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The distribution of ratio of random variable and product of two random variables and its application in performance analysis of multi-hop relaying communications over fading channels

***Abstract**. In this paper, we present novel closed-form expressions for the probability density function (PDF) and cumulative distribution function (CDF) of ratio of random variable and product of two random variables for the cases where random variables are Rayleigh, Weibull, Nakagami-m and α-μ distributed. An application of obtained results in performance analysis of multi-hop wireless communication systems in different transmission environments is detailed described. The proposed theoretical analysis is also complemented by various graphically presented numerical results.*

***Streszczenie**. W artykule zaprezentowano wyrażenia na funkcję gęstości prawdopodobieństwa PDF i kumulacyjną funkcję dystrybucji stosunku zmiennej przypadkowej i iloczynu dwóch zmiennych gdy zmienne przypadkowe są dystrybucją Rayleigh, Weibull, Nakagami-m i α-μ. Analiza ma zastosowanie do bezprzewodowych sieci komunikacyjnych w różnych warunkach transmisji. (**Rozkład stosunku zmiennych przypadkowych i iloczynu tych zmiennych oraz wykorzystanie tych parametrów do analizy systemów komunikacji bezprzewodowej**)*

Keywords: fading, multi-hop relaying communications, Nakagami-*m* distribution, Rayleigh distribution, Weibull distribution, *α-μ* distribution.
Słowa kluczowe: komunikacja bezprzewodowa, dystrybucja Rayleigh, dystrybucja Weibull

Introduction

Ratios of random variables have been widely utilized in reporting results in the biological, physical and social sciences. Examples include Mendelian inheritance ratios in genetics, mass to energy ratios in nuclear physics, target to control precipitation in meteorology and inventory ratios in economics [1]. Motivated by this fact, the distributions of ratios of random variables have been studied extensively by several authors [1]-[2].

The distributions of ratios of random variables are also of interest in performance analysis of wireless communication systems [3]-[4]. Radio wave propagation through wireless channels is a complicated phenomenon characterized by fading which is the result of multipath propagation due to reflection, refraction and scattering of radio waves by buildings and other structures. When a received signal experiences fading during transmission, its envelope fluctuates over time. There is a very wide range of statistical models for describing the statistical behavior of signal envelope which accuracy and veracity depend on communication scenario and propagation environment [5]. Reviewing the open technical literature, one can conclude that most of papers concern Rayleigh, Nakagami-*m*, Weibull and *α-μ* models. Desired signal in wireless communication systems is also subjected to cochannel interference (CCI) due to reuse of radio frequencies which is essential in increasing system capacity. In addition to fading, the wireless transmission can be degraded by shadowing which is the result of large obstacles and deviations in terrain profile between transmitter and receiver. In such composite fading-shadowing environment, signal envelope can be modelled with product of two random variables [6].

Multi-hop relaying communication has a number of advantages over traditional direct-link transmission in the areas of connectivity, deployment, power saving and channel capacity. Relaying techniques enable network connectivity where traditional architectures are impractical due to location constraints. Multi-hop networks technology is a promising solution for future cellular, wireless local area networks (WLANs) and hybrid networks. It is reason why dual and multi-hop wireless communication systems operating in fading channels have been an important field of research in the past few years [7]-[11].

Motivated by the preceding, in this paper, closed-form expressions for the probability density function (PDF) and cumulative distribution function (CDF) of ratio of random variable and product of two random variables, $\lambda=x/(yz)$, are derived. The random variable in nominator, x, represents signal envelope which suffers from fading, while the product of random variables in denominator, $yz=t$, represents envelope of CCI simultaneously affected by both fading and shadowing. Therefore, random variable λ presents signal-to-interference ratio (SIR). Rayleigh, Nakagami-*m*, Weibull and *α-μ* distributions are included in our analysis to enable wide range of use of results presented in the paper, i.e. to model different transmission environments. Capitalizing on closed-form expressions derived in the paper, the outage probability of multi-hop system, as an important and widely accepted performance metric, is determined.

Statistics of ratio of random variable and product of two random variables

In this section, closed-form expressions for the PDF and CDF of ratio of random variable and product of two random variables, $\lambda=x/yz$, are obtained. First, we present different distributions describing statistical behavior of variables x, y and z.

a) Rayleigh distribution: In the case of Rayleigh distribution, the PDFs of random variables are given by

$$p_x(x)=\frac{2}{\Omega_x}xe^{-\frac{x^2}{\Omega_x}}, \tag{1}$$

$$p_y(y)=\frac{2}{\Omega_y}ye^{-\frac{y^2}{\Omega_y}}, \tag{2}$$

$$p_z(z)=\frac{2}{\Omega_z}ze^{-\frac{z^2}{\Omega_z}}, \tag{3}$$

where $\Omega_x=\varepsilon\left\langle x^2\right\rangle$, $\Omega_y=\varepsilon\left\langle y^2\right\rangle$, $\Omega_z=\varepsilon\left\langle z^2\right\rangle$ and $\varepsilon\left\langle\cdot\right\rangle$ denotes expectation.

b) Weibull distribution: The Weibull random variables are distributed according to

$$p_x(x)=\frac{\beta}{\Omega_x}x^{\beta-1}e^{-\frac{x^\beta}{\Omega_x}}, \tag{4}$$

(5) $$p_y(y)=\frac{\beta}{\Omega_y}y^{\beta-1}e^{-\frac{y^\beta}{\Omega_y}},$$

(6) $$p_z(z)=\frac{\beta}{\Omega_z}z^{\beta-1}e^{-\frac{z^\beta}{\Omega_z}},$$

where $\Omega_x=\varepsilon\left\langle x^\beta\right\rangle$, $\Omega_y=\varepsilon\left\langle y^\beta\right\rangle$, $\Omega_z=\varepsilon\left\langle z^\beta\right\rangle$ and β is Weibull parameter (for the special case of β=2 Weibull PDFs reduces to Rayleigh PDFs).

c) Nakagami-*m* distribution: The Nakagami-*m* PDFs are

(7) $$p_x(x)=\frac{2{m_x}^{m_x}}{\Gamma(m_x)\Omega_x^{m_x}}x^{2m_x-1}e^{-\frac{m_x x^2}{\Omega_x}},$$

(8) $$p_y(y)=\frac{2{m_y}^{m_y}}{\Gamma(m_y)\Omega_y^{m_y}}y^{2m_y-1}e^{-\frac{m_y y^2}{\Omega_y}},$$

(9) $$p_z(z)=\frac{2{m_z}^{m_z}}{\Gamma(m_z)\Omega_z^{m_z}}z^{2m_z-1}e^{-\frac{m_z z^2}{\Omega_z}},$$

where $\Omega_x=\varepsilon\left\langle x^2\right\rangle$, $\Omega_y=\varepsilon\left\langle y^2\right\rangle$, $\Omega_z=\varepsilon\left\langle z^2\right\rangle$, $\Gamma(\cdot)$ is gamma function and m_x, m_y and m_z are Nakagami-*m* parameters that range from 0.5 to ∞. The Nakagami-*m* distribution includes the one-sided Gaussian distribution (m=0.5) and the Rayleigh distribution (m=1) as special cases.

d) *α-μ* distribution: The *α-μ* distributed random variables are described with following equations

(10) $$p_x(x)=\alpha\left(\frac{\mu_x}{\Omega_x}\right)^{\mu_x}\frac{x^{\alpha\mu_x-1}}{\Gamma(\mu_x)}e^{-\frac{\mu_x x^\alpha}{\Omega_x}},$$

(11) $$p_y(y)=\alpha\left(\frac{\mu_y}{\Omega_y}\right)^{\mu_y}\frac{y^{\alpha\mu_y-1}}{\Gamma(\mu_y)}e^{-\frac{\mu_y y^\alpha}{\Omega_y}},$$

(12) $$p_z(z)=\alpha\left(\frac{\mu_z}{\Omega_z}\right)^{\mu_z}\frac{z^{\alpha\mu_z-1}}{\Gamma(\mu_z)}e^{-\frac{\mu_z z^\alpha}{\Omega_z}},$$

where $\Omega_x=\varepsilon\left\langle x^\alpha\right\rangle$, $\Omega_y=\varepsilon\left\langle y^\alpha\right\rangle$, $\Omega_z=\varepsilon\left\langle z^\alpha\right\rangle$, α is parameter related to the non-linearity and μ_x, μ_y, and μ_z are the inverse of the normalized variance of x^α, y^α and z^α, respectively, (μ_x, μ_y, $\mu_z\geq 0.5$). The *α-μ* distribution is a general distribution that includes as special cases Nakagami-*m* distribution for α=2 and Weibull distribution for μ=1.

PDF of λ can be derived as

(13) $$p_\lambda(\lambda)=\int_0^\infty |J|\,p_x(\lambda\, t)\,p_t(t)\,dt,$$

where the Jacobian transformation is given by |J|=|dt/dλ|=t and

(14) $$p_t(t)=\int_0^\infty |J|\,p_y\left(\frac{t}{z}\right)p_z(z)\,dz,$$

with |J|=|dy/dt|=1/z. CDF of λ can be obtained by definition as

(15) $$F_\lambda(\lambda)=\int_0^\lambda p_\lambda(s)\,ds.$$

After applying the described procedure, with the aid of [12, eqs. (3.461) and (6.631)], [13, eq. (9)], [14], [15, eq. (26)], the PDFs and CDFs of λ in different scenarios can be expressed in terms of Meijer G functions

$$G_{p,q}^{m,n}\left(\gamma\left|\begin{matrix}a_1,a_2,...,a_p\\ b_1,b_2,...,b_q\end{matrix}\right.\right).$$

a) Rayleigh scenario:

(16) $$p_\lambda(\lambda)=\frac{2}{\lambda^2}\sqrt{\frac{\Omega_x}{\Omega_y\Omega_z}}G_{2,1}^{1,2}\left(\frac{\Omega_y\Omega_z}{\Omega_x}\lambda^2\left|\begin{matrix}\frac{1}{2},\frac{1}{2}\\ \frac{3}{2}\end{matrix}\right.\right),$$

(17) $$F_\lambda(\lambda)=\frac{1}{\lambda}\sqrt{\frac{\Omega_x}{\Omega_y\Omega_z}}G_{3,2}^{1,3}\left(\frac{\Omega_y\Omega_z}{\Omega_x}\lambda^2\left|\begin{matrix}\frac{1}{2},\frac{1}{2},\frac{3}{2}\\ \frac{3}{2},\frac{1}{2}\end{matrix}\right.\right),$$

b) Weibull scenario:

(18) $$p_\lambda(\lambda)=\beta\lambda^{-\frac{\beta}{2}-1}\sqrt{\frac{\Omega_x}{\Omega_y\Omega_z}}G_{2,1}^{1,2}\left(\frac{\Omega_y\Omega_z}{\Omega_x}\lambda^\beta\left|\begin{matrix}\frac{1}{2},\frac{1}{2}\\ \frac{3}{2}\end{matrix}\right.\right),$$

(19) $$F_\lambda(\lambda)=\lambda^{-\frac{\beta}{2}}\sqrt{\frac{\Omega_x}{\Omega_y\Omega_z}}G_{3,2}^{1,3}\left(\frac{\Omega_y\Omega_z}{\Omega_x}\lambda^\beta\left|\begin{matrix}\frac{1}{2},\frac{1}{2},\frac{3}{2}\\ \frac{3}{2},\frac{1}{2}\end{matrix}\right.\right),$$

c) Nakagami-*m* scenario:

(20) $$p_\lambda(\lambda)=2\left(\frac{m_y m_z}{m_x}\right)^{\frac{1}{2}(m_y+m_z-1)}\times\left(\frac{\Omega_x}{\Omega_y\Omega_z}\right)^{\frac{1}{2}(m_y+m_z-1)}\frac{\lambda^{-(m_y+m_z)}}{\Gamma(m_x)\Gamma(m_y)\Gamma(m_z)}$$
$$\times G_{2,1}^{1,2}\left(\frac{\Omega_y\Omega_z}{\Omega_x}\frac{m_x}{m_y m_z}\lambda^2\left|\begin{matrix}\frac{1}{2}(1+m_y-m_z),\frac{1}{2}(1-m_y+m_z)\\ \frac{1}{2}(2m_x+m_y+m_z-1)\end{matrix}\right.\right),$$

(21) $$F_\lambda(\lambda)=\left(\frac{m_y m_z}{m_x}\right)^{\frac{1}{2}(m_y+m_z-1)}\times\left(\frac{\Omega_x}{\Omega_y\Omega_z}\right)^{\frac{1}{2}(m_y+m_z-1)}\frac{1}{\Gamma(m_x)\Gamma(m_y)\Gamma(m_z)}\lambda^{(1-m_y-m_z)}$$
$$\times G_{3,2}^{1,3}\left(\frac{\Omega_y\Omega_z}{\Omega_x}\frac{m_x}{m_y m_z}\lambda^2\left|\begin{matrix}\frac{1}{2}(1+m_y-m_z),\frac{1}{2}(1-m_y+m_z),\frac{1}{2}(1+m_y+m_z)\\ \frac{1}{2}(2m_x+m_y+m_z-1),\frac{1}{2}(m_y+m_z-1)\end{matrix}\right.\right),$$

d) *α-μ* scenario:

$$p_\lambda(\lambda)=\alpha\left(\frac{\mu_y\mu_z}{\mu_x}\right)^{\frac{1}{2}(\mu_y+\mu_z-1)} \tag{22}$$

$$\times\left(\frac{\Omega_x}{\Omega_y\Omega_z}\right)^{\frac{1}{2}(\mu_y+\mu_z-1)}\frac{1}{\Gamma(\mu_x)\Gamma(\mu_y)\Gamma(\mu_z)}\lambda^{-\frac{\alpha}{2}(\mu_y+\mu_z-1)-1}$$

$$\times G_{2,1}^{1,2}\left(\frac{\Omega_y\Omega_z}{\Omega_x}\frac{\mu_x}{\mu_y\mu_z}\lambda^\alpha\left|\begin{matrix}\frac{1}{2}\left(1+\mu_y-\mu_z\right),\frac{1}{2}\left(1-\mu_y+\mu_z\right)\\ \frac{1}{2}(2\mu_x+\mu_y+\mu_z-1)\end{matrix}\right.\right),$$

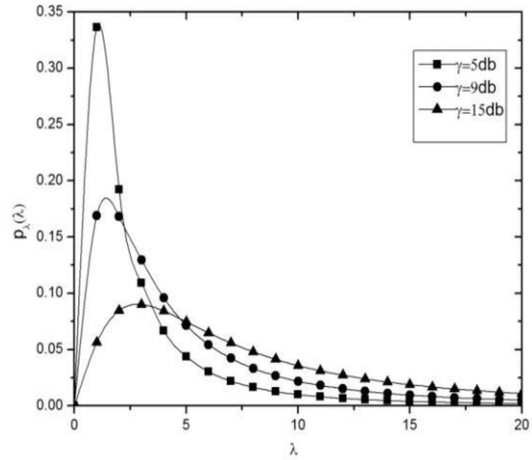

Fig. 1. PDF of *λ* in Rayleigh scenario

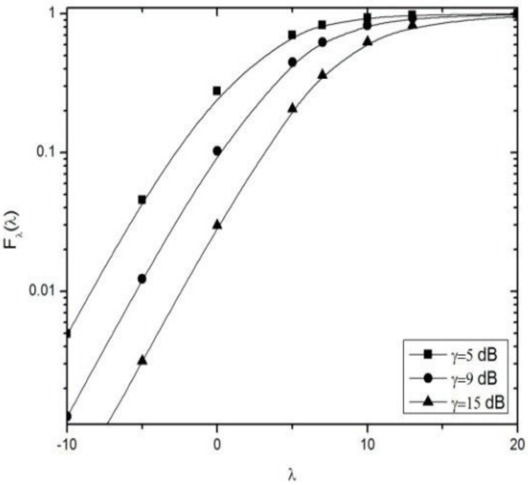

Fig. 2. CDF of *λ* in Rayleigh scenario

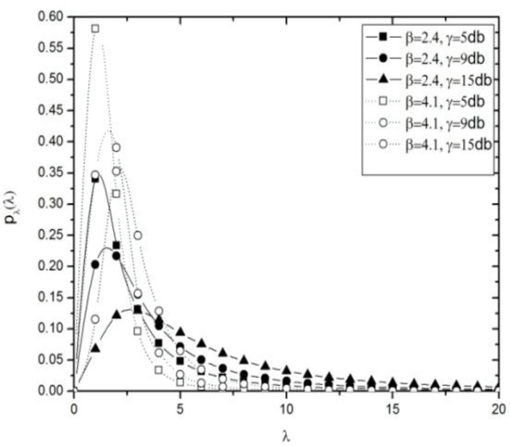

Fig. 3. PDF of *λ* in Weibull scenario

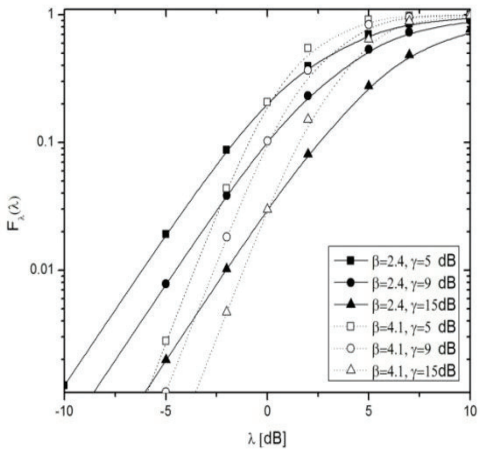

Fig. 4. CDF of *λ* in Weibull scenario

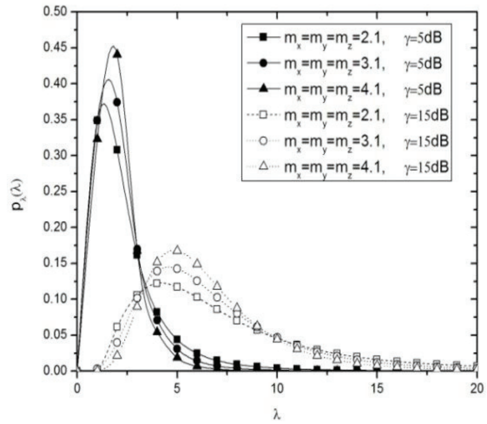

Fig. 5. PDF of *λ* in Nakagami-*m* scenario

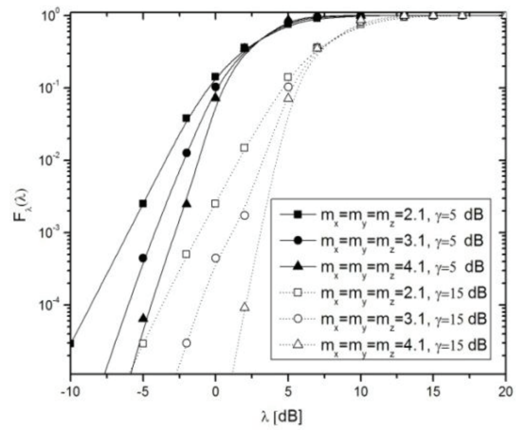

Fig. 6. CDF of *λ* in Nakagami-*m* scenario

$$F_\lambda(\lambda)=\left(\frac{\mu_y\mu_z}{\mu_x}\right)^{\frac{1}{2}(\mu_y+\mu_z-1)} \tag{23}$$

$$\times\left(\frac{\Omega_x}{\Omega_y\Omega_z}\right)^{\frac{1}{2}(\mu_y+\mu_z-1)}\frac{1}{\Gamma(\mu_x)\Gamma(\mu_y)\Gamma(\mu_z)}\lambda^{-\frac{\alpha}{2}(\mu_y+\mu_z-1)}$$

$$\times G_{3,2}^{1,3}\left(\frac{\Omega_y\Omega_z}{\Omega_x}\frac{\mu_x}{\mu_y\mu_z}\lambda^\alpha\left|\begin{matrix}\frac{1}{2}\left(1+\mu_y-\mu_z\right),\frac{1}{2}\left(1-\mu_y+\mu_z\right),\frac{1}{2}\left(1+\mu_y+\mu_z\right)\\ \frac{1}{2}\left(2\mu_x+\mu_y+\mu_z-1\right),\frac{1}{2}\left(\mu_y+\mu_z-1\right)\end{matrix}\right.\right).$$

The PDFs and CDFs of λ in all considered scenarios are presented in Figs. 1-8.

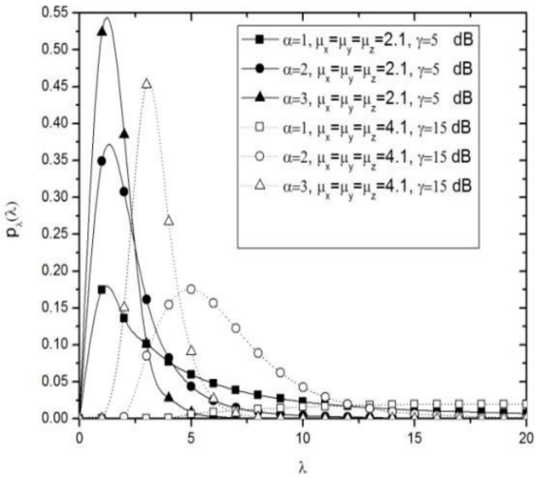

Fig. 7. PDF of λ in α-μ scenario

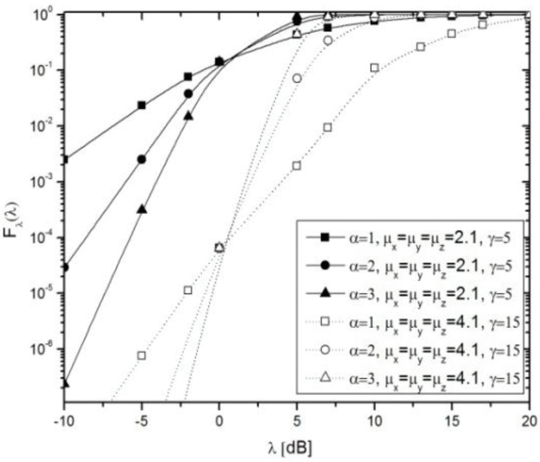

Fig. 8. CDF of λ in α-μ scenario

An application of presented theoretical results in wireless communication systems: the performance analysis of multi-hop systems

As shown in Fig. 9, *N*-hop transmission is a technique which enables that the source terminal *S* communicates with the destination terminal *D* through *N*-1 nodes terminals (relays) R_1, R_2, …, R_{N-1}.

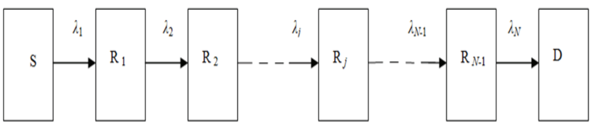

Fig. 9. *N*-hop transmission model

In theoretical study in previous section of the paper, the random variable x_i can represent desired signal envelope which suffers from fading while the product of random variables, $t_i = y_i z_i$, can represent CCI signal envelope which suffers simultaneously from both fading and shadowing. In that case, the random variable $\lambda_i = x_i / t_i$ represents SIR value at the input of *i*-th terminal ($i=\overline{1,N}$). Therefore, presented closed-form expressions for PDF and CDF of ratio of random variable and product of two random variables can be efficiently used in performance analysis of relayed communication systems.

Depending on the nature of the radio propagation environment, there are different distributions which model the statistical behavior of signal envelope. It is reason why preceding theoretical analysis includes Rayleigh, Weibull, Nakagami-*m* and *α-μ* model. The Rayleigh distribution is frequently used to model multipath fading with no direct line-of-sight (LOS) path [5]. The Weibull distribution fits well with experimental fading channel measurements, for both indoor [16] and outdoor [17] propagation environments. Nakagami-*m* model describes multipath scattering with relatively large delay-time spreads, with different clusters of reflected waves [18]. It provides good fits to collected data in indoor and outdoor mobile-radio environments and is used in many wireless communication applications [19]. Fading severity in Weibull and Nakagami-*m* environments is described by Weibull parameter *β* and Nakagami parameter *m*, respectively. As these parameters increase fading severity decreases. The *α-μ* distribution is a general fading distribution that can be used to better represent the small-scale variation of the fading signal [20]. Parameter *α* is related to the non-linearity of the environment, while parameter *μ* is associated to the number of multipath clusters are given [21].

Outage probability is an important and widely accepted system's performance measure defined as the probability that SIR value falls below a given outage threshold λ_0, also known as a protection ratio. The outage threshold is determined by expected quality-of-service (QoS). The system failure can occur in sections S-R_1, R_1-R_2, R_2-R_3, …, R_{j-1}-R_j, …,R_{N-1}-D when some of values of λ_1, λ_2, λ_3, …, λ_j, …, λ_N are below the predetermined threshold. It implies that the PDF of minimum of λ_i , $\lambda=\min\{\lambda_1, \lambda_2,\ldots, \lambda_N\}$, is important for analyzing multi-hop relayed communication systems. The PDF of λ can be obtained based on previous results as

$$p_\lambda(\lambda) = \sum_{n=1}^{N} p_{\lambda_n}(\lambda) \prod_{\substack{k=1 \\ k\neq n}}^{N} \left(1 - F_{\lambda_k}(\lambda)\right). \tag{24}$$

The outage probability of multi-hop system is defined as

$$P_{out} = \int_0^{\lambda_0} p_\lambda(s)\, ds. \tag{25}$$

As an illustrative example, the outage probability of dual-hop communication system can be obtained as

$$P_{out} = F_{\lambda_1}(\lambda)\left(1-F_{\lambda_2}(\lambda)\right) + F_{\lambda_2}(\lambda)\left(1-F_{\lambda_1}(\lambda)\right) + F_{\lambda_1}(\lambda) F_{\lambda_2}(\lambda). \tag{26}$$

The PDF of $\lambda=\min\{\lambda_1, \lambda_2\}$ and the outage probability of dual-hop communication system in Nakagami-*m* fading environment are shown in Fig. 10 and Fig. 11, respectively. Without loss of generality, equality of the ratios of average powers on terminals inputs, $\gamma_i = \Omega_{x_i} / \Omega_{y_i} \Omega_{z_i}$, *i*=1, 2, is assumed. Namely, signal is amplified in terminal *R* so that the ratio of average powers at the input of *D* terminal is equal to the ratio of average powers at the input of *R* terminal. It is clearly shown that system performance deteriorates, i.e. the outage probability increases when *γ* decreases and/or Nakagami parameters decreases. Only for higher values of λ_0, lower values of Nakagami parameters m_y and m_z, i.e. deep fading and shadowing behavior for CCI signal lead to the system performance enhancement.

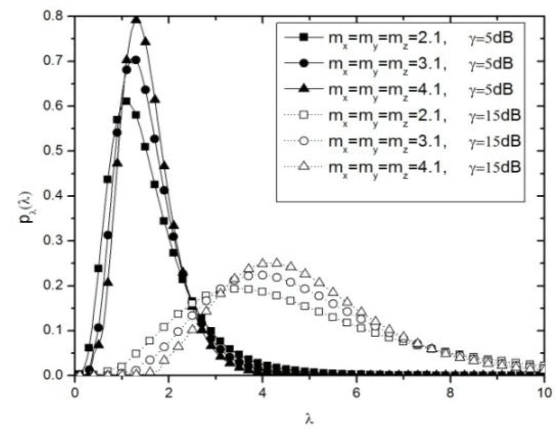

Fig. 10. PDF of λ=min{λ_1, λ_2} in Nakagami-*m* environment

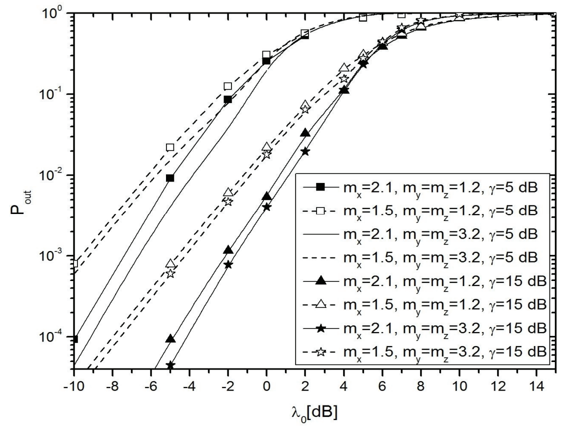

Fig. 11. Outage probability of dual-hop communication system in Nakagami-*m* environment

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