Zhang, E-mail: yjzhang@ysu.edu.cn

**Abstract**. This paper proposes an approach to analyze the performance of radio frequency/underwater wireless optical communication (RF/UWOC) systems using Mellin inverse transform. This analysis combines heterodyne detection (HD) and direct detection /intensity modulation (IM/DD). The RF link from land ground stations to relay stations follows the Nakagami-*m* distributed channel. The UWOC link from the relay station to the underwater vehicle is modeled using the double generalized gamma (GG) distribution with pointing errors. By employing the Fixed Gain Amplification and Forwarding (AF) protocol, the probability density function (PDF) of the RF/UWOC link is derived using the Mellin inverse transform, expressed in the form of the Meijer-G function. In addition, expressions for the outage probability and bit error rate of the mixed system were derived. Monte Carlo simulations validated the analysis results, which demonstrated the superior performance of HD technology.

***Keywords**:* Mellin inverse transform, RF/UWOC, amplify-and-forward relaying, pointing errors.

## 1. INTRODUCTION

Relay transmission has become a well-known technology for its long communication distance and high reliability. In recent years, relay transmission has been gradually applied to UWOC system [1–3]. Especially the RF/UWOC system has received more and more attention due to its ability to meet the needs of underwater IoT and ocean exploration. The overall design of RF/UWOC communication systems is significantly influenced by channel characteristics, which are key factors in determining wireless communication performance. Atmospheric turbulence encountered by the signal during propagation, along with pointing errors between the transmitter and receiver, can cause signal flickering and distort the amplitude and phase. Additionally, data errors are inevitable during underwater transmission, which considerably degrades the communication performance of RF/UWOC systems. By considering the effects of atmospheric turbulence, pointing errors, and underwater turbulence on signal transmission, the channel model for the constructed system achieves broader applicability, thereby meeting the needs for a comprehensive evaluation of RF/UWOC system communication performance across diverse channel environments.

Many researchers begin to conduct in-depth research on system performance. Security and secrecy of mixed RF/UWOC communication systems have been investigated [4–5]. RF/UWOC system outage probability and channel capacity are analyzed by using fixed-gain AF [6] or decode-and-forward (DF) relays [7]. The performance of the system and the derivation of the asymptotic expressions has been extensively studied in RF/UWOC links [8–11]. However, these papers use the traditional MGF-based approach [12–13] and PDF-based approach [14–15] to get the joint distribution function of the dual-hop RF/UWOC system, which is relatively complicated. Few researchers have solved the joint PDF of multi-hop systems by a simple approach. Therefore, this paper aims to solve the PDF of the RF/UWOC system through Mellin transformation.

This paper analyzes the performance of RF/UWOC mixed systems based on the AF protocol using Mellin transform and Mellin inverse transform [16–17]. The performance of RF/UWOC systems using HD and IM/DD technologies is evaluated considering turbulent channels and pointing errors.

The rest of this paper is organized as follows. The model of the system and channel is given in Section 2. The expressions of Cumulative Distribution Function (CDF) and PDF for mixed RF/UWOC systems are derived in Section 3. Then these results are applied to Section 4 to get expressions for the outage probability and average bit error rate of the system; that is to evaluate the performance of wireless communication system. Section 5 uses Monte Carlo to simulate and verify the impact of system parameters on system performance.

## 2. SYSTEM AND CHANNEL MODEL

Considered a mixed dual-hop RF/UWOC system, the RF link between the terrestrial ground station (S) to relay (R) is modeled as the Nakagami-*m* distributed channel. The UWOC link between the relay to the underwater vehicle (D) is modeled by the Gamma-Gamma distribution with pointing error.

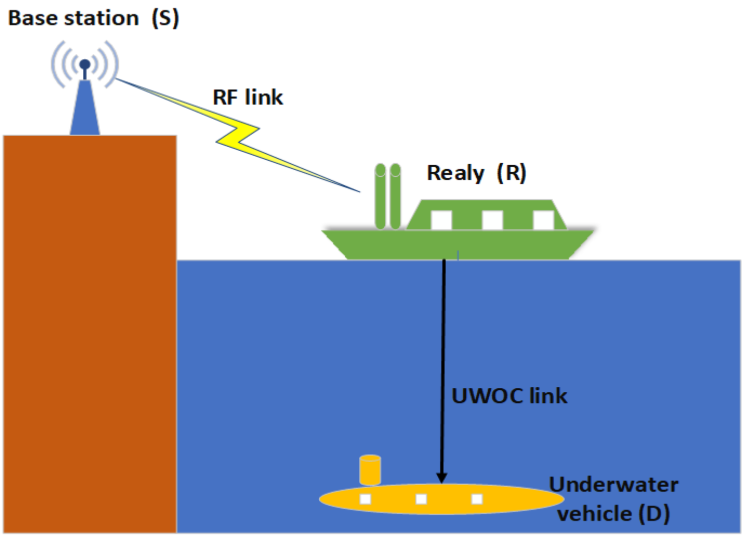


Fig. 1 – The model of RF/UWOC system.

### 2.1. RF channel model

The signal received by R can be expressed as

$$y_{SR} = I_{SR}x + n_{SR} \tag{1}$$

where $I_{SR}$ is the Nakagami-*m* distributed channel gain from S to R, $x$ represents the signal transmitted by S, $n_{SR}$ denotes the additive white Gaussian noise (AWGN), with zero mean and $\sigma_{SR}^2$, and the instantaneous SNR of the RF link $r_{SR} = |I_{SR}|^2\overline{r}_{SR}$, in which $E_{SR}/\sigma_{SR}^2$ is the average SNR of the S-R link and $E_{SR}$ is the signal power of $x$. The RF link suffers from the Nakagami-*m* distribution, whose PDF can be given by [18]

$$f_{SR}(r_{SR}) = \frac{m^m r_{SR}^m}{\Gamma(m)\overline{r}_{SR}^m}\exp\left(\frac{-mr_{SR}}{\overline{r}_{SR}}\right) \tag{2}$$

where *m* represents the fading degree of the distribution function, $\Gamma(.)$represents the Gamma function [17].

### 2.2. UWOC channel model

The signal received by D can be expressed as

$$y_{SD} = GI_{RD}y_{SR} + n_{RD} \tag{3}$$

where $I_{RD}$ is the Nakagami-*m* distributed channel gain from R to D. Suppose $\sigma_{SR}^2 = \sigma_{RD}^2 = N_0$.

Assume that the underwater link follows the G-G fading distribution with pointing error, and the PDF of SNR is given by [19]

$$f_{r_{RD}} = \frac{\varepsilon^2}{\mathrm{tr}RD\,\Gamma(\alpha)\Gamma(\beta)} G_{1,3}^{3,0}\left[h\alpha\beta\left(\frac{r_{R,D}}{u_t}\right)^{1/t} \middle| \begin{matrix} \varepsilon^2+1 \\ \varepsilon^2,\ \ \alpha,\beta \end{matrix}\right] \tag{4}$$

where $t$ is the parameter that determines the type of detection technique, we have $h = \frac{\varepsilon^2}{\varepsilon^2+1}$, $\varepsilon^2$ represents the ratio between the equivalent beam radius at the receiver and the standard deviation of the pointing error displacement. When $\varepsilon^2 \to \infty$ negligible pointing error. $\alpha$ and $\beta$ are fading parameters related to atmospheric turbulence conditions. $t = 1$ for HD and $t = 2$ for IM/DD. When $t = 1$, $u_1 = \overline{r}_{RD}$ and when $t = 2$, $u_2 = \frac{\overline{r}_{RD}\alpha\beta(\varepsilon^2+2)}{(\varepsilon^2+1)(\alpha+1)(\beta+1)}$.

## 3. PDF OF RF/UWOC SYSTEM

In this section, novel analytical expressions are derived for the PDF and the CDF. Figure 2 is a schematic diagram of the system analysis. Specifically, asymmetric fading environments were considered, assuming that the RF link follows Nakagami-*m* fading while the UWOC link experiences G-G fading, which accurately describes the fading model of light intensity under weak to strong turbulence conditions. The detector receives the signal $y_{sd}$, thereby obtaining the system signal-to-noise ratio $r_{eq}$, the closed form expressions of CDF and PDF for hybrid RF/UWOC systems were derived based on Mellin transform and inverse Mellin transform. A new closed form expression for outage probability and average bit error rate was given using the exported CDF and PDF expressions.

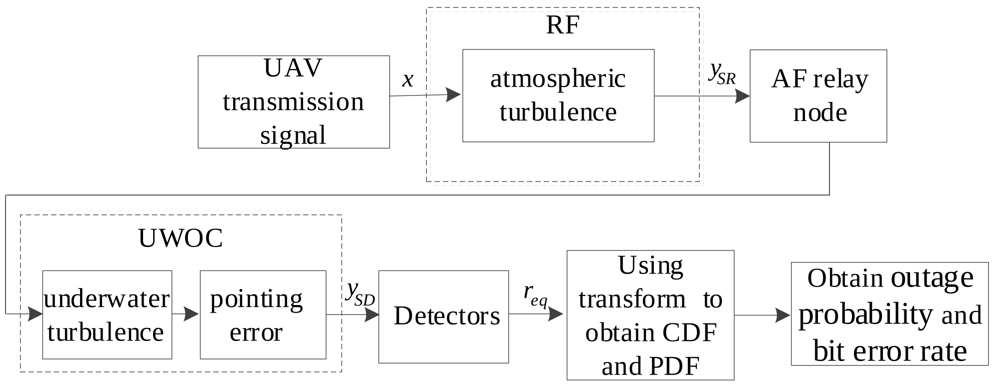


Fig. 2 – System Block Diagram.

Consider the RF/UWOC communication system, where the RF link is modeled by Nakagami-*m* fading and the UWOC link is modeled by Gamma-Gamma distributed with pointing error. For fixed-gain AF relay systems, the instantaneous SNR [20] at D can be expressed as

$$r_{eq} = \frac{r_{SR}r_{RD}}{C + r_{RD}} \tag{5}$$

$r_{SR}$ and $r_{RD}$ are the instantaneous signal-to-noise ratios of the RF link and the UWOC link, respectively. $r_1$ and $r_2$ are the instantaneous signal-to-noise ratios of the RF link and UWOC link, respectively, and it is assumed that $r_{SR} = r_{RD}$. $C$ is a fixed constant related to the relay gain. We have $C = \frac{1}{G^2N_0}$.

The definition of Mellin transform is as follows [21]:

$$M_f(s) = \int_0^\infty x^{s-1} f(x)\,\mathrm{d}x \tag{6}$$

Definition of the corresponding inverse Mellin transform [21]:

$$f(x) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} x^{-s} M_f(x)\, \mathrm{d}x \tag{7}$$

The Mellin transform of the instantaneous SNR of RF/UWOC systems can be derived

$$M_{SR}(s) = \int_0^\infty (r_{SR})^{s-1} f_{SR}(r_{SR})\, \mathrm{d}r_{SR} \tag{8}$$

$$M_{RD}(s) = \int_0^\infty \left(\frac{r_{RD}}{r_{RD} + C}\right)^{s-1} f_{RD}(r_{RD})\, \mathrm{d}r_{RD} \tag{9}$$

where $\left(\frac{r_{RD}}{r_{RD}+C}\right)^{s-1}$ can be expressed in the form of Meijer-G [22, eq.(9.121.1)]

$$\left(\frac{r_{R,D}}{r_{R,D} + C}\right)^{s-1} = G_{1,1}^{1,1}\left[\frac{r_{R,D}}{C} \,\middle|\, \begin{matrix} 1 \\ s-1 \end{matrix}\right] \tag{10}$$

The Meijer-G function in equation (10) is expanded into the form containing Hypergeometry function [22,eq.(9.14.1)], which can be simplified to

$$G_{1,1}^{1,1}\left[\frac{r_{R,D}}{C} \,\middle|\, \begin{matrix} 1 \\ s-1 \end{matrix}\right] = \sum_{k=0}^{\infty} \frac{\Gamma(s+k-1)C^{-s}}{\Gamma(s-1)(k+1)C^k} (r_{RD})^{s+k-1} \tag{11}$$

It can be calculated from the integral of the product of the Meijer-G function and the definition of the gamma function $M_{SR}(s)$

$$M_{SR}(s) = 1/\Gamma(m) \left(\frac{m}{\bar{r}_{SR}}\right)^{1-s} \Gamma(s+m-1) \tag{12}$$

Similarly, $M_{RD}(s)$ can be derived as follows

$$\begin{aligned} M_{RD}(s) = \sum_{k=0}^{\infty} &\frac{\Gamma(s+k-1)(-1)^k (B_t C)^{-s} A}{\Gamma(s-1)\,\Gamma(k+1)\, C^k {B_t}^{t(k-1)}} \\ &\times \frac{\Gamma(t(s+k-1)+\varepsilon^2)\,\Gamma(t(s+k-1)+\beta)\,\Gamma(t(s+k-1)+\alpha)}{\Gamma(t(s+k-1)+\varepsilon^2+1)} \end{aligned} \tag{13}$$

Using [21], Eq.(13) can be simplified

$$\begin{aligned} M_{RD}(s) = \sum_{k=0}^{\infty} &\frac{\Gamma(s+k-1)(-1)^k (B_t C)^{-s} A H t^{2tk} t^{2ts}}{\Gamma(s-1)\Gamma(k+1) C^k {B_t}^{t(k-1)}} \\ &\times \frac{\prod_{i=0}^{t-1} \Gamma(s+k-1+\frac{\varepsilon^2+i}{t}) \prod_{i=0}^{t-1} \Gamma(s+k-1+\frac{\alpha+i}{t}) \prod_{i=0}^{t-1} \Gamma(s+k-1+\frac{\beta+i}{t})}{\prod_{i=0}^{t-1} \Gamma(s+k-1+\frac{\varepsilon^2+1+i}{t})} \end{aligned} \tag{14}$$

After calculation, the expression of the Mellin transform of the instantaneous signal-to-noise ratio of the RF/UWOC system is obtained

$$M_{r_{eq}}(s) = M_{SR}(s) M_{RD}(s) \tag{15}$$

The inverse Mellin transform [17] of $M_{r_{eq}}(s)$ is

$$f_{r_{eq}}(r) = \sum_{k=0}^{\infty} \frac{m(-1)^k AHt^{2tk}}{\overline{r}_{SR}\, \Gamma(m)\, \Gamma(k+1)\, C^k {B_t}^{t(k-1)}} G_{t+1,3t+2}^{3t+2,0}\left[\frac{CB_t mr}{\overline{r}_{SD} t^{2t}} \middle| \begin{matrix} -1, \Delta\dfrac{1+\varepsilon^2}{t} \\ k-1, m-1, \Delta\dfrac{\varepsilon^2}{t}, \Delta\dfrac{\alpha}{t}, \Delta\dfrac{\beta}{t} \end{matrix}\right] \tag{16}$$

where $A = \frac{\varepsilon^2}{\Gamma(\alpha)\Gamma(\beta)}$, $B = \frac{h\alpha\beta}{(u_r)^{1/t}}$, $H = t^{\alpha+\beta-2-2t}(2\pi)^{1-t}$, $i$ is taken one by one from $0$ to $t$, $\Delta\frac{\varepsilon^2}{t} = \frac{i+\varepsilon^2}{t} + k - 1$, $\Delta\frac{\alpha}{t} = \frac{i+\alpha}{t} + k - 1$, $\Delta\frac{1+\varepsilon^2}{t} = \frac{i+1+\varepsilon^2}{t} + k - 1$, $\Delta\frac{\beta}{t} = \frac{i+\beta}{t} + k - 1$.

From (16), the CDF [23] of $r_{eq}$ is formulated as

$$F_{r_{eq}}(r) = \sum_{k=0}^{\infty} \frac{m(-1)^k AHt^{2tk} r}{\overline{r}_{SR}\, \Gamma(m)\, \Gamma(k+1)\, C^k {B_t}^{t(k-1)}} G_{t+2,3t+3}^{3t+2,1}\left[\frac{CB_t mr}{\overline{r}_{SD} t^{2t}} \middle| \begin{matrix} 0, -1, \Delta\dfrac{1+\varepsilon^2}{t} \\ k-1, m-1, \Delta\dfrac{\varepsilon^2}{t}, \Delta\dfrac{\alpha}{t}, \Delta\dfrac{\beta}{t}, -1 \end{matrix}\right] \tag{17}$$

## 4. STATISTICAL CHARACTERISTICS OF THE SYSTEM

### 4.1. Outage probability

The outage probability [24] is considered as an important index to judge the system performance. Mathematically, outage probability can be expressed as

$$p_{out} = \Pr(r_{eq} < r_{th}) = \int_0^{r_{th}} f_{r_{eq}}(r)\, \mathrm{d}r_{eq} \tag{18}$$

Take (18) into (19), the expression of outage probability can be obtained

$$p_{out} = F_{r_{eq}}(r_{\mathrm{th}}) =$$
$$= \sum_{k=0}^{\infty} \frac{m(-1)^k AHt^{2tk} * r_{th}}{\overline{r}_{SR}\, \Gamma(m)\, \Gamma(k+1)\, C^k {B_t}^{t(k-1)}} G_{t+2,3t+3}^{3t+2,1}\left[\frac{CB_t mr_{th}}{\overline{r}_{SD} t^{2t}} \middle| \begin{matrix} 0, -1, \Delta\dfrac{1+\varepsilon^2}{t} \\ k-1, m-1, \Delta\dfrac{\varepsilon^2}{t}, \Delta\dfrac{\alpha}{t}, \Delta\dfrac{\beta}{t}, -1 \end{matrix}\right] \tag{19}$$

### 4.2. Bit error rate

The bit error rate of the instantaneous SNR modulated by MPSK [25] is defined as follows

$$p_e = \varepsilon_M \sum_{i=1}^{\tau_M} Q(a_i\sqrt{r}) = \frac{2\varepsilon_M}{\sqrt{\pi}} \sum_{i=1}^{\tau_M} G_{1,2}^{2,0}\left[\frac{a_i^2 r}{2} \middle| \begin{matrix} 1 \\ 0, 1/2 \end{matrix}\right] \tag{20}$$

where $Q(.)$ is the Q-function and $Q(x) = 1/2\, \mathrm{erfc}(\frac{x}{\sqrt{2}})$, $\varepsilon_M = \frac{2}{\max(\log_2^M, 2)}$, $a_i = \sqrt{2}\sin\frac{(2i-1)\pi}{M}$, $\tau_M = \max(\frac{M}{4}, 1)$.

By introducing formula (20) to (21), the expression of bit error rate can be obtained as

$$\bar{p}_e = \int_0^{\infty} p_e f_{r_{eq}}(r)\, \mathrm{d}r_{eq} =$$
$$= \sum_{k=0}^{\infty} \sum_{i=1}^{\tau_M} \frac{4\varepsilon_M m(-1)^k AHt^{2tk}}{\overline{r}_{SR}\, \Gamma(m)\, \Gamma(k+1)\, C^k {a_i}^2 \sqrt{\pi}} G_{1,2}^{2,0}\left[\frac{2CB_t m}{\overline{r}_{SD} t^{2t} {a_i}^2} \middle| \begin{matrix} -1, \Delta\dfrac{1+\varepsilon^2}{t}, 0, \dfrac{-1}{2} \\ k-1, m-1, \Delta\dfrac{\varepsilon^2}{t}, \Delta\dfrac{\alpha}{t}, \Delta\dfrac{\beta}{t}, -1 \end{matrix}\right] \tag{21}$$

## 5. SIMULATION AND ANALYSIS

In this section, we provide some numerical results on the outage probability and average bit error rate of dual hop RF/UWOC systems under IM/DD and HD detection technologies. The expressions for outage probability and bit error rate are expressed in the form of Meijer-G [15] and numerically simulated. We apply Monte Carlo analysis to validate the system performance expression. Monte Carlo method is a statistical simulation method for generating random signals. There are Monte Carlo analysis settings in Zemax, which set the frequency, threshold, and distribution type separately. Compare the simulation results of the obtained data with the numerical simulation results of the performance expression. When the simulation point falls on the numerical simulation curve, it indicates the correctness of the expression. We analyze the changes of outage probability under strong, medium and weak turbulence conditions and the bit error rate with MPSK modulation of the RF/UWOC system. The exact expressions of the PDF, outage probability and bit error rate of RF/UWOC system are obtained by means of Meijer-G function expansion and Mellin inverse transformation. When the parameter is, the difference between the PDF when $k = 70$ (the addition of the 70 terms of the series expansion) and $k = 60$ (the addition of the 60 terms of the series expansion) is $2.775557 \times e^{-17}$. This difference is too small and can be ignored, so the formula (16) can be accurate to $k = 70$. We assume that C in the instantaneous signal-to-noise ratio of the system is a constant, and $r_{th} = 0.1$dB. We can obtain Figs. 3, 4 through numerical simulation based on Equation (19), and Figs. 5, 6 through numerical simulation based on Equation (21).

To verify the influence of parameter $m$ on the outage probability, Fig. 3 shows the numerical simulation and simulation results of outage probability changes with RF link parameter $m$ under HD technology and IM/DD technology. From this figure, it can be observed that the simulation and analysis results are basically consistent. The error rate performance under HD technology is superior to IM/DD technology. The channel parameter $m$ of the RF link is $m = 2$, $m = 4$, and $m = 10$. With the increase of channel parameter $m$, the outage probability decreases. Therefore, it is necessary to study the influence of the parameter $m$ on the outage probability. After careful observation, it can be found that with the increase of $m$, the decrease in outage probability becomes less pronounced. This indicates that with the increase of parameter $m$, the impact on outage probability becomes smaller and smaller.

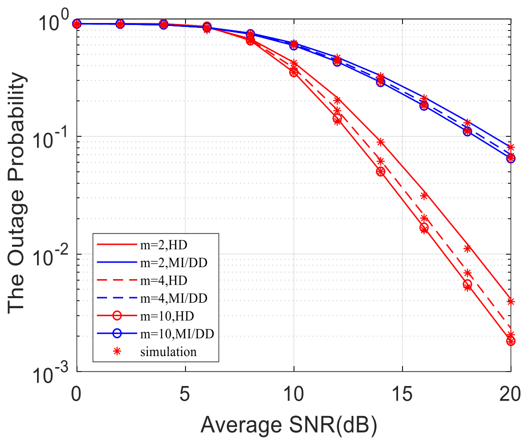


Fig. 3 – The relationship between $m$ and outage probability.

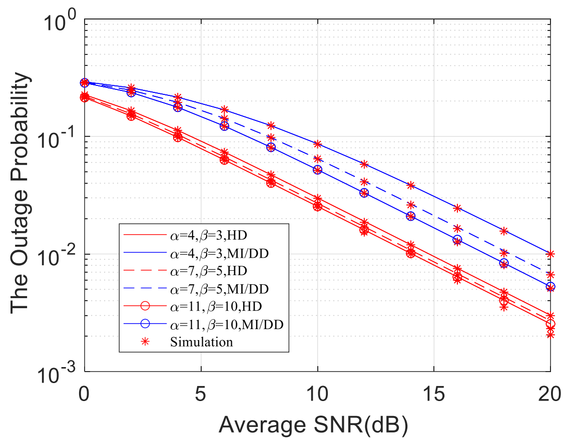


Fig. 4 – The relationship between α, β and outage probability

In order to verify the influence of turbulence intensity on bit error rate, Fig. 5 simulates the magnitude of the influence of turbulence parameters on bit error rate. Figure 5 simulates the change of the bit error rate of UWOC link under strong turbulence, medium turbulence and weak turbulence. Let $m = 5$, the strong pointing error. It can be observed from the figure that the analysis results are consistent with the simulation results. The system performance achieved using HD ($t = 1$) technology is superior to that achieved using IM/DD technology ($t = 2$). Furthermore, under the same modulation technology, with the increasing of and the turbulence intensity decreases and the bit error rate decreases. To verify the influence of MPSK modulation parameters and channel parameter $m$ on bit error rate in Fig. 6, we illustrate the bit error rate with MPSK modulation under IM/DD technology and HD technology. We take $M = 2$, $M = 4$ and the RF link parameter $m = 8$, $m = 20$. From the graph, it can be seen that the outage probability becomes serious as $M$ increases (*i.e.*, the higher the value, the greater the OP). Moreover, for the RF link parameter *m*, the larger the *m*, the better the system performance. In addition, it is obvious that the performance of the bit error rate obtained by HD technology is better than that obtained by IM/DD technology.

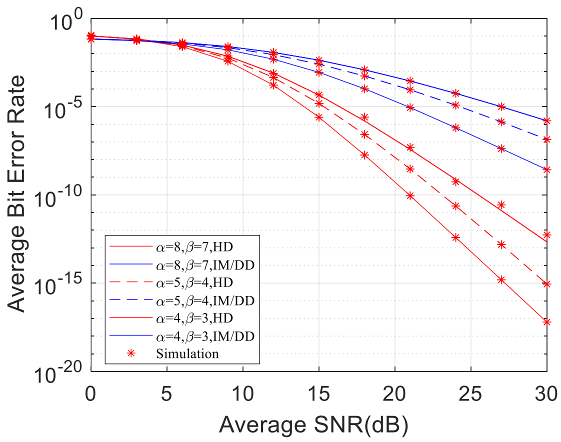


Fig. 5 – The relationship between parameters of turbulent channels and error rate of turbulent channels.

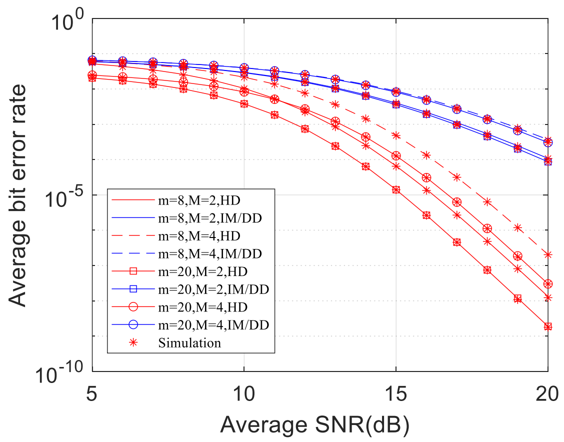


Fig. 6 – The relationship between modulation order and bit error rate.

## 6. CONCLUSIONS

This paper examines the performance of a mixed RF/UWOC system employing an amplifying and forwarding relay under both HD and IM/DD technologies. The analysis involves expanding the hypergeometric function into a series form and deriving exact expressions for the PDF and CDF of the mixed system using inverse Mellin transform. The expressions of outage probability and bit error rate under MPSK modulation are also obtained. Through numerical calculation and simulation, it is concluded that although HD technology is more complex, compared with IM/DD technology, the performance of the system using HD technology is superior, and the system performance becomes worse with the increase of turbulence intensity. The expressions for outage probability and bit error rate under MPSK modulation are derived. Numerical calculations and simulations indicate that despite its increased complexity compared to IM/DD technology, HD technology offers superior system performance. However, this performance degrades as turbulence intensity increases.

ACKNOWLEDGEMENTS

This work has been supported by National key Research and Development Program of China (2019YFC1407904).

## REFERENCES

[1] Zhou B, Wang P, Cao T, Li G, Li S, Yang P. Performance analysis of AUV-carried RISs-aided multihop UWOC convergent with RF MRC systems over WGG oceanic turbulence. Vehicular Communications 2024;45:100722.
[2] Kaushal H, Kaddoum G. Underwater optical wireless communication. IEEE Access 2016;4:1518–1547.
[3] Zhu S, Chen X, Liu X, Zhang G, Tian P. Recent progress in and perspectives of underwater wireless optical communication. Prog. Quantum Electron 2020;73:100274.
[4] Lou Y, Sun R, Chengand J, Nie D, Qiao G. Secrecy outage analysis of two-hop decode-and-forward mixed RF/UWOC systems. IEEE Commun. Lett. 2022;26(5):989–993.
[5] Pei Q, Zhang Y, Liu F, Lian W, Fu X, Li J. Unified performance analysis of direct air-to-underwater RF/UWOC systems. Photonics 2024;11(1):21.
[6] Li S, Yang L, Da Costa DB, Yu S. Performance analysis of UAV-based mixed RF-UWOC transmission systems. IEEE Trans. Commun. 2021;69:5559–5572.

[7] Yadav S, Vats A, Aggarwal M, Ahuja S. Performance analysis and altitude optimization of UAV-enabled dual-hop mixed RF-UWOC system. IEEE Trans. Veh. Technol. 2021;70:12651–12661.
[8] Ramavath PN, Udupi SA, Krishnan P. Co-operative RF-UWOC link performance over hyperbolic tangent log-normal distribution channel with pointing errors. J. Opt. Commun. 2020;469:125774.
[9] Lei H, Zhang Y, Park K-H, Ansari IS, Pan G, Alouini M-S. Performance analysis of dual-hop RF-UWOC systems. IEEE Photon. J. 2020;12:1–15.
[10] Kumar LB, Krishnan P. Multi-hop convergent FSO-UWOC system to establish a reliable communication link between the islands. Opt. Commun. 2020;474:126107.
[11] Zhang J, Liu H, Feng L, Pan G. Performance analysis for wireless-powered relaying UWOC-RF systems. Journal of the Franklin Institute 2024;361;1115–1126.
[12] Hasna MO, Alouini M-S. Harmonic mean and end-to-end performance of transmission systems with relays. IEEE Trans. Commun. 2004;52:130–135.
[13] Hasna MO, Alouini M-S. End-to-end performance of transmission systems with relays over Rayleigh-fading channels. IEEE Syst. J. 2003;2:1126–1131.
[14] Karagiannidis GK, Tsiftsis TA, Mallik RK. Bounds for multihop relayed communications in Nakagami-m fading. IEEE Trans. Commun. 2006;54:18–22.
[15] Wang X., Gao Y., Zhang G., Guo M. Security performance analysis of cell-free massive MIMO over spatially correlated Rayleigh fading channels with active spoofing attack. In: 2020 International Conference on Wireless Communications and Signal Processing (WCSP). 2020, pp. 540–545.
[16] Zedini E, Kammoun A, Soury H, Hamdi M, Alouini M-S. Performance analysis of dual-hop underwater wireless optical communication systems over mixture Exponential-Generalized Gamma turbulence channels. IEEE Trans. Commun. 2020;68: 5718–5731.
[17] Salo J, El-Sallabi HM, Vainikainen P. The distribution of the product of independent Rayleigh random variables. IEEE Transactions on Antennas and Propagation 2006;54:639–643.
[18] Zedini E, Ansari IS, Alouini MS. Performance analysis of mixed Nakagami-*m* and Gamma-Gamma dual-hop FSO transmission systems. IEEE Photonics Journal 2015;7.
[19] Yang L, Zhu Q, Li S, Ansari IS, Yu SY. On the performance of mixed FSO-UWOC dual-hop transmission systems. IEEE Wireless Communications Letters 2021;10:2041–2045.
[20] Zhang JY, Dai LL, Zhang Y, Wang ZC. Unified performance analysis of mixed radio frequency/free-space optical dual-hop transmission systems. IEEE Journal of Lightwave Technology 2015;33:2041–2045.
[21] Mathai AM, Provost SB. Generalized Boltzmann factors induced by Weibull-type distributions. Physica A: Statistical Mechanics and its Applications 2013;392:545–551.
[22] Gradshteyn IS, Ryzhik IM. Table of integrals, series, and products. 5nd ed. San Diego, CA: Academic Press; 1994.
[23] The Wolfram Functions Site, https://functions.wolfram.com/HypergeometricFunctions/MeijerG/ ; 2015.
[24] Rakia T, Yang HC, Alouini MS, Gebali F. Outage analysis of practical FSO/RF hybrid system with adaptive combining. IEEE Communications Letters 2015;19:1366–1369.
[25] Jang Y, Yoon D, Lee SK. Generalized BER expression of MPSK in the presence of phase error. IEEE Communications Letters 2013;17:2213–2216.

*Received March 29, 2024*