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Coverage Probability Analysis of Device-to-Device Communication Underlaid Cellular Networks in Uplink Over $\kappa - \mu/\eta - \mu$ Fading Channels

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Abstract

Device-to-device (D2D) communication is an emerging technique for future cellular networks to extend the network coverage. In D2D communication, two nearby mobile users can communicate directly without involving the base-station by sharing the uplink/downlink resource with cellular users. The performance of wireless communication deteriorates due to multipath fading and shadowing. Two generalized fading distributions namely $\kappa - \mu$ and $\eta - \mu$ have been proposed to characterize the line-of-sight and non-line-of-sight propagation effects respectively. In this paper, the expression of coverage probability for D2D communication, when D2D direct link undergoes $\kappa - \mu$ fading with random values of κ and μ, and interferers undergo $\eta - \mu$ fading with random values of η and μ has been derived. The stochastic geometry has been utilized to derive the expression of D2D coverage probability. The Lauricella's function, a special mathematical function has been used to represent the expression of D2D coverage probability which is easy to calculate numerically. The effects of fading parameters over coverage probability have been analyzed. Further, using the properties of Lauricella's function and particular values of fading parameters, D2D coverage probability expression has been simplified for four special cases. The D2D coverage probability results obtained from the analytical analysis have been validated through Monte-Carlo simulation.

Keywords Device-to-device communication · Coverage probability · Uplink resource · General $\kappa - \mu$ fading distribution · General $\eta - \mu$ fading distribution · Stochastic geometry

1 Introduction

Device-to-device (D2D) communication has become a major research area due to its various advantages in Long-Term Evolution-Advanced (LTE-A) and beyond cellular networks to meet the ever-increasing demands for local area services [1–3]. In D2D communication, the cellular users are able to communicate directly without involving any fixed network infrastructure or base station (BS). The standardization of D2D underlaid cellular networks have been dealt by the 3rd Generation Partnership Project (3GPP) [4]. The D2D communications are mainly divided into two major categories i.e. in-band and out-band. In case of in-band D2D communication, licensed cellular spectrum is used, while unlicensed ISM bands are used for out-band D2D mode of communication [5]. The overlaid D2D network and underlaid D2D network are two categories of in-band D2D mode. The out-band D2D has been categorized into the controlled and autonomous mode. As some resources are wasted in overlaid D2D networks, underlaid D2D networks are popularly used. Interference caused by the cellular user and D2D transmitters is the main challenge in D2D underlaid in-band cellular networks that need to be minimized [6].

A decade before, two generalized fading distributions i.e. $\kappa - \mu$ and $\eta - \mu$ were proposed by Yacoub [7]. The $\kappa - \mu$ distribution is mainly used to model and characterize the effects of line-of-sight (LoS) propagation whereas $\eta - \mu$ distribution for Non-line-of-sight (NLoS) propagation. The spacial cases of $\kappa - \mu$ distribution are the Rayleigh, the Rician, the Nakagami-m and the One-sided Gaussian distributions. Similarly the spacial cases of $\eta - \mu$ distribution are the Rayleigh, the

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Nakagami-m, Hoyt (Nakagami-q) and the One-sided Gaussian distributions [8]. The $\eta-\mu$ fading distribution has two different format on the basis of physical meaning of the parameter η. The effect of shadowing over D2D communication, when D2D direct link experiences $\kappa-\mu$ shadowed fading has been analyzed in [9]. The channel modeling using $\kappa-\mu$ shadowed fading to characterize the shadowing due to human body in D2D communication has been discussed in [10]. The outage probability and spectral efficiency of D2D communication in overlay mode have been analyzed over generalized $\kappa-\mu$ and $\eta-\mu$ fading [8]. To model and characterize the LoS and NLoS channels in cellular network using $\kappa-\mu$ and $\eta-\mu$ fading with shadowing has been analyzed in [11]. The outage probability and the ergodic capacity of cognitive radio network has been derived, when all the links experience $\kappa-\mu$ fading with shadowing by choosing arbitrary parameters value [12]. Average channel capacity and outage probability expression over $\kappa-\mu$/gamma shadowed faded channel are derived in [13]. Coverage and capacity of D2D communication have been improved with the help of full duplex amplify and forward relay in [14]. The exact closed-form expressions of outage probability (OP) for mobile D2D networks with transmit antenna selection (TAS) were derived for incremental amplify-and-forward (IAF) relaying in which the simulation results show that optimal TAS scheme has a better OP performance than suboptimal TAS scheme [15]. Authors in [16], derived the exact closed-form OP expressions for IAF relaying D2D networks with TAS over N-Nakagami fading channels and simulation results show that optimal TAS scheme has a better OP performance than suboptimal TAS scheme.

The researchers working in wireless communication consider the coverage probability as the key parameter to measure the performance of cellular networks. The coverage probability is basically the complementary cumulative distribution function (CCDF) of the instantaneous Signal-to-Interference Ratio (SIR) in the interference limited environment. In literature, generalized $\kappa-\mu/\eta-\mu$ fading was widely used to characterize the behavior of the wireless channel. Literature survey shows that k-mu and eta-mu fading have not been used for analyzing the performance of D2D communication. In D2D communication, users are basically in short distance therefore $\kappa-\mu$ fading for D2D link and $\eta-\mu$ fading for interfering links are more suitable. Hence, in this paper the D2D coverage probability for underlaid cellular networks has been analyzed by considering $\kappa-\mu$ and $\eta-\mu$ fading for D2D link and interfering links respectively.

The main contributions of this paper are as follows:

- The generalized $\kappa-\mu$ and $\eta-\mu$ fading have been used for modeling D2D link and interfering links respectively.
- The expression of D2D coverage probability has been derived in terms of Lauricellas function which makes calculation easier.
- The Monte-Carlo simulations have been performed to validate the derived expressions.
- The effect of various system parameters such as D2D pair distance, SIR threshold, and different fading parameters on D2D coverage probability has been shown.

The remainder of this paper is organized as follows: Sect. 2 describes the proposed system model and the assumptions made for the analysis. In Sect. 3, expression for the D2D coverage probability has been derived. The results of D2D coverage probability for different cases with discussions are provided in Sect. 4. Finally, the conclusion of the paper is given in Sect. 5.

Notation The following notations are used in this paper. $f_X(\cdot)$ indicates the probability density function (pdf) and $F_X(\cdot)$ indicates the cumulative distribution function (CDF) of a random variable X. $\mathbb{P}(\cdot)$ denotes the probability measure. $\Gamma(\cdot)$ is the gamma function. $\gamma(\cdot,\cdot)$ is the lower incomplete gamma function. $\mathcal{L}_X(\cdot)$ is the Laplace transformation of X, $\mathbb{E}[\cdot]$ represents the expectation and $var[\cdot]$ represents the variance of a random variable. $I_a(\cdot)$ is the modified Bessel function of the first kind and order a.

2 System Model

In this section, the considered system model details, assumptions made and involved parameters are given. A single circular cell with radius R, composed of multiple user equipments (UEs) and a single evolved Node B (eNB) located in the center of the cell is given as shown in Fig. 1. The uplink radio resource of cellular network has been reused by D2D users. The considered network employs the orthogonal frequency division multiple access (OFDMA) scheme to avoid interference from other UEs inside the cell. All UEs and eNB are equipped with a single omni-directional antenna. The UEs are communicated either

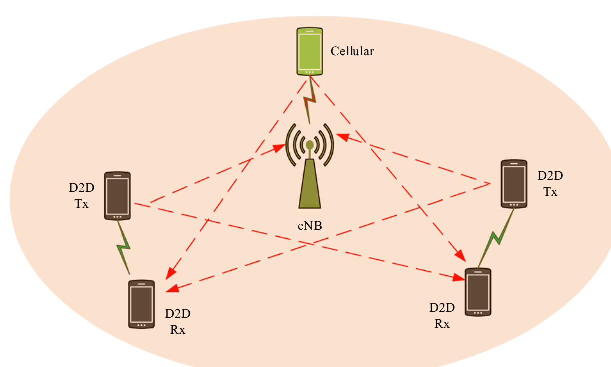

Fig. 1 System model of D2D communication underlaid cellular networks with uplink resource sharing. Directed lines indicate interference

into cellular mode or into D2D mode depends on the distance between them. In cellular mode, communication between UEs has been performed via eNB but in D2D mode, two UEs communicate directly with each other without involving eNB. It is assumed that the mode of communication of each UE has been decided by eNB and inter-cell interference is managed efficiently with the inter-cell interference control (ICIC) mechanism. Hence, we focus only on the intra-cell interference caused by the coexistence of a cellular UE and D2D pairs. Let a cellular user and a set of D2D pairs $\mathcal{D} = \{1, 2, \dots, N\}$ inside the cell and each D2D pair consists of a transmitter and a receiver.

All UEs inside the cell are randomly distributed and modeled as spatial poisson point process (PPP) on the two dimensional plane $\mathbb{R}^2$. The propagation loss over a distance d is assumed to follow a power exponent path loss model $d^{-\alpha}$, where $\alpha \geq 2$ is the path-loss exponent. In case of interference limited system, noise is omitted and therefore the received Signal-to-Interference-Ratio (SIR) in D2D communication for D2D pair i is given as

$$\mathrm{SIR}_i = \frac{g_{i,i} r_{i,i}^{-\alpha}}{G_{c,i} d_{c,i}^{-\alpha} + \sum\limits_{i' \in \mathcal{D}, i' \neq i} G_{i',i} d_{i',i}^{-\alpha}} \tag{1}$$

where $g_{i,i}$, G_{cd} and $G_{i',i}$ are the channel gain between the D2D Tx and the D2D Rx of typical pair i, between the CUE and the D2D Rx of typical pair i and between the transmitter of D2D pair i' and the receiver of D2D pair i, respectively. The distance from the transmitter to the receiver of D2D pair i is denoted as $r_{i,i}$, from CUE to the receiver of D2D pair i is $d_{c,i}$ and from transmitter of D2D pair i' and the receiver of D2D pair i is $d_{i',i}$.The gain $g_{i,i}$ is assumed to experiences $\kappa - \mu$ fading and the gain of interfering channels experience $\eta - \mu$ fading. The symbol $\mathcal{D}$ represents the set of all D2D pairs. The pdf of $\kappa - \mu$ power RV $g_{i,i}$ is given by [7, Eq. (2)]:

$$f_{g_{i,i}}(x) = \frac{\mu(1+\kappa)^{\frac{\mu+1}{2}} x^{\frac{\mu-1}{2}}}{\kappa^{\frac{\mu-1}{2}} \exp(\mu\kappa)} \mathrm{e}^{-\mu(1+\kappa)x} I_{\mu-1}\left(2\mu\sqrt{k(1+k)x}\right) \tag{2}$$

where κ is the real non-negative shaping parameter and defined as the ratio of the total power of dominant components to that of scattered waves total power, and $\mu = \frac{\mathbb{E}^2[g]}{var[g]} \frac{1+2\kappa}{(1+\kappa)^2}$. The modified Bessel function of first kind used in (2) can be expressed as an infinite series expansion form i.e. $I_a(x) = \sum_{j=0}^{\infty} \frac{1}{j!\Gamma(j+a+1)} \left(\frac{x}{2}\right)^{2j+a}$. Therefore the pdf expressed in (2) also can be rewritten as:

$$f_g(x) = \frac{\mu^\mu (1+\kappa)^\mu x^{\mu-1}}{\exp(\mu\kappa)} \mathrm{e}^{-\mu(1+\kappa)x} \sum_{j=0}^{\infty} \frac{\left(\mu^\mu \kappa(1+\kappa)x\right)^j}{j!\Gamma(j+\mu)} \tag{3}$$

As the gain of the interfering channels are assumed to experience the $\eta - \mu$ fading, therefore the pdf of the $\eta - \mu$ power RV $G_{i',i}$ is given by [7, Eq. (26)],

$$f_{G_i}(x) = \frac{2\sqrt{\pi}\mu_i^{\mu_i+\frac{1}{2}} h_i^{\mu_i} x^{\mu_i-\frac{1}{2}}}{\Gamma(\mu_i) H_i^{\mu_i-\frac{1}{2}}} \mathrm{e}^{-2\mu_i h_i x} I_{\mu-\frac{1}{2}}(2\mu_i H_i x) \tag{4}$$

where $\mu_i > 0$ is given by $\mu_i = \frac{\mathbb{E}^2[G_i]}{2var[G_i]}\left[1 + \left(\frac{H_i}{h_i}\right)^2\right]$. The statistical model of the pdf given in (4), comprises two different fading formats with different physical meanings of the parameter η_i and different definitions of the parameters H_i and h_i. In format (i), the parameter $0 < \eta_i < \infty$ represents the power ratio between the independent in-phase and quadrature components of the fading signal in each multipath cluster, and the parameters H_i and h_i are defined as

$$H_i = \frac{\eta_i^{-1} - \eta_i}{4}, \quad \text{and} \quad h_i = \frac{2 + \eta_i^{-1} + \eta_i}{4}. \tag{5}$$

In format (ii), the parameter $-1 < \eta_i < 1$ represents the correlation coefficient between the in-phase and quadrature scattered waves in each multipath cluster with a power ratio of unity, and the parameters H_i and h_i are specified as

$$H_i = \frac{\eta_i}{1 - \eta_i^2}, \quad \text{and} \quad h_i = \frac{1}{1 - \eta_i^2}. \tag{6}$$

In the denominator of SIR given in (1), the total interfering channels are N, since $N - 1$ D2D transmitters and one cellular user interfere to typical D2D receiver. The derivation of moment generating function (MGF) for the generalized $\eta - \mu$ fading distribution of (4) has been given in [17]. Kalyani and Karthik in [18] shows that MGF of generalized $\eta - \mu$ power variates can be expressed as the product of the MGFs of two gamma distribution with the same shape parameter μ and different scale parameters $\lambda_1 = \frac{1}{2\mu(h+H)}$ and $\lambda_2 = \frac{1}{2\mu(h-H)}$. Since the G_i is sum of two Gamma variates and multiplied with $d_i^{-\alpha}$ as the weight. Hence the total interference I is the sum of weighted gamma variates. According to the weighting property, the weighted gamma variates $G_i' = G_i d_i^{-\alpha}$ can be written as gamma variates with weighted scale parameter. If $G_i = \mathcal{G}(\mu_i, \lambda_i)$ then $G_i' = \mathcal{G}(\mu_i, \lambda_i d_i^{-\alpha})$. The cumulative interference $I = \sum_{i=1}^{N}(a_i' + b_i')$ of $2N$ i.n.i.d. gamma RVs, where $a_i' \sim \mathcal{G}(\mu_i, \lambda_{2i-1})$ with $\lambda_{2i-1} = \lambda_{2i-1}' d_i^{-\alpha}$ and $b_i' \sim \mathcal{G}(\mu_i, \lambda_{2i})$ with $\lambda_{2i} = \lambda_{2i}' d_i^{-\alpha}$ has a pdf given by [18, 19]

$$f_I(x) = \frac{x^{\sum_{i=1}^{N} 2\mu_i - 1}}{\prod_{i=1}^{N}(\lambda_{2i}\lambda_{2i-1})^{\mu_i}\Gamma\left(\sum_{i=1}^{N} 2\mu_i\right)} \Phi_2^{(2N)} \left(\mu_1, \mu_1, \dots, \mu_N, \mu_N; \sum_{i=1}^{N} 2\mu_i; \frac{-x}{\lambda_1}; \cdots; \frac{-x}{\lambda_{2N}}\right) \tag{7}$$

where $\Phi_2^{(N)}(\cdots)$ denotes the confluent Lauricella multivariate hypergeometric function [20]. The CDF of the total interference I can be obtain by integrating the pdf expression (7), and given as [18]

$$F_I(x) = \frac{x^{\sum_{i=1}^{N} 2\mu_i}}{\prod_{i=1}^{N}(\lambda_{2i}\lambda_{2i-1})^{\mu_i}\Gamma\left(\sum_{i=1}^{N} 2\mu_i + 1\right)}\Phi_2^{(2N)} \left(\mu_1, \mu_1, \ldots, \mu_N, \mu_N; \sum_{i=1}^{N} 2\mu_i + 1; \frac{-x}{\lambda_1}; \cdots ; \frac{-x}{\lambda_{2N}}\right) \tag{8}$$

3 Coverage Probability of D2D Communication

Coverage probability is defined as the probability of received Signal-to-Interference-Ratio (SIR) can be greater than the predefined SIR threshold (T). The coverage probability of D2D communication underlaid cellular networks can be defined as

$$P_{cov} = \mathbb{P}[\mathrm{SIR}_i > T] = \mathbb{P}\left[\frac{g_{i,i}r_{i,i}^{-\alpha}}{I} > T\right] = \mathbb{P}\left[I < \frac{g_{i,i}}{Tr_{i,i}^{\alpha}}\right] \tag{9}$$

where T is the predefined SIR threshold for D2D communication. $I = G_{c,i}d_{c,i}^{-\alpha} + \sum_{i'\in D, i'\neq i} G_{i',i}d_{i',i}^{-\alpha}$. For simplicity, we assume that the term $g_{i,i} = g$, $r_{i,i} = r$ and $G_{i',i} = G_i$. Now, using the CDF of the total interference I given in (8), coverage probability of D2D communication becomes

$$P_{cov} = \mathbb{E}_g\left[\frac{\left(\frac{g}{Tr^{\alpha}}\right)^{\sum_{i=1}^{N} 2\mu_i}}{\prod_{i=1}^{N}(\lambda_{2i}\lambda_{2i-1})^{\mu_i}\Gamma\left(2\sum_{i=1}^{N} \mu_i + 1\right)}\Phi_2^{(2N)} \left(\mu_1, \mu_1, \ldots, \mu_N, \mu_N; \sum_{i=1}^{N} 2\mu_i + 1; \frac{-g}{Tr^{\alpha}\lambda_1}; \cdots ; \frac{-g}{Tr^{\alpha}\lambda_{2N}}\right)\right] \tag{10}$$

where $\mathbb{E}_g[\cdot]$ is the expectation with respect to RV g, since g is a power RV and experiences $\kappa - \mu$ fading with pdf given in (3), therefore (10) can be simplified as:

$$P_{cov} = \int_0^{\infty}\left(\frac{\left(\frac{g}{Tr^{\alpha}}\right)^{\sum_{i=1}^{N} 2\mu_i}}{\prod_{i=1}^{N}(\lambda_{2i}\lambda_{2i-1})^{\mu_i}\Gamma\left(\sum_{i=1}^{N} 2\mu_i + 1\right)}\Phi_2^{(2N)} \left(\mu_1, \mu_1, \ldots, \mu_N, \mu_N; \sum_{i=1}^{N} 2\mu_i + 1; \frac{-g}{Tr^{\alpha}\lambda_1}; \cdots ; \frac{-g}{Tr^{\alpha}\lambda_{2N}}\right) \times \frac{\mu^{\mu}(1+\kappa)^{\mu} g^{\mu-1}}{\exp(\mu\kappa)} \mathrm{e}^{-\mu(1+\kappa)g} \sum_{j=0}^{\infty} \frac{\left(\mu^{\mu}\kappa(1+\kappa)g\right)^j}{j!\Gamma(j+\mu)}\right)dg. \tag{11}$$

To solve (11), we need to interchange summation with integration. The procedure is given in [21, Appendix A]. After interchanging summation with integration, coverage probability given in (11) can be written as

$$P_{cov} = A\sum_{j=0}^{\infty}\frac{\left(\mu^2\kappa(1+\kappa)\right)^j}{j!\Gamma(j+\mu)}\int_0^{\infty} g^{\sum_{i=1}^{N} 2\mu_i+\mu+j-1}e^{-\mu(1+\kappa)g} \times \Phi_2^{(2N)}\left(\mu_1, \mu_1, \ldots, \mu_N, \mu_N; \sum_{i=1}^{N} 2\mu_i + 1; \frac{-g}{Tr^{\alpha}\lambda_1}; \cdots ; \frac{-g}{Tr^{\alpha}\lambda_{2N}}\right)dg. \tag{12}$$

where $A = \frac{\mu^{\mu}(1+\kappa)^{\mu}}{\exp(\mu\kappa)\Gamma\left(\sum_{i=1}^{N} 2\mu_i+1\right)}\prod_{i=1}^{N}\left(\frac{1}{\lambda_{2i}\lambda_{2i-1}T^2r^{2\alpha}}\right)^{\mu_i}$. Replacing $\mu(1+\kappa)g = t$ in (12) and rewrite again

$$P_{cov} = A\sum_{j=0}^{\infty}\frac{\left(\mu^2\kappa(1+\kappa)\right)^j}{j!\Gamma(j+\mu)}\left(\frac{1}{\mu(1+\kappa)}\right)^{\sum_{i=1}^{N} 2\mu_i+\mu+j} \times \int_0^{\infty} t^{\sum_{i=1}^{N} 2\mu_i+\mu+j-1}e^{-t} \times \Phi_2^{(2N)}\left(\mu_1, \mu_1, \ldots, \mu_N, \mu_N; \sum_{i=1}^{N} 2\mu_i + 1; \frac{-t}{Tr^{\alpha}\lambda_1\mu(1+\kappa)}; \cdots ; \frac{-t}{Tr^{\alpha}\lambda_{2N}\mu(1+\kappa)}\right)dt. \tag{13}$$

To solve the integral in (13), use the relation between confluent Lauricella multivariate hypergeometric function and Lauricella's function of the fourth kind [22] as given below

$$F_D^{(N)}[a, b_1, \ldots, b_N; c; x_1, \ldots, x_N] = \frac{1}{\Gamma(a)}\int_0^{\infty} t^{a-1}e^{-t}\Phi_2^{(N)}[b_1, \ldots, b_N; c; x_1 t, \ldots, x_N t]dt \tag{14}$$

Using the relationship given in (14) to solve (13), we get

$$P_{cov} = B\sum_{j=0}^{\infty}\frac{\Gamma\left(\sum_{i=0}^{N} 2\mu_i + \mu + j\right)(\mu\kappa)^j}{j!\Gamma(j+\mu)}F_D^{(2N)}\left[\sum_{i=1}^{N} 2\mu_i + \mu + j, \mu_1, \mu_1, \ldots, \mu_N, \mu_N; \sum_{i=1}^{N} 2\mu_i + 1; \frac{-1}{Tr^{\alpha}\lambda_1\mu(1+\kappa)}, \ldots, \frac{-1}{Tr^{\alpha}\lambda_{2N}\mu(1+\kappa)}\right] \tag{15}$$

where $B = \frac{1}{\exp(\mu\kappa)\Gamma\left(\sum_{i=1}^{N} 2\mu_i+1\right)}\prod_{i=1}^{N}\left(\frac{1}{\lambda_{2i}\lambda_{2i-1}T^2r^{2\alpha}\mu^2(1+\kappa)^2}\right)^{\mu_i}$

where $F_D^{(2N)}[\cdot]$ is Lauricella's function of the fourth kind [22] and defined as

$$F_D^{(N)}[a,b_1,\dots,b_N;c;x_1,\dots,x_N] = \sum_{i_1\dots i_N=0}^{\infty} \frac{(a)_{i_1+\dots+i_N}(b_1)_{i_1}\cdots(b_N)_{i_N}}{(c)_{i_1+\dots+i_N}} \frac{x_1^{i_1}}{i_1!}\cdots\frac{x_N^{i_N}}{i_N!} \tag{16}$$

$max\{|x_1|,\dots,|x_N|\} < 1$, where $(a)_n$ is the pochammer symbol defined as $(a)_n = \frac{\Gamma(a+n)}{\Gamma(a)}$. The nature of (16) will be convergent only if $max\{|x_1|,\dots,|x_N|\} < 1$. However from (16) it is clear that the condition for convergence not satisfied. To make it convergent, following property of $F_D^{(N)}[\cdot]$ has been used.

$$F_D^{(N)}[a,b_1,\dots,b_N;c;x_1,\dots,x_N] = \prod_{i=1}^{N}\left(\frac{1}{1-x_i}\right)^{b_i} \times F_D^{(N)}\left[c-a,b_1,\dots,b_N;c;\frac{x_1}{x_1-1},\dots,\frac{x_N}{x_N-1}\right] \tag{17}$$

Using (17), (15) becomes

$$P_{cov} = C\sum_{j=0}^{\infty}\frac{\Gamma\left(\sum_{i=0}^{N}2\mu_i+\mu+j\right)(\mu\kappa)^j}{j!\Gamma(j+\mu)}F_D^{(2N)} \Big[1-\mu-j,\mu_1,\mu_1,\dots,\mu_N,\mu_N; \sum_{i=1}^{N}2\mu_i+1;\frac{1}{1+Tr^\alpha\lambda_1\mu(1+\kappa)},\dots,\frac{1}{1+Tr^\alpha\lambda_{2N}\mu(1+\kappa)}\Big] \tag{18}$$

where $C = \frac{e^{-\mu\kappa}}{\Gamma\left(\sum_{i=1}^{N}2\mu_i+1\right)}\prod_{i=1}^{N}\left[\frac{1}{(1+\lambda_{2i-1}Tr^\alpha\mu(1+\kappa))(1+\lambda_{2i}Tr^\alpha\mu(1+\kappa))}\right]^{\mu_i}$.

Now scale parameter of gamma distribution λ_i can be expressed in terms of shaping parameters of $\eta-\mu$ fading i.e. μ_i and η_i.The final expression of coverage probability of D2D communication can be given as

$$P_{cov} = C\sum_{j=0}^{\infty}\frac{\Gamma\left(\sum_{i=0}^{N}2\mu_i+\mu+j\right)(\mu\kappa)^j}{j!\Gamma(j+\mu)}F_D^{(2N)}\Bigg[1-\mu-j,\mu_1,\mu_1,\dots,\mu_N,\mu_N;\sum_{i=1}^{N}2\mu_i+1; \frac{1}{1+\frac{Tr^\alpha\mu(1+\kappa)}{d_1^\alpha\mu_1(1+\eta_1^{-1})}},\frac{1}{1+\frac{Tr^\alpha\mu(1+\kappa)}{d_1^\alpha\mu_1(1+\eta_1)}},\dots, \frac{1}{1+\frac{Tr^\alpha\mu(1+\kappa)}{d_N^\alpha\mu_N(1+\eta_N^{-1})}},\frac{1}{1+\frac{Tr^\alpha\mu(1+\kappa)}{d_N^\alpha\mu_N(1+\eta_N)}}\Bigg] \tag{19}$$

where $C = \frac{\prod_{i=1}^{N}\left[\left(1+\frac{Tr^\alpha\mu(1+\kappa)}{d_i^\alpha\mu_i(1+\eta_i^{-1})}\right)\left(1+\frac{Tr^\alpha\mu(1+\kappa)}{d_i^\alpha\mu_i(1+\eta_i)}\right)\right]^{-\mu_i}}{\exp(\mu\kappa)\Gamma\left(\sum_{i=1}^{N}2\mu_i+1\right)}$.

The expression given in (19) is the D2D coverage probability when D2D direct link follows generalized $\kappa-\mu$ fading with random parameter and interferers follow generalized $\eta-\mu$ fading with random parameters. The different special cases of D2D coverage probability are given depending on fading experiences by D2D direct link and interferers.

Case I D2D coverage probability expression when D2D direct link undergoes Rayleigh fading and interferers undergo $\eta-\mu$ fading.

The Rayleigh fading is one of the special case of generalized $\kappa-\mu$ fading when shaping parameters become $\kappa=0$ and $\mu=1$. By applying the property of Lauricella function $F_D^{(N)}[0,\beta_1,\dots,\beta_N;\gamma;x_1,\dots,x_N]=1$ in (12), coverage probability of D2D communication becomes

$$P_{cov} = \prod_{i=1}^{N}\left[\left(\frac{d_i^\alpha\mu_i(1+\eta_i^{-1})}{d_i^\alpha\mu_i(1+\eta_i^{-1})+Tr^\alpha}\right)\left(\frac{d_i^\alpha\mu_i(1+\eta_i)}{d_i^\alpha\mu_i(1+\eta_i)+Tr^\alpha}\right)\right]^{\mu_i} \tag{20}$$

The μ_i and η_i are the arbitrary parameters of generalized $\eta-\mu$ fading. The effect of SIR threshold over D2D coverage probability has been analyzed against D2D pair distance. Assuming all the interferers are equidistant and value of shaping parameters are $\mu_i=0.5\forall_i$ and $\eta_i=1.5\forall_i$.

Case II D2D coverage probability expression when D2D direct link undergoes Nakagami-*m* fading and interferers experiences generalized $\eta-\mu$ fading.

The Nakagami-*m* fading is a more feasible and widely accepted for small scale fading. It can be obtained as a special case of generalized $\kappa-\mu$ fading when shaping parameters set to $\kappa=0$ and $\mu=m$. After simplifying (19), D2D coverage probability becomes

$$P_{cov} = \frac{\prod_{i=1}^{N}\left[\left(\frac{d_i^\alpha\mu_i(1+\eta_i^{-1})}{d_i^\alpha\mu_i(1+\eta_i^{-1})+Tr^\alpha}\right)\left(\frac{d_i^\alpha\mu_i(1+\eta_i)}{d_i^\alpha\mu_i(1+\eta_i)+Tr^\alpha}\right)\right]^{\mu_i}\Gamma\left(\sum_{i=1}^{N}2\mu_i+m\right)}{\Gamma(m)\Gamma\left(\sum_{i=1}^{N}2\mu_i+1\right)} \times F_D^{(2N)}\Bigg[1-m,\mu_1,\mu_1,\dots,\mu_N,\mu_N;\sum_{i=1}^{N}2\mu_i+1; \frac{1}{1+\frac{Tr^\alpha m}{d_1^\alpha\mu_1(1+\eta_1^{-1})}},\frac{1}{1+\frac{Tr^\alpha m}{d_1^\alpha\mu_1(1+\eta_1)}},\dots, \frac{1}{1+\frac{Tr^\alpha m}{d_N^\alpha\mu_N(1+\eta_N^{-1})}},\frac{1}{1+\frac{Tr^\alpha m}{d_N^\alpha\mu_N(1+\eta_N)}}\Bigg] \tag{21}$$

where m is the parameter of the Nakagami-*m* fading distribution. The effect of m over D2D coverage probability has been analyzed.

Case III D2D coverage probability expression when D2D direct link undergoes Rician fading and interferers experiences $\eta-\mu$ fading.

The Rician fading can be obtained from generalized $\kappa-\mu$ fading by setting $\mu=1$ in (3). The parameter κ correspond to well-known Rice parameter K. After putting $\mu=1$ and $\kappa=K$ in (19), D2D coverage probability becomes

$$P_{cov} = C \sum_{j=0}^{\infty} \frac{\Gamma\left(\sum_{i=1}^{N} 2\mu_i + j + 1 \right) K^j}{j! \Gamma(j+1)} F_D^{(2N)} \left[-j, \mu_1, \mu_1, \ldots, \mu_N, \mu_N; \sum_{i=1}^{N} 2\mu_i + 1; \frac{1}{1 + \frac{Tr^\alpha(1+K)}{d_1^\alpha \mu_1 (1+\eta_1^{-1})}}, \frac{1}{1 + \frac{Tr^\alpha(1+K)}{d_1^\alpha \mu_1 (1+\eta_1)}}, \ldots, \frac{1}{1 + \frac{Tr^\alpha(1+K)}{d_N^\alpha \mu_N (1+\eta_N^{-1})}}, \frac{1}{1 + \frac{Tr^\alpha(1+K)}{d_N^\alpha \mu_N (1+\eta_N)}} \right] \tag{22}$$

where $C = \frac{\Pi_{i=1}^{N} \left[\left(\frac{d_i^\alpha \mu_i (1+\eta_i^{-1})}{d_i^\alpha \mu_i (1+\eta_i^{-1}) + Tr^\alpha} \right) \left(\frac{d_i^\alpha \mu_i (1+\eta_i)}{d_i^\alpha \mu_i (1+\eta_i) + Tr^\alpha} \right) \right]^{\mu_i}}{\exp(K) \Gamma\left(\sum_{i=1}^{N} 2\mu_i + 1 \right)}$

Case IV D2D coverage probability expression when D2D direct link undergoes Rayleigh fading and interferers experiences Nakagami-m fading.

The general $\kappa - \mu$ fading becomes Rayleigh fading by putting $\kappa = 0$ and $\mu = 1$. In case of generalized $\eta - \mu$ fading, the Nakagami-m fading can be obtained by putting $\mu_i = \frac{m_i}{2}$ and $\eta_i = 1$. Therefore for this special case, the D2D coverage probability given in (19) can be simplified as

$$P_{cov} = \prod_{i=1}^{N} \left(\frac{m_i}{m_i + Tr^\alpha d_i^{-\alpha}} \right)^{m_i} \tag{23}$$

The effect of SIR threshold T over D2D coverage probability has been analyzed.

4 Results and Discussion

In this section, the effect of fading parameters on D2D coverage probability has been shown numerically and validated through Monte-Carlo simulations. The analytical expression of D2D coverage probability when D2D direct link follows generalized $\kappa - \mu$ fading and interferers follow generalized $\eta - \mu$ fading with arbitrary parameters has been plotted for different set of fading parameters to analyze the effects. The D2D coverage probability expressions for various special cases have been obtained to analyze the effect of fading parameters and SIR threshold. MATLAB, a computational software has been used for performance analysis.

Figure 2 shows the D2D coverage probability of D2D communication with respect to the SIR threshold for different values of κ and fixed value of μ. D2D coverage probability increases with the increase in D2D direct link fading parameter κ. The reason is that effective SIR increases with the increase of κ because κ is the ratio of total dominant power to that of total power of scattered waves. Similarly,

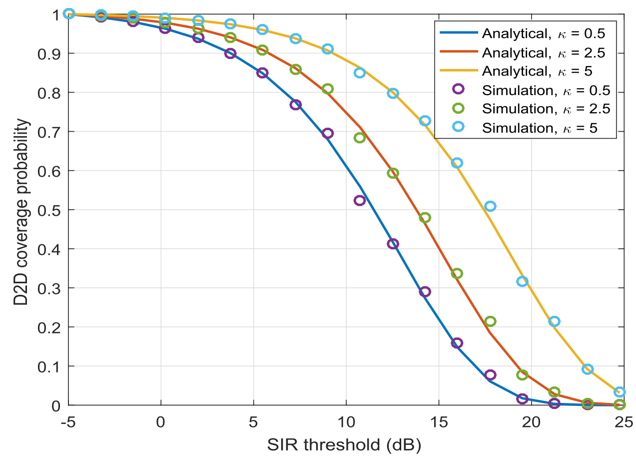

Fig. 2 D2D coverage probability versus SIR threshold plot when D2D direct link follows general $\kappa - \mu$ fading and interferers follow general $\eta - \mu$ fading for different value of κ. Taking $\mu = 1.5$, $r = 20$ m, $\alpha = 3.5$, $N = 31$, $\eta_i = 1.5\ \forall_i$ and $\mu_i = 0.5\ \forall_i$

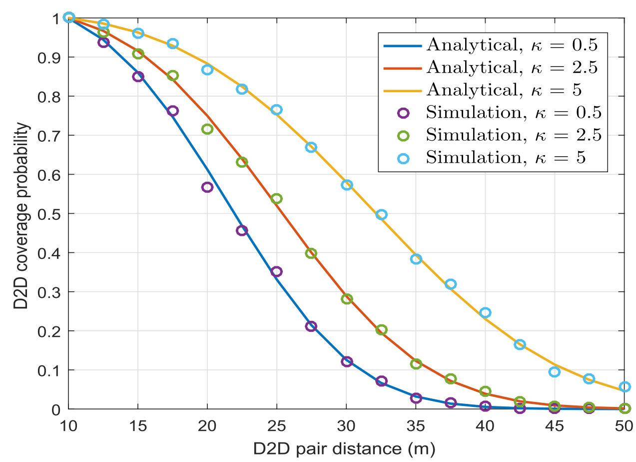

Fig. 3 D2D coverage probability versus D2D pair distance plot when D2D direct link follows general $\kappa - \mu$ fading and interferers follow general $\eta - \mu$ fading for different value of κ. Taking $\mu = 1.5$, $T = 0$ dB, $\alpha = 3.5$, $N = 31$, $\eta_i = 1.5\ \forall_i$ and $\mu_i = 0.5\ \forall_i$

Fig. 3 shows the D2D coverage probability with respect to D2D pair distance for different values of κ and fixed value of μ. Again the coverage probability increases with the increase in fading parameter κ due to more received power of dominant component.

Figure 4 depicts the D2D coverage probability with respect to D2D pair distance for different value of SIR threshold as derived in *case I*. It is observed that the low SIR threshold attain the high coverage as compare to high SIR threshold. The reason is that high SIR required for high threshold. Figure 5 shows the D2D coverage probability respect to the D2D pair distance for different values

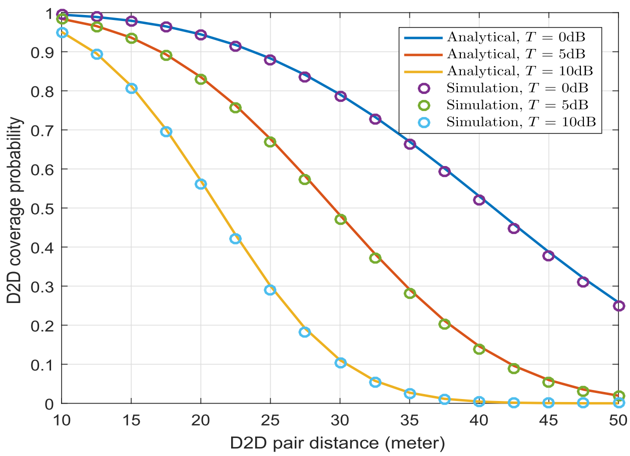

Fig. 4 Coverage probability versus D2D pair distance plot when D2D link undergoes Rayleigh fading and interferers undergo $\eta - \mu$ fading for different value of D2D SIR threshold. Here $\alpha = 3.5$, $N = 31$, $\eta_i = 1.5\ \forall_i$ and $\mu_i = 0.5\ \forall_i$

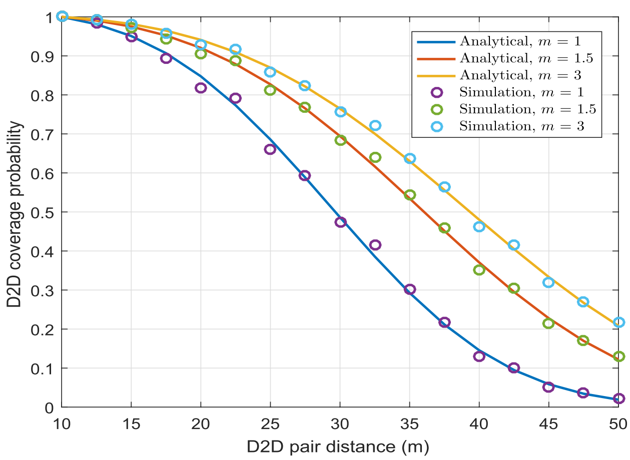

Fig. 5 Coverage probability versus D2D pair distance plot when D2D link undergoes Nakagami-m fading and interferers undergo $\eta - \mu$ fading for different value of fading parameter m. Here $T = 0$ dB, $\alpha = 3.5$, $N = 31$, $\eta_i = 1.5\ \forall_i$ and $\mu_i = 0.5\ \forall_i$

of fading parameter m as derived in *case II*. It is observed that the coverage probability increases with increase in fading parameter m. The reason is that the received signal power is high for high value of fading parameter m.

In Fig. 6, D2D coverage probability for *case III* has been plotted against D2D pair distance for different values of Rician factor K. The D2D coverage increases with increase of Rician factor. Again the reason is that the received signal power increases with increase in K.

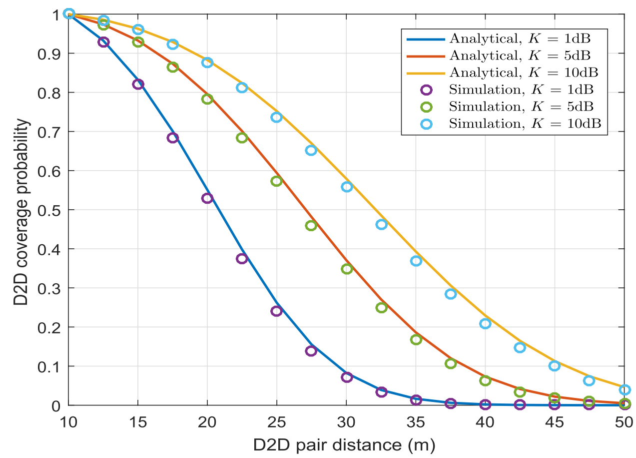

Fig. 6 Coverage probability versus D2D pair distance plot when D2D link undergoes Rician fading and interferers undergo $\eta - \mu$ fading for different value of Rice parameter K. Here $T = 0$ dB, $\alpha = 3.5$, $N = 31$, $\eta_i = 1\ \forall_i$ and $\mu_i = 0.5\ \forall_i$

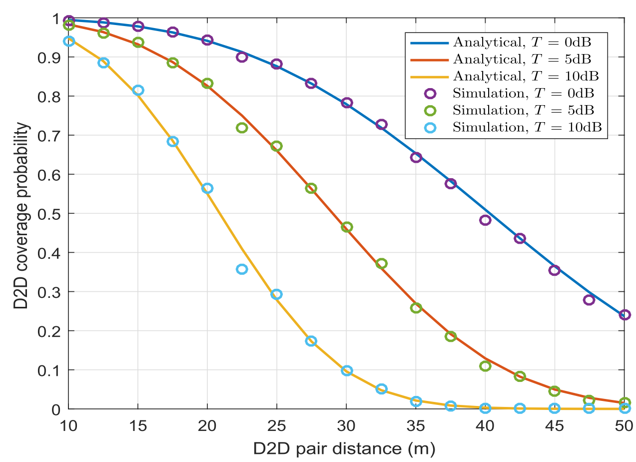

Fig. 7 Coverage probability versus D2D pair distance plot when D2D link undergoes Rayleigh fading and interferers undergo Nakagami-m fading for different value of SIR threshold. Here $\alpha = 3.5$, $N = 31$, $m_i = 1\ \forall_i$

Figure 7, shows the relation between D2D coverage probability obtained in *case IV* and D2D pair distance for different value of D2D SIR threshold. The higher value of D2D SIR threshold gives less D2D coverage.

5 Conclusion

In this paper, the coverage probability of D2D communication underlaid cellular networks has been derived for uplink transmission under generalized $\kappa - \mu/\eta - \mu$ fading channels. The spatial locations of cellular and D2D UEs are modeled as homogeneous PPP and the stochastic geometry is utilized for system modeling. The D2D direct link and interfering links are assumed to experience generalized $\kappa - \mu$ fading and $\eta - \mu$ fading distribution respectively. The analytical expression of D2D coverage probability has been expressed in terms of Lauricella's function which makes calculation easier. The effect of fading parameters over D2D coverage probability has been shown. The results show that the D2D coverage probability decreases with the increase of SIR threshold and D2D pair distance. These expressions may provide the guidelines for operators to plan and deploy D2D communication in future cellular networks as an underlay mode.

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