

# Detection Probability of Passive RFID Systems under Cascaded Rician and Rayleigh Fading Channel

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**Abstract**—Radio Frequency Identification (RFID) system uses the principle of radiative power transfer between the reader and the tag antenna. The main performance metric for RFID system is the reliable reading coverage, where the tag can be read with higher detection probability. Most of current researches consider the reader coverage to be determined only by its read range assuming monostatic configuration with omni-directional antennas. In this paper, we model and study the effect of cascaded channel fading and readers antenna orientation on the passive RFID tags, in terms of detection probability. We derive a closed-form expression for passive RFID detection probability taking into consideration the relative reader-tag antennas orientations and cascaded Rician-forward/Rayleigh-reverse fading channel. The derived formulas can be useful for design and optimization of passive RFID communication systems from RF point of view.

## I. INTRODUCTION

Ultra High Frequency Radio Frequency Identification (UHF RFID) system has gained attraction as an effective wireless technology for object identification. It has been widely adopted for applications like asset management, indoor localization, access control, and industrial automation [1]–[3]. RFID communication link is fundamentally different from that of conventional RF communication because it involves two distinct links: the power-up (Forward) link for powering passive RF tags, and the backscatter (Reverse) link for describing backscatter communication. Other ways in which RFID systems differ from conventional radio are some unique design factors that may create potential challenges for interference mitigation which include [4]: 1) the integrated circuits (IC) embedded in RFID tags has limited tuning capability, and thus it is more susceptible to interference from RF signals, 2) the UHF Gen2 tags do not generate their own signal on a separate channel and they simply reflect the reader signal with the same frequency, adding modulation to represent their data, and 3) the reflected signal by the tag is many orders of magnitude weaker than the signals transmitted by the readers. The main factors influencing the reliability of a tag response include tag location and orientation, impedance mismatch between tag antenna and chip [5], multipath fading [6], communication blind spot [7], and interference (i.e. tag-to-tag, reader-to-tag and reader-to-reader interference). Furthermore, tag placement on a highly dielectric materials (i.e.

liquids) or conductors (i.e. metal) can drastically change the properties of a tag antenna, and consequently reducing reading efficiency and shortening the reading range to the point of becoming completely unreadable at any distance in some cases [8]. Usually, these factors are beyond the control of the system user and therefore, for a maximum reliable reading range (i.e. 100% successful detection rate), proper conditions should be analyzed and defined before any implementation of the RFID system. The main performance metric for RFID system is the reading range or coverage. It is defined as the maximum distance between a reader and a tag where the radiation field from the reader is strong enough to power up the tag and the backscatter signal from the tag reaches the reader with sufficient power (i.e. with power above readers sensitivity threshold). Although, many studies related to the passive UHF RFID system reading coverage improvement have been conducted, there are few analytical models that highlight the effects of the channel fading [9]–[12] and readers antenna orientation [13]–[14] on the interrogation zone reliability. In [9], the authors measured and compared the multipath channel fading for both single and multiple RFID antennas. The probability for successful tags detection is evaluated in [10] assuming that the RFID channel fading was modeled by Rician distribution. A statistical model suitable for bistatic and monostatic RFID configurations with multiple reader and tag antennas was presented in [11] where diversity gains were investigated by utilizing multiple tags. In [12], the interrogation zone with multiple transmit/receive antennas at the reader was analyzed where the forward and reverse channels are assumed to take the Nakagami- $m$  distribution. However, all these models calculate the interrogation range assuming omnidirectional antennas while poor tag orientation with respect to the reader antennas can result in an unfavorable link loss and thus dramatically reduce the reading reliability. On the other hand, other research efforts have focused on modeling and analyzing the effect of the readers antenna orientation on the reading coverage [13]–[14]. In [13], the authors introduced a multipath model taking into account the antennas placement, orientation and polarization. Using the proposed model, the optimization of the antennas position and tilt angle was carried out. A systematic formulation for the reading range of the reader-tag platform in the presence of multipath,

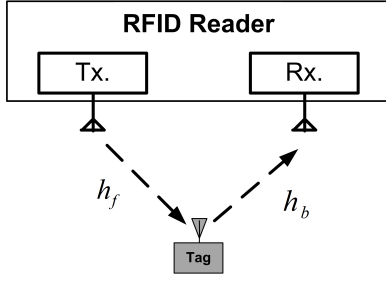


Fig. 1. Basic Configuration of Passive RFID System.

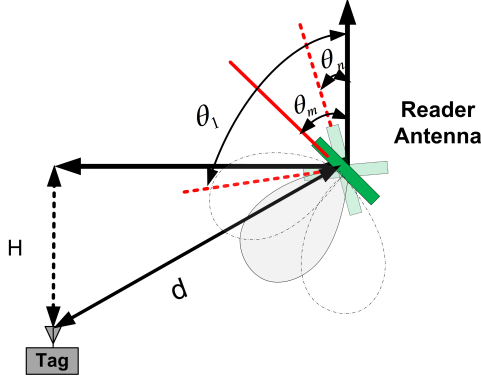


Fig. 2. Reader Antenna Orientation Relative to the Tag Position.

which is suitable for single-lobe directional antennas, was proposed in [14]. The reading region was approximated by an ellipsoid including reader antenna's location, while its axes depend on the half-power beamwidth of the antenna. However, these models do not provide statistical analysis of the reliable interrogation range in the presence of fading channels.

In this paper, we model and study the effect of cascaded channel fading and readers antenna orientation on the passive RFID tags, in terms of detection probability. It is defined as the probability that the instantaneous received power falls below a specified received sensitivity. We derive a closed-form expression for passive RFID detection probability taking into consideration the reader antennas orientations and cascaded forward and reverse fading channel. To the best of our knowledge, this is the first work that provides 3-D closed-form expression analysis of RFID system in cascaded RFID channels, where the forward and reverse link are modeled by Rician and Rayleigh fading distribution respectively.

The paper is organized as follows. In Section II, the main expressions of passive RFID channel model are revised. A closed-form expression for passive RFID system detection probability is presented in Section III. Simulation results are given in Section IV where the effect of fading in the reading coverage are studied. Finally, Section V concludes the paper.

## II. CHANNEL MODELING OF PASSIVE RFID SYSTEM

The operation of RFID system requires the communication between the RFID reader and the tag through two distinct links: the forward link and the backscatter link. Fig.1 illustrated the basic configuration of passive RFID communication

system. The forward link (denoted by a subscript  $f$ ), also called the reader-to-tag link, describes signal propagation from the reader's transmitter to the RF tag, while the backscatter link (denoted by a subscript  $b$ ), or the tag-to-reader link, describes signal propagation from the RF tag to the reader receiver. For a successful tag detection, two things must be realized: 1) the power received at the tag must be higher than the power up threshold (i.e. tag sensitivity), and 2) the reader must be sensitive enough to detect correctly the backscattered modulation from the tag.

The Forward link power impinging on the tag antenna using reader directional antenna can be expressed as follows:

$$P_{r,T} = \rho_L P_{Tx} G_T G_R(d, H, \theta, \phi) PL(d) |h_f|^2, \quad (1)$$

where  $P_{Tx}$  is the power transmitted by the reader antenna,  $d$  is the reader to tag distance,  $G_R(d, H, \theta, \phi)$  and  $G_T$  are the gain of the RFID reader and tag antennas respectively,  $PL(d)$  is the channel pathloss, and  $\rho_L$  polarization loss factor (PLF) which reflects the loss due to the mismatch between the polarization of a transmitter antenna and a receiver antenna. When readers have a circular-polarized antenna, the PLF is 0.5 (i.e. 3 dBm loss) no matter what polarization the dipole tag antenna has [1]. The parameter  $h_f$  is the link fading coefficient where its envelope can follow the Rician or Rayleigh distributions. In a pure multipath environment, where many equal amplitude and uniformly distributed phase replicas of the transmitted signal arrive at the receiver, the short term fading envelope will have a Rayleigh probability density function (pdf) given by [15]:

$$h_{Ray}(r) = \begin{cases} \frac{r}{\sigma^2} \exp(-\frac{r^2}{2\sigma^2}) & r \geq 0 \\ 0 & \text{elsewhere} \end{cases} \quad (2)$$

where  $r$  is the envelope of the received voltage (i.e.  $r^2/2$  is the short term signal power) and  $\sigma$  its root mean square (rms) value before envelope detection. However, when there is a line-of-sight or at least a dominant specular component the short term fading envelope will have a Rician pdf given by [15]:

$$h_{Rice}(r) = \begin{cases} \frac{r}{\sigma^2} \exp(-\frac{r^2+a^2}{2\sigma^2}) I_0(\frac{ra}{\sigma^2}) & r \geq 0, a \geq 0 \\ 0 & \text{elsewhere} \end{cases} \quad (3)$$

where  $I_0(\cdot)$ , is the modified Bessel function of the first kind and order zero, and  $a$  denotes the peak amplitude of the dominant signal of the dominant component. It can be noticed that the Rayleigh distribution is a special case of the Rician distribution when  $a = 0$  (i.e. complete disappearance of the specular power). A commonly used notation for the dominant to multipath signal power ratio for the Rician distribution is  $K = a^2/(2\sigma^2)$ . The parameter  $K$  is then called *Rician K-Factor* and when it is large, it indicates a strong dominant path. This type of multipath, i.e. Rician fading, presents more realistic environment in RFID communication.

Assuming the scenario illustrated in Fig.2, and adopting the expression provided by [16], a modified directional gain of a patch antenna can be expressed as follows:

$$G_R(d, H, \theta, \phi) = 3.136 \left[ \tan(\alpha) \sin(\frac{\pi}{2} \cos(\alpha) \sin(\phi)) \right]^2 \quad (4)$$

where  $\alpha = \theta + \arcsin(\frac{H}{d})$ ;  $\theta$  and  $\phi$  are the inclination and azimuthal angles of the patch antenna respectively.  $H$  is the distance between tag location and its orthogonal projection on the reader plane  $(x, y)$  when  $\theta = 0$ . In the following and for the sake of simplicity of notations, we replace  $G_R(d, H, \theta, \phi)$  by  $G_R$ .

If the power received by the tag is sufficient to operate the tag (i.e.  $P_{r,T} > P_{TS}$ ), a backscattered signal from the tag is received by the desired reader. Thus the total backscattered power  $P_{r,R}$  received by the reader is given by:

$$P_{r,R} = \tau \mu_T \rho_L P_{Tx} |G_T G_R PL(d)|^2 |h_f|^2 |\Gamma|^2 |h_b|^2 \quad (5)$$

where the subscript notation  $f$ , and  $b$  are used to describe the forward link and backscattered link respectively and  $\mu_T \in [0, 1]$  is the power transfer efficiency, which quantifies how well the tag is impedance-matched to the antenna. The normalized coefficient  $\tau$  quantifies the specific data encoding modulation details and it can be calculated using Power Density Distribution (PSD) of the tag's signal [17]. According to the EPCglobal C1G2 specifications[18], any tag in the interrogation zone of the reader can send back his information by reflecting the incoming continuous wave using a FM0 or Miller subcarrier (Miller-2, Miller-4 or Miller-8) encoding schemes and an Amplitude Shift Keying (ASK) modulation. The parameter  $\Gamma = \Gamma_1 - \Gamma_2$  is the differential reflection coefficient of the tag, where  $\Gamma_1$  and  $\Gamma_2$  are the complex power wave reflection coefficients between tag antenna impedance  $Z_A$  and chip impedance  $Z_{1,2}$  in modulating states 1 and 2 and defined by the following equation:

$$\Gamma_{1,2} = \frac{Z_{1,2} - Z_A^*}{Z_{1,2} + Z_A} \quad (6)$$

Usually, the parameter  $\Gamma$  is defined as a function of *Radial Cross Section*  $\sigma_{RCS}$ , tag antenna gains  $G_T$  and the communication wavelength  $\lambda$  as follows:

$$|\Gamma|^2 = \frac{4\pi\sigma_{RCS}}{\lambda^2 |G_T|^2} \quad (7)$$

### III. PASSIVE RFID SYSTEM DETECTION PROBABILITY

The channel fading in RFID system can often follow a cascaded Rician distribution resulting in deeper fades compared to the signal received by the RFID tag (forward link) [6]. In this paper, we consider a RFID system configuration, where it is commonly accepted to have a Non-line-of-sight (NLOS) in the reverse link and thus the short term fading envelope can be modeled by a Rayleigh distribution. Therefore, If we denote the coefficient  $h = h_f h_b$  as a cascaded channel fading, where  $h_f$  and  $h_b$  are the Rician-forward and Rayleigh-backscattered link fading parameters respectively, the envelope of  $h$  can follow a statistical distribution where its pdf is given by [19]:

$$p_h(r) = \frac{r \exp(-K)}{\sigma_f^2 \sigma_b^2} \sum_{i=0}^{\infty} \frac{1}{(i!)^2} \left( \frac{Kr}{2\sigma_f \sigma_b} \right)^i \mathbf{K}_i \left( \frac{r}{\sigma_f \sigma_b} \right), r \geq 0 \quad (8)$$

where  $K$  is the Rician factor,  $\mathbf{K}_\nu$  is the modified Bessel function of the second kind with order  $\nu$ , and  $\sigma_f$  and  $\sigma_b$  are the

*rms* value of received voltage signal before envelope detection for both forward and backscattered link respectively.

The passive RFID system detection probability  $P_D$  can be defined as the probability that the instantaneous received power is higher than the specified reader's antenna sensitivity and expressed as follows:

$$P_D(P_{RS}) = \Pr(P_{r,R} \geq P_{RS}) = 1 - \Pr(P_{r,R} \leq P_{RS}) \quad (9)$$

Let's denote  $A_{th}$  as a ratio  $A_{th} = \sqrt{P_{RS}/P_{r,R}^{(0)}}$ , where  $P_{RS}$  is the RFID reader power sensitivity and  $P_{r,R}^{(0)}$  is defined as follows:

$$P_{r,R}^{(0)} = \tau \mu_T \rho_L P_{Tx} |G_T G_R PL(d)|^2 |\Gamma|^2 \quad (10)$$

We know that the average received power  $\bar{P}_{r,R}$  can be written as:

$$\bar{P}_{r,R} = P_{r,R}^{(0)} (2\sigma_f \sigma_b)^2 (K+1) \quad (11)$$

therefore,

$$A_{th} = (\sigma_f \sigma_b) \sqrt{\frac{4(K+1)P_{RS}}{\bar{P}_{r,R}}} \quad (12)$$

Now, the equation Eq.9 can be rewritten as:

$$\begin{aligned} P_D(P_{RS}) &= 1 - \int_0^{A_{th}} p_h(r) dr \\ &= 1 - \frac{\exp(-K)}{\sigma_f^2 \sigma_b^2} \sum_{i=0}^{\infty} \frac{1}{(i!)^2} \left( \frac{K}{2\sigma_f \sigma_b} \right)^i \\ &\quad \times \int_0^{A_{th}} r^{i+1} \mathbf{K}_i \left( \frac{r}{\sigma_f \sigma_b} \right) dr \end{aligned} \quad (13)$$

Finally, solving the integral in Eq.13 [20], and after some manipulations, a closed-form expression of the detection probability  $P_D$  can be calculated as a function of the average received power  $\bar{P}_{r,R}$ , the forward link Rician  $K$ -factor and the RFID reader antenna sensitivity  $P_{RS}$  that is:

$$\begin{aligned} P_D(P_{RS}) &= 2 \exp(-K) \sum_{i=0}^{\infty} \frac{1}{(i!)^2} (K)^i \left( \frac{(K+1)P_{RS}}{\bar{P}_{r,R}} \right)^{\frac{i+1}{2}} \\ &\quad \times \mathbf{K}_{i+1} \left( \sqrt{\frac{4(K+1)P_{RS}}{\bar{P}_{r,R}}} \right). \end{aligned} \quad (14)$$

In the case of cascaded Rayleigh fading (i.e.  $K = 0$ ), the reader detection probability can be simplified to:

$$P_{D,K=0}(P_{RS}) = 2 \times \sqrt{\frac{P_{RS}}{\bar{P}_{r,R}}} \times \mathbf{K}_1 \left( \sqrt{\frac{4P_{RS}}{\bar{P}_{r,R}}} \right). \quad (15)$$

### IV. SIMULATION RESULTS

In order to examine the impact of multipath fading on passive RFID system performance, we assume that we have two reader's antennas are placed on the ceiling of a (10 m  $\times$  10 m  $\times$  3 m) room size, and specifically located at positions  $P_1(0, 5, 3)$  and  $P_2(10, 5, 3)$ . The readers antennas are facing each others as illustrated in Fig.2. The numerical results of the tags detection probability and reader reading coverage are

TABLE I  
PASSIVE RFID SYSTEM PARAMETERS

Parameter	Value
Operating Frequency	865.7 MHz
Transmit Power ( $P_{Tx}$ )	+33 dBm EIRP
Modulation Efficiency ( $\tau$ )	0.5
Polarization Loss Factor ( $\rho_L$ )	0.5
Power Transfer Efficiency ( $\mu_T$ )	1
Differential Reflection Coefficient ( $\Gamma$ )	0.1
Tag Ant Gain ( $G_t$ )	0 dBi
Tag Ant sensitivity ( $P_{TS}$ )	-15 dBm
Tag Height ( $H$ )	1.5m
Reader Ant Sensitivity ( $P_{RS}$ )	-75 dBm
Reader Ant Elevation Angle ( $\theta$ )	$\pi/4$
Reader Ant Azimuth Angle ( $\phi$ )	0
Room Height	3 m
Room Width	10 m

generated and studied based on equations Eq. 5, Eq. 14 and Eq. 15. The overall system parameters are set in Table.I.

In this paper, the detection probability will be used as performance metric of RFID system in fading channels. It is defined as the probability that the instantaneous received power falls below a specified received sensitivity. Usually the reader sensitivity is defined with respect to a certain signal-to-noise ratio, here we consider it as the minimum level of the tag signal which the reader can detect and resolve. Figure 3 shows an example of the 3-D reading coverage of a reader for the case of nearly free space environment (i.e.  $K = 100$ ) and severe multipath environment (i.e.  $K = 1$ ). The area where the tag backscattered power is below reader sensitivity is shaded in black. It is clear from the plots that the reliable reading range reduces when the Rician  $K$ -factor decreases. This is because a smaller  $K$ -factor (i.e.,  $K = 1$ ) represents stronger multipath fading effect, which introduces larger random power fluctuation in the interrogation zone. Therefore the backscattered signals exposed in such environment are more likely to be interrupted and hence undetectable by the reader.

Figure 4 illustrates how the tag detection probability varies with average received power for different values of  $K$ -factor. As expected, the tag detection probability is lowest when  $K = 0$  (cascaded Rayleigh) due to the absence of the Line of Sight (LOS) in both forward and backscattered link. When  $K$  increases the forward link is exposed to stronger LOS environment, and the tag detection probability is increased accordingly. However, the tag detection probability begins to saturate when  $K$  reaches 100 (nearly free space environment) and further increasing  $K$  does not provide extra benefits in the tag detection probability. Hence the maximum benefits on the tag detection probability brought by increasing  $K$ -factor is around 10% on average. After this point, the detection probability is mainly dominated by Rayleigh faded backscattered link, which results in reduced detection probability even when the average received power is well above reader sensitivity.

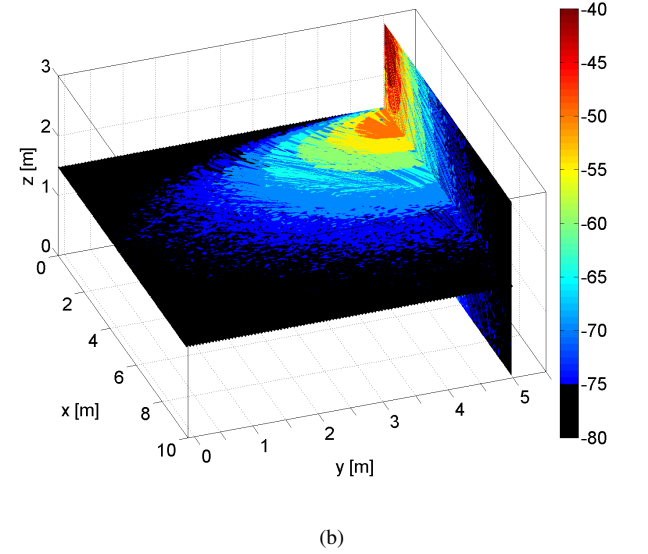
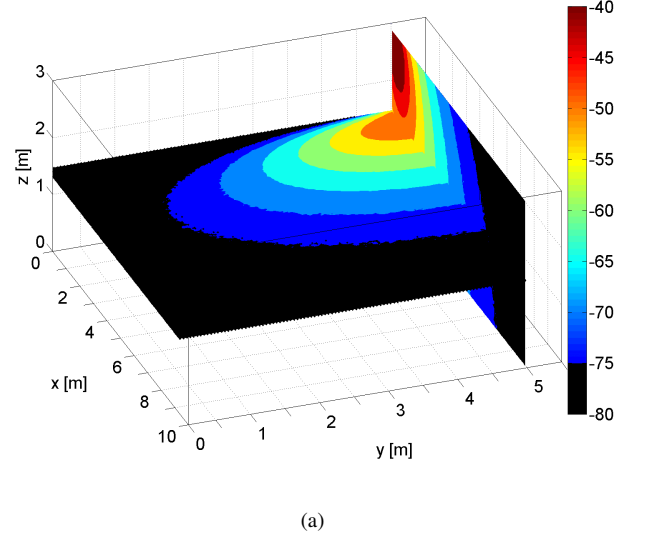


Fig. 3. 3D view of passive RFID reading coverage when (a)  $K = 100$  and (b)  $K = 1$

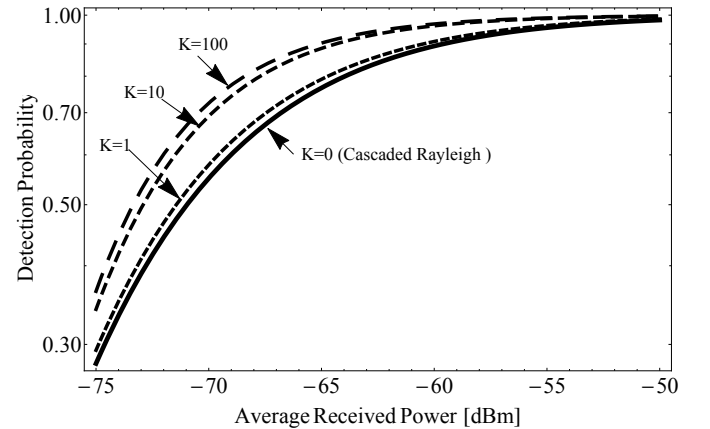


Fig. 4. Detection probability as a function of average received power for different values of  $K$ -factor.

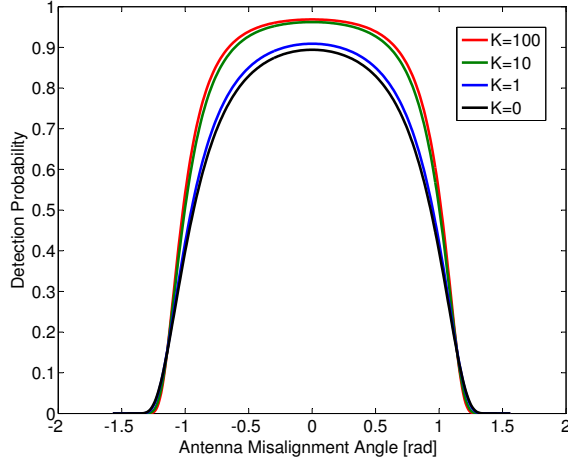


Fig. 5. Detection probability as a function of  $K$ -factor for different values of average received power.

To investigate the impact of reader tag misalignment on the tag detection probability, Fig.5 plots how detection probability varies with antenna misalignment angle from  $-\pi/2$  to  $\pi/2$ , for different values of  $K$  factor. The antenna misalignment angle is defined as the angle between the antenna main lobe and its pointing direction to the tag. As expected, when the main lobe of an antenna is perfectly aligned with the tag direction (i.e. misalignment angle equals 0), the tag detection probability reaches its maximum for all  $K$  values. When the antenna main lobe and the tag become misaligned the tag detection probability reduces exponentially. As the misalignment angle reaches 1.25 rad the tag detection probability drops to almost 0. Hence the misalignment angle has a major impact on the tag detection probability. In addition, it is noticeable that the  $K$ -factor has a more significant impact on the tag detection probability when misalignment angle is small (between  $-0.5$  rad to  $0.5$  rad), where different values of  $K$ -factor can result in nearly 10% difference in the detection probability. However, when the misalignment angle is large, the tag detection probability is mainly affected by misalignment angle and therefore the value of  $K$ -factor has little impact on the tag detection probability.

To highlight the impact of  $K$ -factor on the tag detection probability, Figure 6 plots how the tag detection probability varies with  $K$ -factor for different values of average received power. It is noticed that the detection probability increases with  $K$ -factor, although this trend is only significant with lower average received power. This is because when the average received power is high it is more immune to multipath fading effect and therefore the tag detection probability is very close to 1, regardless of different values of  $K$ -factor. In contrast, when the average received power is marginal the tag detection probability is more likely to be affected by multipath effect. For instance, when the average received power is  $-75$  dBm the tag detection probability is increased by approximately 8% from severe multipath environment (i.e.,  $K = 1$ ) to nearly free space environment (i.e.,  $K = 100$ ), whereas the tag detection

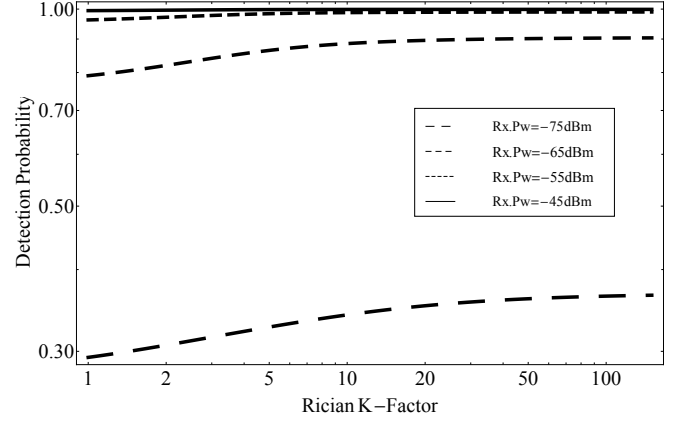


Fig. 6. Detection probability as a function of  $K$ -factor for different values of average received power.

probability is almost the same for all  $K$  values with  $-45$  dBm average received power.

The impact of Rician  $K$  factor on the tag detection probability of tags located on the same floor is analyzed in Fig.7. The average received power is obtained according to the two-ray model, where tag signal is calculated as the vector sum of both the direct LOS signal and ground reflection signal. The results, in general, indicate that the reliable reading region is strongly affected by both the height of tags above ground and multipath fading effect ( $K$ -factor). It can be observed from Fig.7 that the maximum reliable reading range decreases from approximately  $5m$  to  $3.5m$  from nearly free space environment ( $K = 100$ , Fig.7(a) and Fig.7(c)) to severe multipath environment ( $K = 1$ , Fig.7(b) and Fig.7(d)). This represents a 30% reduction in the reliable reading range from nearly free space environment to strong multipath environment. In addition, it is noticed that the shape of detection probability is more distorted (or unpredictable) when tag plane is closer to the ground (Fig.7(c) and Fig.7(d)). This is expected since tags closer to the ground are more affected by ground reflection.

## V. CONCLUSION

In this paper, we have studied the performance of passive RFID system under cascaded channel fading from the RF point of view. We have presented a 3-D analytical model for RFID system and studied the effect of cascaded channel fading and readers antenna orientation on the passive RFID tags, in terms of detection probability. We have derived a closed-form expression for passive RFID detection probability taking into account the relative reader-tag antennas orientations and Rician-forward and Rayleigh-reverse channel fading parameters. The derived formulas can be useful for design and optimization of passive RFID communication systems.

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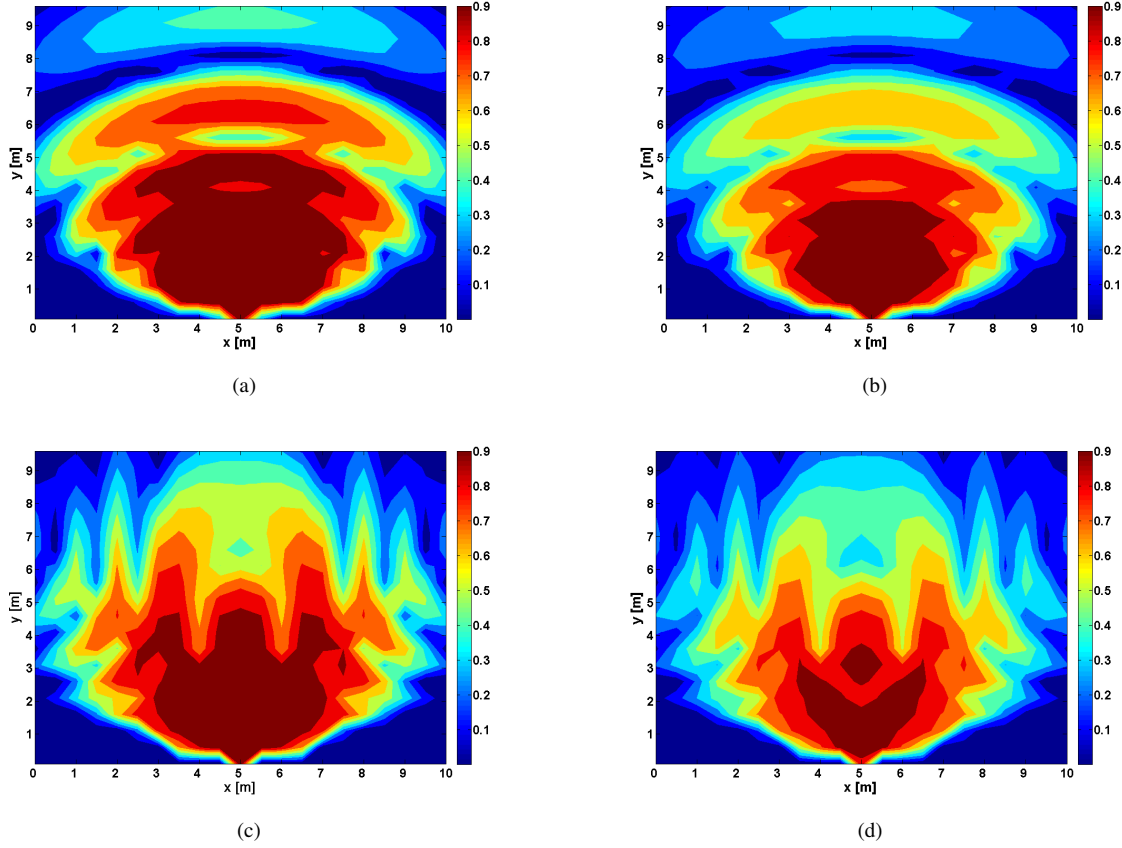


Fig. 7. 2D-distribution of the detection probability for tags located on the same floor (a)  $K = 100$ , tag height 1.5m, (b)  $K = 1$ , tag height 1.5m, (c)  $K = 100$ , tag height 0.5m (d)  $K = 1$ , tag height 0.5m.

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