Energy Detection over Composite $\kappa-\mu$ Shadowed Fading Channels with Inverse Gaussian Distribution

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***Abstract*—This paper investigates the characteristics of energy detection (ED) over composite κ–μ shadowed fading channels in device-to-device (D2D) networks. We have derived the closed-form expressions of the probability density function (PDF) of signal-to-noise ratio (SNR) based on the Inverse Gaussian (*IG*) distribution. By adopting some novel integration and mathematical transformation techniques, we derive a truncation-based closed-form expression for the average detection probability for the first time. It can be observed from our simulations that the number of propagation paths has a more pronounced effect on average detection probability compared to average SNR, which contrasts with earlier studies that focus on D2D networks. It suggests that for D2D networks design, we shall consider enhancing transmitter-receiver placement and antenna alignment strategies, rather than relying solely on increasing the D2D average SNR.**

***Index Terms*—Energy detection, composite LoS shadowed fading, average detection probability, truncation terms, 6G.**

I. Introduction

During the last decade, spectrum efficiency has been considered an important performance metric of next-generation wireless networks [1]-[4]. As a non-coherent signal processing technology, energy detection (ED) has been widely used in multiple scenarios, such as radar communication systems, ultra-wide-band (UWB) systems, and millimeter-wave (MM-wave) communication networks [3], [4]. The authors of [4] initially studied the detection of unknown signals over flat band-limited Gaussian noise channels, focusing on a binary hypothesis-testing problem to derive the probability of detection P_d and the likelihood of false alarm P_f, which follow non-central and central chi-square distributions, respectively. Based on the favorable characteristics of ED, i.e., non-coherent structure and low implementation complexity, Digham *et al.* examined its performance over classical fading channels such as Rayleigh, Rician, and Nakagami-*m*, particularly in the context of radar communication systems, UWB communications, and mmWave networks [3], [4].

As a parallel development, the generalized κ–μ distribution-based fading channel models were proposed to provide an accurate small-scale characterization for line-of-sight (LoS) propagation. By selecting appropriate values for κ and μ, it encompasses several classical fading models as special cases, including Nakagami-*m*, Rayleigh, Rician, and one-sided Gaussian fading [5]-[7]. To characterize severe fading scenarios in mobile radio propagation, the κ–μ extreme distribution was introduced in [8]. Furthermore, to incorporate both multi-path and shadowing effects, composite shadowed fading models have also been explored for ED, including Nakagami-*m*/lognormal, κ–μ/lognormal, and η–μ/lognormal fading channels [8]-[10]. In addition, *IG* distribution has been adopted to model the shadowing component, as it effectively captures the tail behavior of lognormal distributions with large variance and enhances the probability of low-amplitude channel realizations, which is relative to the Gamma distribution [8]-[12]. However, the closed-form expression of the detection probability over LoS/lognormal fading channels is intractable to derive, as integral functions are difficult to resolve.

Motivated by the above discussions, this work investigates energy detection over composite $\kappa-\mu$ shadowed fading channels in D2D networks. Similar to [6], [8], we mainly consider ED over fading channels with single-input single-output (SISO) scenarios in D2D communication without multiple-antenna combining at the receiver [13]. Main contributions are summarized as follows:

- With the aid of *IG* distribution, we have transformed LoS/lognormal distribution into LoS/*IG* distribution. Then, we derive the closed form expressions of PDFs of envelope and instantaneous SNR for composite $\kappa-\mu$ shadowed fading channels.
- To the best of our knowledge, this is the first investigation of deriving the new expression of average detection probability over composite $\kappa-\mu$ shadowed fading channels, by leveraging a set of novel integration and mathematical transformation techniques. Besides, we introduce truncation-based approximations for practical evaluation. Furthermore, we have performed simulations to demonstrate that a finite set of truncated terms is sufficient to accurately evaluate the average detection probability.
- Through Monte Carlo simulations, we present a new

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insight into transmission behavior under composite $\kappa-\mu$ shadowed fading channels: the transmission mode has a greater influence on the detection performance than the average SNR. By contrast, increasing the D2D SNR is enough to improve detection probability under conventional LoS fading scenarios [3], [4]. Our simulation results show that in composite $\kappa-\mu$ shadowed fading channels, the number of propagation paths has a more significant impact on the detection probability than the average SNR. Therefore, in D2D mobile networks, we shall jointly consider the number of paths and the average SNR to ensure reliable signal detection.

This paper is organized as follows: **Section II** introduces the ED system model and composite $\kappa-\mu$ shadowed fading channels. **Section III** we derive the closed-form expression of average detection probability using ED. **Section IV** illustrates our simulation results. Finally, we conclude this paper in **Section V**.

II. ED MODEL AND $\kappa-\mu$ FADING WITH *IG* DISTRIBUTION

The ED pattern is assumed to be binary hypothesis-testing problem to determine absence or presence of unknown signal which can be formulated as [6]

$$\begin{cases} H_0 : y(t) = n(t) \\ H_1 : y(t) = hs(t) + n(t), \end{cases} \tag{1}$$

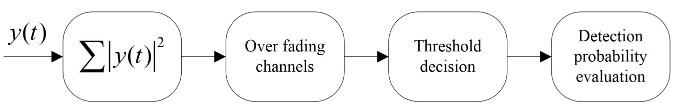

Fig. 1. ED over composite $\kappa-\mu$ shadowed fading channels.

where H_0 denotes the signal is absent, while H_1 represents the signal is present, $y(t)$ is the received signal, $n(t)$ denotes zero-mean complex additive white Gaussian noise (AWGN), h is the wireless channel gain, and $s(t)$ denotes the transmitted signal. As illustrated in Fig. 1, the received signal test statistics can be expressed as [6]:

$$Y \sim \begin{cases} H_0 : \chi^2_{2u} \\ H_1 : \chi^2_{2u}(2\gamma), \end{cases} \tag{2}$$

where $u = TW$ denotes time bandwidth product with time interval T and single-sided signal bandwidth W, χ^2_{2u} is a central chi-square distribution with degrees of freedom $2u$, $\chi^2_{2u}(2\gamma)$ is a non-central chi-square distribution with degrees of freedom $2u$ and a non-centrality parameter 2γ, where γ denotes instantaneous SNR. Consequently, the detection probability P_d can be formulated as [6]:

$$P_d = P_r(y > \lambda | H_1) = Q_u^{ED}(\sqrt{2\gamma}, \sqrt{\lambda}), \tag{3}$$

where $P_r(\cdot)$ is probability, $Q_u^{ED}(\cdot,\cdot)$ is the u-th order generalized Marcum Q-function, and λ denotes the ED threshold.

The $\kappa-\mu$ distribution is a generic fading distribution which illustrates small-scale and LoS fading scenario, which involves several clusters. Each cluster has multipath components with identical powers, and a dominant component has arbitrary power. The parameter κ is the ratio between the total power of the dominant components and the total power of the scattered waves, and parameter μ is the related variable of multi-path clusters. Specifically, Rician distribution is obtained when $\mu = 1$ and Nakagami-m distribution with $\kappa \to 0$, whereas Rayleigh distribution can be attained using $\mu = 1$ and $\kappa \to 0$, and one sided Gaussian distribution is achieved with $\mu = 0.5$ and $\kappa \to 0$ [8]. The envelope PDF can be expressed as [8]:

$$\begin{aligned} f(\rho) =& \frac{2\mu(1+\kappa)^{\frac{\mu+1}{2}}}{\kappa^{\frac{\mu-1}{2}}\exp(\mu\kappa)}\rho^{\mu}\exp[-\mu(1+\kappa)\rho^2] \\ & I_{\mu-1}[2\mu\sqrt{\kappa(1+\kappa)}\rho], \end{aligned} \tag{4}$$

where $f(\cdot)$ is the PDF, ρ is independent variable and $I_v(\cdot)$ denotes the modified Bessel function of the first kind. Based on the principles of composite shadowed statistical distribution, the PDF of composite $\kappa-\mu$ shadowed channels can be derived as

$$f_{\log}^{\kappa-\mu}(r) = \int_0^{\infty} f_{R|y}^{\kappa-\mu}(r|y) f_{\log}(y) dy, \tag{5}$$

where r is independent variable, $y = \bar{r}^2$ with $\bar{r} = \sqrt{\mathbb{E}(r^2)}$ where $\mathbb{E}(\cdot)$ is the expectation operator. Moreover, $f_{r|y}^{\kappa-\mu}(r|y)$ is the conditional envelope PDF of $\kappa-\mu$ fading channels, r denotes the envelop of fading signal and $f_{\log}(y)$ is the PDF of lognormal shadowing distribution. The conditional PDF of $\kappa-\mu$ distribution can be shown as [9]

$$\begin{aligned} f_{R|y}^{\kappa-\mu}(r|y) =& \frac{2\mu(1+\kappa)^{\frac{\mu+1}{2}}}{\kappa^{\frac{\mu-1}{2}}\exp(\mu\kappa)} \frac{r^{\mu}}{y^{\frac{\mu+1}{2}}} \exp\left[-\mu(1+\kappa)\frac{r^2}{y}\right] \\ & I_{\mu-1}\left[2\mu\sqrt{\kappa(1+\kappa)}\frac{r}{y^{\frac{1}{2}}}\right]. \end{aligned} \tag{6}$$

Besides, the PDF of lognormal shadowing distribution is given by [9], [10]

$$f_{\log}(y) = \frac{\xi}{\sqrt{2\pi}\sigma y}\exp\left[-\frac{(10\lg y - \psi)^2}{2\sigma^2}\right], \tag{7}$$

where y is independent variable with the constant $\xi = 4.342$, ψ and σ are the mean and standard deviation of lognormal random variable $\lg y$. To obtain a more efficient expression to calculate (6), we can exploit the *IG* distribution to present the log-normal shadowing distribution, yielding

$$\eta = \frac{\exp(\psi)}{2\sinh(\sigma^2/2)}, \theta = \exp(\psi + \sigma^2/2), \tag{8}$$

where η, θ are functions that include ψ, σ^2. We define polynomial as

$$A = \frac{\sqrt{2\eta}\mu(1+\kappa)^{\frac{\mu+1}{2}}}{\sqrt{\pi}\kappa^{\frac{\mu-1}{2}}\exp(\mu\kappa)}. \tag{9}$$

Consequently, the envelope PDF of composite $\kappa-\mu$ fading channels with IG distribution is expressed as

$$\begin{aligned} f_{\log/IG}^{\kappa-\mu}(r) =& A\int_0^{\infty} r^{\mu}\frac{1}{y^{\frac{\mu}{2}+2}} I_{\mu-1}\left[2\mu\sqrt{\kappa(1+\kappa)}\frac{r}{y^{\frac{1}{2}}}\right] \\ & \exp\left[-\mu(1+\kappa)\frac{r^2}{y} - \frac{\eta}{2\theta^2}\frac{(y-\theta)^2}{y}\right] dy, \end{aligned} \tag{10}$$

Then, with the help of [8], the PDF based on instantaneous SNR can be derived as (11), where $\bar{\gamma}$ is average instantaneous SNR.

$$f^{\kappa-\mu}_{\log/IG}(\gamma)=\frac{A\exp(\frac{\eta}{\theta})\theta^{\frac{\mu}{2}-1}}{2}\int_0^\infty \frac{\gamma^{\frac{\mu}{2}-\frac{1}{2}}}{\bar{\gamma}^{\frac{\mu}{2}+\frac{1}{2}}}\frac{1}{y^{\frac{\mu}{2}+2}}I_{\mu-1}\left[2\mu\sqrt{\kappa(1+\kappa)}\frac{\theta^{\frac{1}{2}}\gamma^{\frac{1}{2}}}{\bar{\gamma}^{\frac{1}{2}}y^{\frac{1}{2}}}\right]\exp\left[-\mu(1+\kappa)\frac{\theta\gamma}{\bar{\gamma}y}-\frac{\eta y}{2\theta^2}-\frac{\eta}{2y}\right]dy. \tag{11}$$

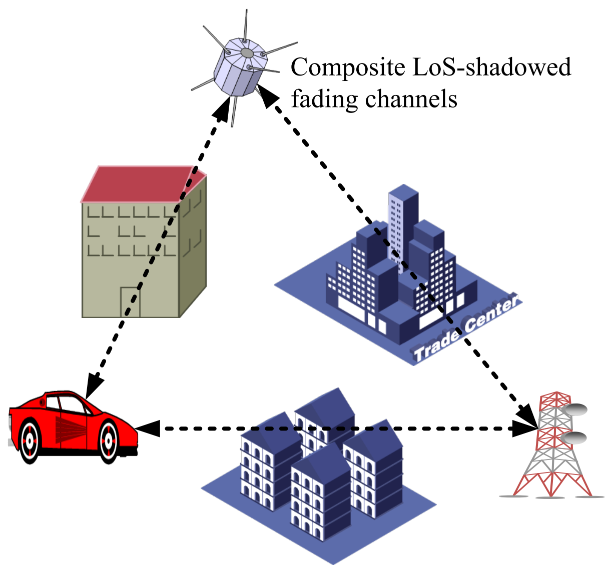

Fig. 2. Composite $\kappa-\mu$ shadowed fading channels in D2D networks.

III. Average Detection Probability over $\kappa-\mu/IG$ Fading Model

As shown in Fig. 2, in composite $\kappa-\mu$ shadowed fading channels, the LoS channel components may be blocked due to physical obstructions. To capture this characteristic accurately, we investigate the detection probability of ED over composite $\kappa-\mu$ fading channels with lognormal shadowing. The average detection probability of ED over the proposed $\kappa-\mu/IG$ fading channel model can be derived as

$$\overline{P}^{\kappa-\mu}_{d\log/IG}=\int\limits_0^\infty Q_u^{ED}(\sqrt{2\gamma},\sqrt{\lambda})f^{\kappa-\mu}_{\log/IG}(\gamma)d\gamma. \tag{12}$$

where $Q_u^{ED}(\sqrt{2\gamma},\sqrt{\lambda})$ is detection probability of ED in [6], and $f^{\kappa-\mu}_{\log/IG}(\gamma)$ is the PDF of $\kappa-\mu/IG$ fading channel model based on instantaneous SNR in (11). The expression of the analytical detection probability can be formulated as [6]

$$Q_u^{ED}(\sqrt{2\gamma},\sqrt{\lambda})=\sum_{l=0}^{\infty}\frac{\exp(-\gamma)\gamma^l\Gamma\left(l+u,\frac{\lambda}{2}\right)}{\Gamma(l+1)\Gamma(l+u)}. \tag{13}$$

where $\Gamma(\cdot)$ is the Gamma function and $\Gamma(\cdot,\cdot)$ is the incomplete Gamma function. We define polynomial B as

$$B=A\frac{\Gamma\left(l+u,\frac{\lambda}{2}\right)}{2\Gamma(l+1)\Gamma(l+u)}\exp\left(\frac{\eta}{\theta}\right)\theta^{\frac{\mu}{2}-1}. \tag{14}$$

Based on (11)-(14), average detection probability is expressed as (15), which is shown at the top of next page. Since (15) involves integration variables γ and y, we simplify the variable integral over γ firstly. We define variable integral of instantaneous SNR as

$$\begin{aligned}D_1=&\int\limits_0^\infty \gamma^{l+\frac{\mu}{2}-\frac{1}{2}}\exp\left[-\gamma-\mu(1+\kappa)\frac{\theta\gamma}{y\bar{\gamma}}\right]\\&I_{\mu-1}\left[2\mu\sqrt{\frac{\kappa(1+\kappa)\theta\gamma}{\bar{\gamma}y^{\frac{1}{2}}}}\right]d\gamma.\end{aligned} \tag{16}$$

With the help of [14, (6.643.2)], we can simplify $\gamma^{\frac{1}{2}}$ in $I_v(\cdot)$ and D_1 as

$$\begin{aligned}D_1=&\frac{\Gamma\left(\frac{l}{2}+\mu\right)y^{\frac{1}{2}}\bar{\gamma}^{\frac{1}{2}}}{2\Gamma(\mu)\mu\kappa^{\frac{1}{2}}(1+\kappa)^{\frac{1}{2}}\theta^{\frac{1}{2}}}\exp\left[\frac{\mu^2\kappa(1+\kappa)\theta}{2y\bar{\gamma}+\mu(1+\kappa)\theta}\right]\\&\left[\frac{y\bar{\gamma}}{y\bar{\gamma}+\mu(1+\kappa)\theta}\right]^{l+\frac{\mu}{2}}M_{-l-\frac{\mu}{2},\frac{\mu-1}{2}}\left[\frac{\mu^2\kappa(1+\kappa)\theta}{y\bar{\gamma}+\mu(1+\kappa)\theta}\right],\end{aligned} \tag{17}$$

where $M_{u,v}(z)$ denotes the Whittaker hypergeometric function. We define polynomial C as

$$C=\frac{\Gamma(l+\mu)\mu^{\mu-1}\kappa^{\frac{\mu-1}{2}}(1+\kappa)^{\frac{\mu-1}{2}}\bar{\gamma}^l}{\Gamma(\mu)}. \tag{18}$$

Upon leveraging [14, (9.220.2)] to simplify the exponential terms and the Whittaker hypergeometric function terms in (15) and (17), then the average detection probability is derived as

$$\begin{aligned}\overline{P}^{\kappa-\mu}_{d\log/IG}=&\sum_{l=0}^{\infty}BC\int\limits_0^\infty\frac{y^{l-\frac{3}{2}}\exp\left(-\frac{\eta y}{2\theta^2}-\frac{\eta}{2y}\right)}{[\bar{\gamma}y+\mu(1+\kappa)\theta]^{l+\mu}}\\&{}_1F_1\left[l+\mu;\mu;\frac{\mu^2\kappa(1+\kappa)}{y\bar{\gamma}+\mu(1+\kappa)\theta}\right]dy,\end{aligned} \tag{19}$$

where ${}_1F_1(\cdot;\cdot;\cdot)$ is the confluent hypergeometric function. Therefore, we multiply the numerator and denominator of equation (19) by $y\bar{\gamma}$ and obtain

$$\begin{aligned}\overline{P}^{\kappa-\mu}_{d\log/IG}=&\sum_{l=0}^{\infty}BC\int\limits_0^\infty\frac{(y\bar{\gamma})^{l-\frac{3}{2}}\exp\left(-\frac{\eta y\bar{\gamma}}{2\theta^2\bar{\gamma}}-\frac{\eta\bar{\gamma}}{2y\bar{\gamma}}\right)}{\bar{\gamma}^{l-\frac{3}{2}}[\bar{\gamma}y+\mu(1+\kappa)\theta]^{l+\mu}\bar{\gamma}}\\&{}_1F_1\left[l+\mu;\mu;\frac{\mu^2\kappa(1+\kappa)}{y\bar{\gamma}+\mu(1+\kappa)\theta}\right]d(y\bar{\gamma}).\end{aligned} \tag{20}$$

In (20), we define polynomial D_2 as

$$\begin{aligned}D_2=&\int\limits_0^\infty\frac{(y)^{l-\frac{3}{2}}\exp\left(-\frac{\eta y}{2\theta^2\bar{\gamma}}-\frac{\eta\bar{\gamma}}{2y}\right)}{[y+\mu(1+\kappa)\theta]^{l+\mu}}\\&{}_1F_1\left[l+\mu;\mu;\frac{\mu^2\kappa(1+\kappa)}{y+\mu(1+\kappa)\theta}\right]dy,\end{aligned} \tag{21}$$

where confluent hypergeometric function ${}_1F_1(\cdot;\cdot;\cdot)$ [9] is derived as (22), which is shown at the top of the this page. We define $f=\mu(1+\kappa)\theta$ and define polynomial $G(n)$ as

$$G(n)=\frac{(l+\mu)_n\mu^{2n}\kappa^n(1+\kappa)^n}{(\mu)_n n!}. \tag{23}$$

$$\overline{P}_{d_{\log}/IG}^{\kappa-\mu} = \sum_{l=0}^{\infty} B \int_0^{\infty}\int_0^{\infty} \exp(-\gamma)\frac{\gamma^{l+\frac{\mu}{2}-\frac{1}{2}}}{\bar{\gamma}^{\frac{\mu}{2}+\frac{1}{2}}} y^{-\frac{\mu}{2}-2} I_{\mu-1}\left[2\mu\sqrt{\frac{\kappa(1+\kappa)\theta\gamma}{\bar{\gamma}}}\frac{1}{y^{\frac{1}{2}}}\right]\exp\left[-\frac{\eta y}{2\theta^2}-\frac{\eta}{2y}-\mu(1+\kappa)\frac{\theta\gamma}{\bar{\gamma}y}\right] d\gamma dy. \quad (15)$$

$${}_1F_1\left[l+\mu;\mu;\frac{\mu^2\kappa(1+\kappa)}{y+\mu(1+\kappa)\theta}\right] = \sum_{n=0}^{\infty}\frac{(l+\mu)_n}{(\mu)_n}\left[\frac{\mu^2\kappa(1+\kappa)}{y+\mu(1+\kappa)\theta}\right]^n\frac{1}{n!}. \quad (22)$$

where $(\mu)_n = \Gamma(\mu+n)/\Gamma(\mu)$ is the Pochhammer symbol [14]. Upon expanding series expressions with infinite terms in (21), BLUEbased on (22) and letting $\xi = -l-\mu-n$, D_2 can be simplified as

$$D_2 = \sum_{n=0}^{\infty}\int_0^{\infty} G(n) y^{l-\frac{3}{2}}(y+f)^{\xi}\exp\left(-\frac{\eta y}{2\theta^2\bar{\gamma}}-\frac{\eta\bar{\gamma}}{2y}\right)dy, \quad (24)$$

Furthermore, we expand (24) based on Newton binomial series with a negative exponent [14] and obtain

$$D_2 = \sum_{n=0}^{\infty}\sum_{i=0}^{\infty} G(n) C_{\xi}^{i}[\mu(1+\kappa)\theta]^{\xi-i} \int_0^{\infty} y^{l+i-\frac{3}{2}}\exp\left(-\frac{\eta y}{2\theta^2\bar{\gamma}}-\frac{\eta\bar{\gamma}}{2y}\right)dy, \quad (25)$$

where:

$$\begin{pmatrix} a \\ b \end{pmatrix} = \frac{a!}{(a-b)!b!}. \quad (26)$$

According to [14, (3.471.9)] and denoting $\beta = l+i-\frac{1}{2}$, integral D_2 can be deduced as

$$D_2 = 2\sum_{n=0}^{\infty}\sum_{i=0}^{\infty} G(n) C_{\xi}^{i}[\mu(1+\kappa)\theta]^{\xi-i}(\theta\bar{\gamma})^{\beta}K_{\beta}\left(\frac{\eta}{\theta}\right), \quad (27)$$

where $K_v(x)$ with $K_{-v}(x) = K_v(x)$ is v-th order modified Bessel function of the second kind [14]. Finally, the average detection probability over composite $\kappa-\mu$ shadowed channels can be derived as

$$\overline{P}_{d_{\log}/IG}^{\kappa-\mu} = \sum_{l=0}^{l_0}\sum_{n=0}^{N^*}\sum_{i=0}^{\infty}\frac{\sqrt{2\eta}\Gamma\left(l+u,\frac{\lambda}{2}\right)\exp\left(\frac{\eta}{\theta}\right)\theta^{\frac{\mu}{2}-1}}{\sqrt{\pi}\exp(\kappa\mu)\Gamma(l+1)\Gamma(l+u)\Gamma(\mu)} \Gamma(l+\mu)\mu^{\mu}(1+\kappa)^{\mu}\bar{\gamma}^{\frac{1}{2}}G(n)C_{\xi}^{i}[\mu(1+\kappa)\theta]^{\xi-i} (\theta\bar{\gamma})^{\beta}K_{\beta}\left(\frac{\eta}{\theta}\right). \quad (28)$$

where l_0 is the summation count in (13), N^* denotes the number of truncation terms in (24).

IV. Simulation Results and Discussion

This section presents simulation results for the proposed detection framework, focusing on the PDF of the instantaneous SNR and the average detection probability over composite $\kappa-\mu$ shadowed fading channels in D2D networks.

With the aid of (11), Fig. 3 illustrates the PDF of instantaneous SNR for the proposed $\kappa-\mu/IG$ fading model, operating at $\eta = 2$, $\theta = 1$, and average SNR $\bar{\gamma} = 10$ dB, for different values of κ and μ. It can be observed that increasing either κ or μ results in sharper and more peaked PDF curves, indicating a higher probability density around the average SNR $\bar{\gamma} = 10$ dB. Notably, variations in μ have a more pronounced effect on the shape of the PDF curves compared to κ. This implies that the number of multipath clusters associated with μ can play a more dominant role in shaping the fading behavior than the ratio of the total power of dominant components to the scattered power, which corresponds to κ. Furthermore, the distribution becomes more concentrated around $\gamma = 10$ dB when we exploit the parameters κ and μ with higher values, which is constence with the observations from other composite fading channels, involving $\alpha-\mu/\alpha-\mu$ and $\kappa-\mu/\alpha-\mu$ [7]-[12]. These results confirm that the proposed $\kappa-\mu/IG$ model effectively captures the characteristics and can be used to evaluate detection performance under multipath and shadowing conditions.

To evaluate the approximate convergence behavior of the average detection probability, we present simulations with varying numbers of truncation terms upon using $\kappa = 1.1$, $\mu = 1.2$, $\zeta = 2$, $\theta = 1$, $\lambda = 15$, and $u = 4$ in Fig. 4 and Fig.

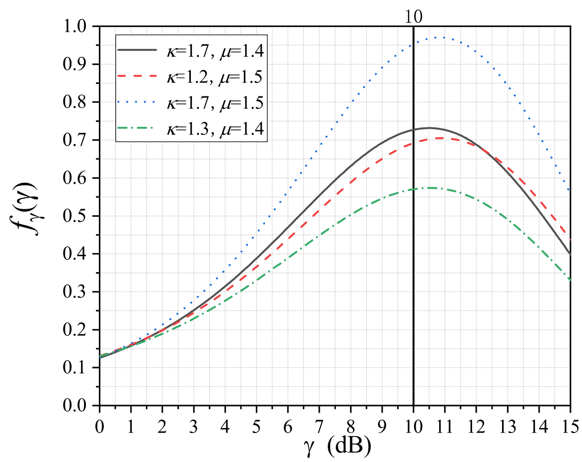

Fig. 3. SNR PDF of $\kappa-\mu/IG$ distribution for $\eta = 2$, $\theta = 1$ and $\bar{\gamma} = 10$ with different κ and μ.

TABLE I
Running time of the closed-form expression of (28) using the parameters in Fig. 4.

Value of l_0	20	30	40
Running time (s)	1.0523	1.5811	2.1142

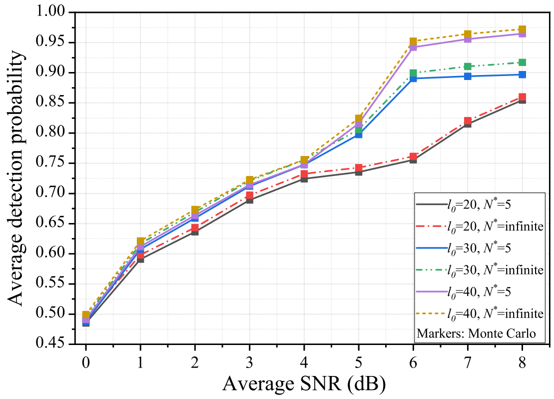

Fig. 4. Average detection probability versus average SNR with truncation terms for κ=1.1, $\mu = 1.2$, $\eta = 2$, $\theta = 1$ and $u = 4$.

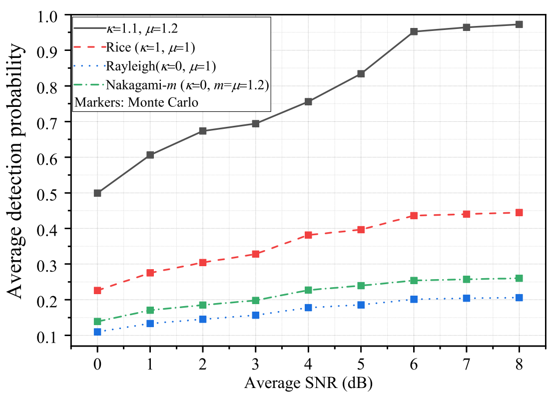

Fig. 5. Average detection probability versus average SNR for classical fading models, $l_0 = 40$, $N^* =$ infinite, $\eta = 2$, $\theta = 1$ and $u = 4$.

5. Based on the closed-form expression of (28), in Table. I. We notice that running time will increase linearly as summation count increases proportionally, and running time with $l_0 = 40$ is nearly twice that of running time with $l_0 = 20$, which verifies our derivation of (28). In addition, Fig. 4 illustrates the relationship between the average detection probability and the average SNR under different truncation levels. It can be observed that, for fixed values of κ and μ, increasing the average SNR leads to improved detection performance. Moreover, the observations confirm that a suitable choice of truncation terms, as guided by the convergence condition in (28), yields accurate approximations with low computational complexity. When the number of truncation terms is increased beyond the minimum required for convergence, the average detection probability estimates become increasingly precise. Moreover, it can be observed from Fig. 4 that there is a perfect overlap between the average detection probability closed-form expression and the Monte Carlo simulations, which validates the accuracy of our analytical results. The running time of calculating (28) is demonstrated in Table. I. Based on Fig. 4 and Table. I, we can see that there is a trade-off between complexity and average detection probability.

In Fig. 5, we demonstrate that the proposed generalized fading model can be reduced to classical fading channels (e.g., Rice, Rayleigh, Nakagami-m) when specific values are assigned to κ and μ. Notably, the analysis also reveals that small increases in μ significantly enhance the average detection probability, whereas increasing the average SNR has a comparatively milder impact. This highlights the critical role of μ, which represents the number of multi-path clusters, in determining detection performance. Therefore, to effectively mitigate shadowing effects and enhance communication quality in D2D mobile networks, priority shall be given to increasing the number of multi-path clusters. This can be achieved by optimizing the physical placement of transmitters and receivers or by adjusting the antenna orientation on mobile devices. Once favorable propagation conditions have been established (such as through optimal positioning of devices or antenna alignment), the transmit power can then be increased to enhance the average SNR and further improve the reliability of D2D communication.

V. Conclusion

In this paper, we address the challenge of performing effective ED over composite $\kappa - \mu$ shadowed fading channels in 6G D2D mobile networks. We have derived the instantaneous PDF of the κ–μ/lognormal fading distribution. Then, by using a series of new integration and transformation techniques, we have obtained a novel closed-form expression of the average detection probability for the first time. Furthermore, due to the difficulty of solving infinite series, we introduce a finite-term truncation approach and demonstrate that it provides an accurate estimation of the average detection probability. Importantly, our analysis reveals a key insight: in composite $\kappa - \mu$ shadowed fading environments, the number of multi-path clusters has a more pronounced impact on detection performance than the D2D SNR. Based on this finding, we recommend that in 6G D2D mobile systems such as Massive Multiple-Input Multiple-Output (M-MIMO) and Extreme Large scale massive Multiple-Input Multiple-Output (XL-MIMO), communication strategies prioritize optimizing transmitter/receiver placement and antenna orientation to increase the number of multi-path clusters before attempting to enhance the D2D SNR.

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