Performance of Passive UHF RFID in Cascaded Correlated Generalized Rician Fading

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***Abstract*—Ultra high frequency radio frequency identification (UHF RFID) systems can use passive tags to reflect the signal from the reader's transmitting antenna back to the reader's receiving antenna for information delivery. This gives a cascaded channel that is a product of two fading components. In this work, the probability of detection, defined as the probability that the received power is above the receiver sensitivity, is derived when the two fading components suffer from correlated generalized Rician fading. This includes the Rayleigh, Rician and Nakagami-m channels in the literature as special cases. Numerical results are presented to show the effects of link distances, receiver sensitivities and channel parameters on the detection probability.**

***Index Terms*—Correlation, detection probability, generalized Rician, radio frequency identification.**

I. Introduction

Ultra high frequency radio frequency identification (UHF RFID) systems have been widely used in various applications. In these applications, passive tags provide a viable solution by receiving power from the reader for battery-less operation. To enable such operation, two links are usually involved: the forward link from the reader to the tag that powers up the passive tag and the reverse link from the tag to the reader that delivers information. In this case, the passive tag does not generate its own signal for information delivery. Instead, it simply reflects the signal from the reader with added modulation. This leads to a cascaded channel.

Previous works on performance analysis of UHF RFID systems include the following. In [1], the effects of various channel impairments, including Rayleigh or Rician fading, on the link budget of the RFID system were discussed. Reference [2] examined the coverage probability for fast and slow fading channels using the Rician and log-normal models. The effect of material was also discussed. Reference [3] considered the use of multiple RF tag antennas to achieve pinhole diversity. Numerical examples were obtained using Monte Carlo simulation. In [4], the reverse link interrogation range of the reader was analyzed as the distance at which a predetermined threshold for the received signal-to-noise ratio at the reader can be achieved. Cascaded Nakagami-m fading channels for monostatic and bistatic structures were considered. In [5], the outage performance of the RFID system with correlated forward and reverse links was obtained, assuming Rayleigh channels and multiple antennas at the reader. In the seminal paper [6], the authors provided a detailed analysis of the detection probability for a cascaded Rician fading channel. Based on the derived detection probability, the maximum distance, similar to that in [5], was calculated.

The aforementioned works have considered either Rician, Nakagami-m or Rayleigh channels. However, it is well known that the generalized Rician model includes all these channels as special cases and therefore, can describe more small-scale fading conditions in the RFID system. Also, these works have assumed either totally correlated forward and reverse links for the monostatic structure or independent forward and reverse links for bistatic structure. However, in some cases, such as collocated backscatter, the transmitting antenna and receiving antennas of the reader may be close such that the forward and reverse links may only be partially correlated.

Motivated by these observations, in this letter, the performance of passive UHF RFID system is analyzed in a cascaded channel with correlated generalized Rician fading. Closed-form expressions for the detection probability are derived. Numerical results are presented to show the effects of link distances, receiver sensitivities and channel parameters on the detection probability.

II. System Model

Consider the same system as that in [6]. The received power at the tag in the forward link can be given as [6, eq. (1)]

$$O_{r,T} = \rho_L O_{tx} G_T G_R^f L(d_f)|h_f|^2 \tag{1}$$

where ρ_L is the polarization loss incurred by the mismatch between the polarization of the reader's transmitting antenna and the tag's antenna, O_{tx} is the reader transmission power, G_T and G_R^f are the antenna gains of the tag and the reader in the forward link, respectively, $L(d_f)$ is the path loss, d_f is the distance in the forward link, and h_f is the fading coefficient in the forward link. Details about the derivation of (1) and its relevant parameters can be found in [6] and are not discussed here to save space.

Upon the reception of (1), a backscatter signal is sent from the tag to the reader. The received power at the reader in the reverse link can therefore be written as [6, eq. (12)]

$$O_{r,R} = \tau\mu_T\rho_L O_{tx}|G_T|^2 G_R^f G_R^v L(d_f)L(d_v)|\Gamma|^2|h_f|^2|h_v|^2 \tag{2}$$

where τ is related to the specific coding and modulation schemes used at the tag, μ_T is the power transfer efficiency determined by the impedance between the tag's antenna and the rest of the tag, G_R^v is the antenna gain of the reader in the reverse link, $L(d_v)$ is the path loss in the reverse link, d_v is

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the distance in the reverse link, Γ is the differential reflection coefficient of the tag, and h_v is the fading coefficient in the reverse link. One sees from (2) that the received power at the reader is determined by the cascaded channel gain $|h_f|^2|h_v|^2$.

To detect the tag successfully, the received power of the tag in (1) must be larger than the tag sensitivity S_T and the received power of the reader in (2) must be larger than the reader sensitivity S_R. Thus, the probability of detection can be defined as

$$P_D = Pr\{O_{r,T} > S_T, O_{r,R} > S_R\}. \quad (3)$$

In this work, the fading coefficients $|h_f|$ and $|h_v|$ are assumed to be correlated generalized Rician random variables with joint probability density function (PDF) given by [7]

$$f_{|h_f|,|h_v|}(x,y) = \frac{e^{-W^2}}{W^{m-1}(\lambda_f^2\sigma_f^2\lambda_v^2\sigma_v^2)^{\frac{m-1}{2}}\Omega_f^2\Omega_v^2} \int_0^\infty t^{-\frac{m-1}{2}} e^{-(1+\frac{\lambda_f^2\sigma_f^2}{2\Omega_f^2}+\frac{\lambda_v^2\sigma_v^2}{2\Omega_v^2})t} I_{m-1}(2W\sqrt{t})x^m e^{-\frac{x^2}{2\Omega_f^2}} I_{m-1}(\frac{x\sigma_f\lambda_f\sqrt{t}}{\Omega_f^2})y^m e^{-\frac{y^2}{2\Omega_v^2}} I_{m-1}(\frac{y\sigma_v\lambda_v\sqrt{t}}{\Omega_v^2})dt, \quad x>0, y>0 \quad (4)$$

where $W^2 = \sum_{l=1}^m (m_{0l}^2 + m_{1l}^2)$ represents the power of the line-of-sight (LOS) component in the channel, m_{0l} and m_{1l} are the in-phase and quadrature parts of the l-th LOS, respectively, σ_f^2 and σ_v^2 represent the average fading powers in the forward and reverse links, respectively, m is the shape parameter of generalized Rician, $I_{m-1}(\cdot)$ is the $(m-1)$-th order modified Bessel function of the first kind [8, eq. (8.406.1)], $\Omega_f^2 = \sigma_f^2(1-\lambda_f^2)/2$, $\Omega_v^2 = \sigma_v^2(1-\lambda_v^2)/2$, λ_f and λ_v determine the correlation coefficient between $|h_f|$ and $|h_v|$ as $\rho = \lambda_f\lambda_v$ with $0 < |\lambda_f| < 1$ and $0 < |\lambda_v| < 1$.

One can verify that, when $m = 1$, (4) becomes the joint PDF of two Rician random variables, and when $m = 1$ and $W = 0$, it becomes the joint PDF of two Rayleigh random variables. Further, when $W = 0$, using [9, eq. (9.6.7)], it becomes the joint PDF of two Nakagami-m random variables. Thus, the generalized Rician model can describe more RFID channel conditions. Also, if one integrates (4) over x or y, the marginal PDF of a generalized Rician random variable can be obtained for $|h_f|$ and $|h_v|$, where their Rician K factors can be derived as $W^2\lambda_f^2$ and $W^2\lambda_v^2$, respectively, using [10, eq. (13)].

It is important to note that $\lambda_f \neq 0$ and $\lambda_v \neq 0$ in (4), as discussed in [7] and [10]. This means that the cases of independent links is not a special case of (4), that is, one cannot set $\lambda_f = \lambda_v = 0$ in (4) to obtain the joint PDF of two independent generalized Rician links. Thus, (4) can only describe the general correlation case. Next, the probability of detection is derived.

III. Derivation

Using (1) and (2) in (3), one has

$$P_D = Pr\{|h_f| > \gamma_1, |h_f||h_v| > \gamma_2\} \quad (5)$$

where $\gamma_1 = \sqrt{\frac{S_T}{\rho_L O_{tx} G_T G_R^f L(d_f)}}$ and $\gamma_2 = \sqrt{\frac{S_R}{\tau\mu_T\rho_L O_{tx}|G_T|^2 G_R^f G_R^v L(d_f)L(d_v)|\Gamma|^2}}$. Then, using (4) in (5), the detection probability can be calculated as

$$P_D = \int_{\gamma_1}^\infty \int_{\gamma_2/x}^\infty f_{|h_f|,|h_v|}(x,y)dydx. \quad (6)$$

To calculate (6), we simplify (4) first. Using [8, eq. (8.445)] to expand the Bessel functions in (4) and using [8, eq. (6.643.2)] to solve the resulting integral, one has

$$f_{|h_f|,|h_v|}(x,y) = \frac{e^{-W^2}}{W^{m-1}(\lambda_f^2\sigma_f^2\lambda_v^2\sigma_v^2)^{\frac{m-1}{2}}\Omega_f^2\Omega_v^2} \sum_{i=0}^\infty\sum_{j=0}^\infty \frac{(\frac{\sigma_f\lambda_f}{2\Omega_f^2})^{m-1+2i}(\frac{\sigma_v\lambda_v}{2\Omega_v^2})^{m-1+2j}x^{2m-1+2i}y^{2m-1+2j}}{i!j!\Gamma(m+i)\Gamma(m+j)e^{\frac{x^2}{2\Omega_f^2}+\frac{y^2}{2\Omega_v^2}}} \frac{\Gamma(m+i+j)e^{\frac{W^2}{2U}}M_{-(m/2+i+j),(m-1)/2}(\frac{W^2}{U})}{W\Gamma(m)U^{m/2+i+j}}. \quad (7)$$

where $\Gamma(\cdot)$ is the Gamma function [8, eq. (8.310.1)], $U = 1+\frac{\lambda_f^2\sigma_f^2}{2\Omega_f^2}+\frac{\lambda_v^2\sigma_v^2}{2\Omega_v^2}$ and $M_{\cdot,\cdot}(\cdot)$ is the Whittaker function [8, eq. (9.220.2)]. Using (7) in (6), the calculation of the detection probability boils down to the calculation of the double integral

$$V = \int_{\gamma_1}^\infty \int_{\gamma_2/x}^\infty x^{2m-1+2i}y^{2m-1+2j}e^{-\frac{x^2}{2\Omega_f^2}-\frac{y^2}{2\Omega_v^2}}dydx. \quad (8)$$

Using [8, eq. (3.381.3)] and [8, eq. (8.352.2)], this gives

$$V = \sum_{k=0}^{m+j-1} \frac{\Gamma(m+j)(2\Omega_v^2)^{m+j}}{4k!(2\Omega_v^2/\gamma_2^2)^k} \int_{\gamma_1^2}^\infty t^{m+i-k-1}e^{-\frac{t}{2\Omega_f^2}-\frac{\gamma_2^2}{2\Omega_v^2 t}}dt. \quad (9)$$

Finally, using the above results, the probability of detection is derived as

$$P_D = \frac{e^{-W^2+\frac{W^2}{2U}}}{W^m(\lambda_f^2\sigma_f^2\lambda_v^2\sigma_v^2)^{\frac{m-1}{2}}\Omega_f^2\Omega_v^2}\sum_{i=0}^\infty\sum_{j=0}^\infty\sum_{k=0}^{m+j-1} \frac{(\frac{\sigma_f\lambda_f}{2\Omega_f^2})^{m-1+2i}(\frac{\sigma_v\lambda_v}{2\Omega_v^2})^{m-1+2j}(2\Omega_v^2)^{m+j}\Gamma(m+i+j)}{i!j!\Gamma(m+i)4k!(2\Omega_v^2/\gamma_2^2)^k\Gamma(m)U^{m/2+i+j}} M_{-(\frac{m}{2}+i+j),\frac{m-1}{2}}(\frac{W^2}{U})\int_{\gamma_1^2}^\infty t^{m+i-k-1}e^{-\frac{t}{2\Omega_f^2}-\frac{\gamma_2^2}{2\Omega_v^2 t}}dt. \quad (10)$$

One sees that (10) has a computational complexity similar to that in [6] with two infinite series.

Two special cases can be discussed to further simplify (10). First, if $\gamma_1 \approx 0$ for reverse link limited (RLL) systems, using [8, eq. (3.471.9)], one has

$$P_D \approx \frac{e^{-W^2+\frac{W^2}{2U}}}{W^m(\lambda_f^2\sigma_f^2\lambda_v^2\sigma_v^2)^{\frac{m-1}{2}}\Omega_f^2\Omega_v^2}\sum_{i=0}^\infty\sum_{j=0}^\infty\sum_{k=0}^{m+j-1} \frac{(\frac{\sigma_f\lambda_f}{2\Omega_f^2})^{m-1+2i}(\frac{\sigma_v\lambda_v}{2\Omega_v^2})^{m-1+2j}(2\Omega_v^2)^{m+j}\Gamma(m+i+j)}{i!j!\Gamma(m+i)2k!(2\Omega_v^2/\gamma_2^2)^k\Gamma(m)U^{m/2+i+j}} M_{-(\frac{m}{2}+i+j),\frac{m-1}{2}}(\frac{W^2}{U})(\frac{\Omega_f\gamma_2}{\Omega_v})^{m+i-k}K_{m+i-k}(\frac{\gamma_2}{\Omega_f\Omega_v}) \quad (11)$$

where $K_n(\cdot)$ is the n-th order modified Bessel function of the second kind [8, eq. (8.407.1)]. Second, if $\gamma_2 \approx 0$ for forward link limited (FLL) systems, using [8, eq. (3.461.3)] and [8, eq. (3.381.3)], one has

$$P_D \approx \frac{e^{-W^2+\frac{W^2}{2U}}}{W^m(\lambda_f^2\sigma_f^2\lambda_v^2\sigma_v^2)^{\frac{m-1}{2}}\Omega_f^2\Omega_v^2}\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\Gamma(m+i+j)$$
$$\frac{(\frac{\sigma_f\lambda_f}{2\Omega_f^2})^{m-1+2i}(\frac{\sigma_v\lambda_v}{2\Omega_v^2})^{m-1+2j}(2\Omega_f^2)^{m+i}(2\Omega_v^2)^{m+j}}{i!j!\Gamma(m+i)4\Gamma(m)U^{m/2+i+j}}$$
$$\Gamma(m+i,\frac{\gamma_1^2}{2\Omega_f^2})M_{-(m/2+i+j),(m-1)/2}(\frac{W^2}{U}). \tag{12}$$

The results in (11) and (12) are approximations but are closed-form expressions. It can be verified that the results for Rician channels can be obtained by setting $m=1$ in (10) - (12). Also, the results for Nakagami-m channels can be obtained by setting $W=0$ in (10) - (12). For example, by setting $W=0$ in (10), the result for Nakagami-m channels in the general case is

$$P_D = \frac{1}{(\lambda_f^2\sigma_f^2\lambda_v^2\sigma_v^2)^{\frac{m-1}{2}}\Omega_f^2\Omega_v^2}\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\sum_{k=0}^{m+j-1} \tag{13}$$
$$\frac{(\frac{\sigma_f\lambda_f}{2\Omega_f^2})^{m-1+2i}(\frac{\sigma_v\lambda_v}{2\Omega_v^2})^{m-1+2j}(2\Omega_v^2)^{m+j}\Gamma(m+i+j)}{i!j!\Gamma(m+i)4k!(2\Omega_v^2/\gamma_2^2)^k\Gamma(m)U^{m+i+j}}$$
$$\int_{\gamma_1^2}^{\infty} t^{m+i-k-1}e^{-\frac{t}{2\Omega_f^2}-\frac{\gamma_2^2}{2\Omega_v^2 t}}dt$$

where [8, eq. (9.210.1)] and [8, eq. (9.220.2)] can be used to expand the Whittaker function. Equation (13) is derived from (10) by using $W=0$ only and does not use any other assumptions, including $\gamma_1 \approx 0$ or $\gamma_2 \approx 0$. For Rayleigh channels, the results can be obtained by setting $W=0$ and $m=1$ in (10) - (12).

IV. Numerical Results and Discussion

In this section, following [6], we set $G_T = 0\ dBi$, $O_{tx} = +33\ dBm$, $G_R^f = G_R^v = +9\ dBi$, $\tau = 0.5$, $\rho_L = 0.5$, $\mu_T = 1$, $\Gamma = 0.1$, the operating frequency 865.7 MHz, $\sigma_f = \sigma_v = 1$. The infinite series is truncated to 20 terms.

Fig. 1 shows the detection probability under different sensitivities for the correlated generalized Rician links. Firstly, from Fig. 1, the detection probability always decreases when the distance d_f increases, as expected, as larger distances lead to larger path loss such that the received power is smaller for detection. Secondly, from Fig. 1, the detection probability decreases when the tag or reader sensitivities decrease. However, P_D is more sensitive to the tag sensitivity than the reader sensitivity in the case considered, as the tag needs to reflect the signal back to the reader. It can also be shown that in this case the detection probability changes little when the distance d_v changes. This implies that the system is FLL, given the settings used in this case, as the detection probability is much more sensitive to d_f than to d_v. To save space, the relationship between P_D and d_v is not presented here.

Fig. 2 shows the detection probability vs. d_f for different W^2 in correlated Rician links when $m=1$. In this case, the Rician K factor is $W^2\lambda^2$ and is determined by W^2 for fixed λ. One sees that the value of W^2 has a significant impact on the detection probability. For example, when W^2 changes from 1 to 4 at $d_f = 12\ m$, P_D increases from 0.6 to 0.92, almost 50% increase. Fig. 3 shows the detection probability vs. d_f for different Nakagami m parameters in correlated Nakagami-m links when $W^2=0$. From this figure, one sees that the Nakagami m parameter has a significant impact on the detection performance too. At $d_f = 12\ m$, the detection probability increases from 0.45 to nearly 1, when the m parameter increases from 1 to 4, giving an increase of more than 100%. Thus, the detection performance is more sensitive to the parameter m than to the parameter W^2.

Fig. 4 compares the detection probability for different channel models included in the generalized Rician model when the forward and reverse links are correlated. As can be seen, the Rayleigh fading channel has the smallest detection probability, while the generalized Rician fading channel has the largest detection probability, as expected, as the Rayleigh fading is the worst channel condition while the generalized Rician fading is the best channel condition, among the cases considered.

Fig. 5 shows P_D vs. d_f for different λ. In this case, $\lambda_f = \lambda_v = \lambda = 0.2, 0.4, 0.6, 0.8$ such that $\rho = \lambda^2 =$

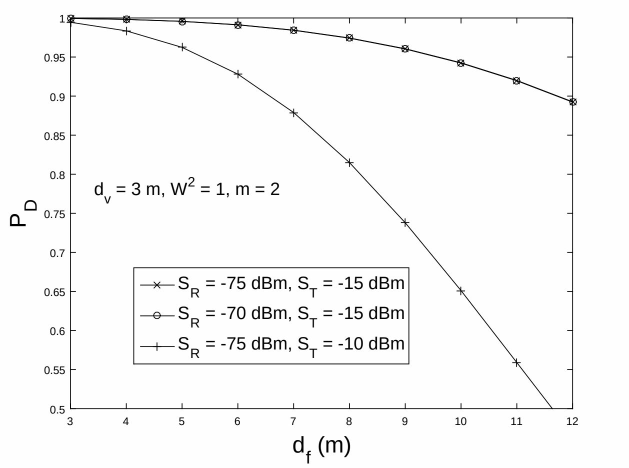

Fig. 1. P_D vs. d_f for different sensitivities when the forward and reverse links are correlated generalized Rician channels with $\lambda = 0.8$.

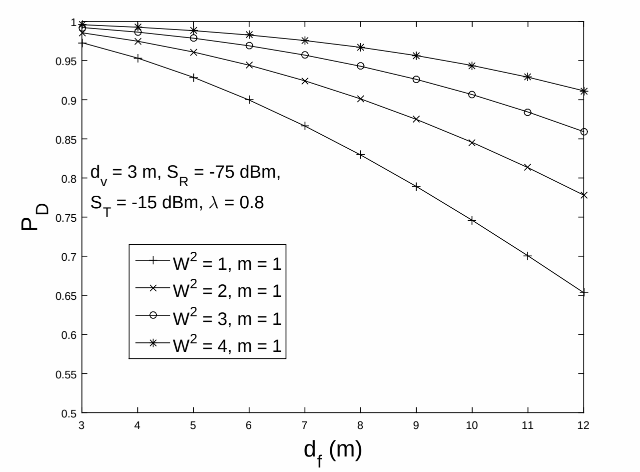

Fig. 2. P_D vs. d_f for different W^2 when the forward and reverse links are correlated Rician channels with $\lambda = 0.8$.

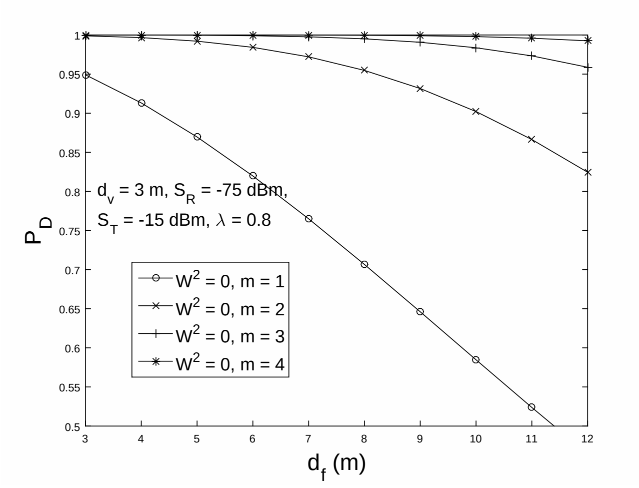

Fig. 3. P_D vs. d_f for different Nakagami m parameters when the forward and reverse links are correlated Nakagami-m channels with $\lambda = 0.8$.

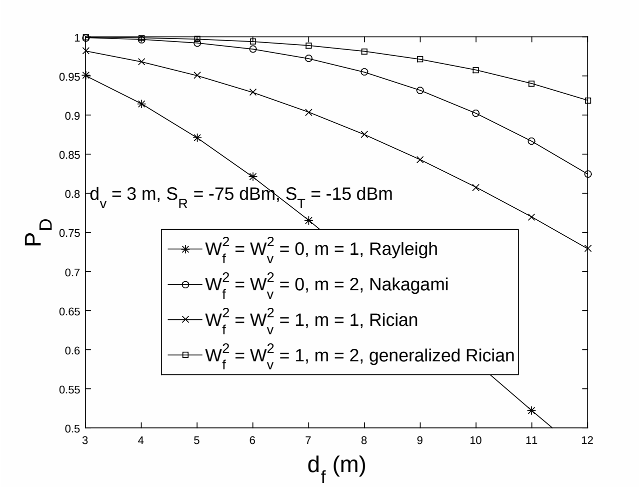

Fig. 4. The detection probability vs. d_f for different channel models when the forward and reverse links are correlated with $\lambda = 0.8$.

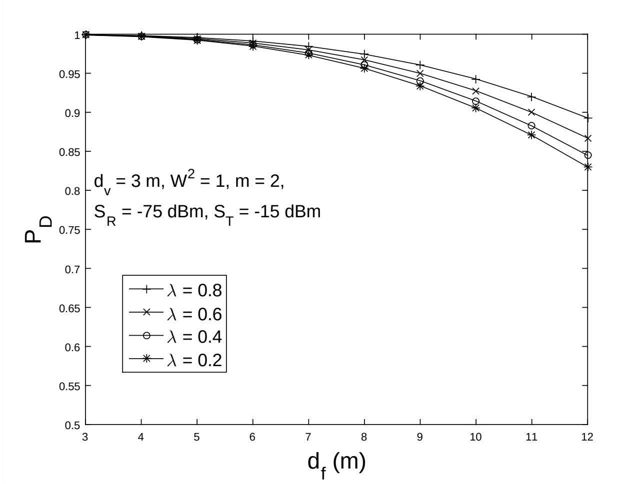

Fig. 5. The detection probability vs. d_f for different λ when the forward and reverse links are correlated generalized Rician channels.

$0.04, 0.16, 0.36, 0.64$, respectively. One sees that P_D increases when λ increases. Reference [12] reported that the performance improves when the link correlation decreases for Rayleigh links. This can be explained as follows. The value of λ determines the correlation coefficient as $\rho = \lambda^2$, but also determines the Rician K factor in generalized Rician channels as $W^2\lambda^2$ from [10, eq. (13)]. From [12], P_D should decrease when λ increases, as ρ increases. However, for generalized Rician fading, the performance also improves when λ increases, as a larger λ gives a larger Rician K factor $W^2\lambda^2$ and therefore better channel conditions in the individual links. The overall effect of λ depends on whether P_D is more sensitive to ρ or the Rician K factor. It can be shown that in the setting of Fig. 5 the detection probability is more sensitive to the Rician K factor. Consequently, the Rician K factor dominates such that P_D increases when λ increases. On the other hand, for Rayleigh links, λ only affects the correlation coefficient and hence the performance degrades when λ increases, as in [12].

V. Conclusion

Analytical results on the detection probability of the UHF RFID system have been derived for cascaded correlated generalized Rician channels. Numerical examples have shown that the detection probability is quite sensitive to the forward link distance, the channel conditions and the tag sensitivity.

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