

EFFECTS OF INTERFERENCES IN UHF RFID SYSTEMS

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Abstract—The Radio Frequency Identification (RFID) applications are growing rapidly, especially in the UHF frequency band that is being used in inventory management. Passive UHF tags are preferred for these applications. In this paper, RFID reader-to-reader interference is analyzed. A model to estimate the minimum distance between readers to achieve a desired probability of detection in real multipath environments is derived and compared to the ideal case (AWGN channel). Diversity techniques to combat multipath and interference effects are proposed and studied.

1. INTRODUCTION

Nowadays there is a significant thrust in RFID use for improving the efficiency of inventory tracking and management in enterprise supply chain management [1–3]. These applications use passive RFID tags, which communicate with the reader by changing (modulating) its reflection coefficient to incoming radiation from the reader, i.e., modulating its scattering/radar cross section. For long-range tags, the UHF bands are often selected. In free space (i.e., with no environmental effects and far away from the source) the RF power density drops off as $1/r^2$, where r is the tag-reader distance. However, for multipath situations (this is the RFID case), with reflections and losses, the drop-off exponent n is situation dependent [4].

Three types of interferences can be considered in a RFID system: tag-to-tag interference, reader-to-tag interference and reader-to-reader interference. The tag-to-tag interference occurs when multiple tags respond to the same reader simultaneously. It can be avoided by

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having each tag responding at different times. Thus, a multi-tag anti-collision algorithm is needed to resolve this interference. Reader-to-tag interference occurs when a tag is in the interrogation zone of multiple readers and more than one reader transmits simultaneously.

The third interference type is between readers and occurs when the signals from neighboring readers interfere (see Figure 1). It can be avoided only by having neighboring readers operating at different times or different frequencies. A multi-reader anti-collision algorithm must be used to resolve this interference.

Serious reader-to-reader interference problems may exist in some deployments (such as supply chains) where tens or hundreds of readers are in operation within a close range to each other. The distance over which a reader can interfere with another reader is much larger than the tag read range, particularly if high-gain reader antennas view each other. Reader-to-reader interference is a problem when signals transmitted from distant readers are strong enough to impede accurate decoding of the backscattered signals at the tags. The most basic solution to reader-to-reader interference is to turn off the reader when it is not needed by using sensors for reader activation. In the United States, roughly 50 hopping channels are available in the 902–928 MHz ISM band [5], and interference is sporadic until tens of readers are in simultaneous operation in a single facility, a situation that is not common yet. However, other jurisdictions provide much narrower bands for RFID operation: ETSI EN 302 208 [6] allows only 2 MHz (865.6–867.6), Hong Kong allows 8 MHz split into two bands, Singapore allows 5 MHz split into two bands and Korea allows 5.5 MHz. In these regions interference is much more likely to be a problem, especially when large facilities are considered.

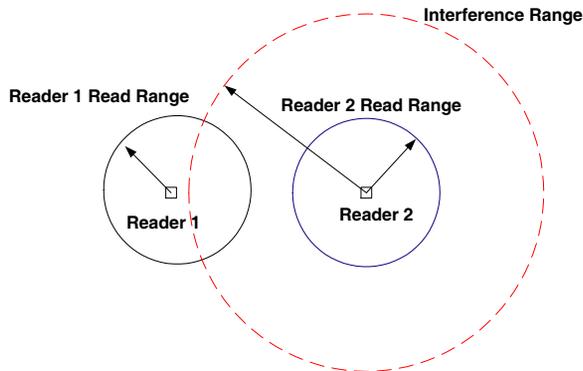


Figure 1. Reader-to-reader interference.

Some attempts to mitigate reader-to-reader interference have been made [7–9]. They are normally based on standard multiple access mechanisms such as frequency-division multiple access (FDMA), time-division multiple access (TDMA), or carrier-sense multiple access (CSMA). For example, the Electronic Product Code for global Class 1 Generation 2 (EPCglobal C1G2) includes spectrum management for UHF RFID operation in densereader environments [7]. However, this does not entirely eliminate reader-to-reader interference due to the incomplete spectral separation, which can still affect reader operation. Recent works have demonstrated the reduction in the interrogation range due to reader-to-reader interference [10].

This paper focuses on the analysis of reader-to-reader interference effects and the employment of diversity techniques to combat interference and multipath effects. It has been shown in [4] that fadings due to multipath must be taken into account in RFID systems and, in consequence, a Rayleigh modeling of the channel must be done. However, the effects of interferences on the error probability have not been reported in the literature up to now, neither for AWGN nor Rayleigh channel. In addition, the probability of error has not been yet reported for FM0 and Miller codes (the ones used in RFID) for Rayleigh channels. To this end, the expressions for error probability in a Rayleigh channel with FM0 and Miller codes are derived. In a second step, these expressions have been extended by taking into consideration the presence of interferences in AWGN and Rayleigh channels. Finally, the concept of antenna diversity [11, 12] is introduced to increase the probability of detection in presence of interferences. Antenna diversity allows for reducing considerably the reader-to-reader distance in a Rayleigh channel down to a distance close to the AWGN channel case. However, antenna diversity works if the antennas are uncorrelated. Little information about correlation between RFID antennas has been found in the literature. To this end, the correlation distance between two typical RFID antennas has been studied in order to demonstrate that space diversity is possible in RFID environments.

The paper is organized as follows. In Section 2, a summary of the main expressions for the power link budget in RFID systems is revised; these expressions are used in the study of reader-to-reader interference. Here, the effect of interferences in the error probability is studied for AWGN and Rayleigh channels. In order to mitigate the interference effects, antenna diversity schemes are proposed in Section 3. Finally, some conclusions are drawn in Section 4.

2. EFFECTS OF INTERFERENCES

2.1. Radio Link Budget in RFID Systems

A typical UHF RFID system consists of a reader and several passive tags. In the forward link communication (addressed as uplink), the reader interrogates the tag with a data transfer that utilizes an ASK modulation scheme; the return data transfer, from tag to reader (addressed as downlink), utilizes a backscattered modulation scheme. In the uplink communication, the carrier signal generated by the reader is radiated out through the antenna. The tag collects energy from the electromagnetic waves coming from the reader and converts it to DC supply for the chip. Once the tag is powered up, the reader sends the commands by modulating its carrier. After commands are completed, the reader sends an un-modulated continuous wave (CW) signal which is used to provide DC supply for the tag. The power available to the tag for operation ($P_{r,tag}$) is given by a modification of Friis transmission equation [4].

In the downlink communication, the tag responds to the reader and the reader must demodulate the signal. The selected tags encode the data and then change the impedance of its antenna by modulating the radar cross section. The power received by the reader in the backscatter communication radio link ($P_{r,reader}$) is a modification of the monostatic radar equation:

$$P_{r,reader}(\text{dBm}) = P_{reader}(\text{dBm}) + 2G_{reader}(\text{dB}) - 2L_{sys}(\text{dB}) \\ + 20 \log |\rho'| + 2G_{tag}(\text{dB}) + 2\Delta G(\text{dB}) - 2L_p \quad (1)$$

where P_{reader} is the power transmitted by the reader, G_{reader} is the gain of the reader antenna, and G_{tag} is the nominal gain of the tag antenna. The term ΔG includes the gain penalty caused by detuning and the gain reduction when the tag is in contact with materials [4]. L_{sys} is the cable loss, L_p is the path loss and ρ' is the differential reflection coefficient of the tag $\rho' = \rho_1 - \rho_2$, where ρ_1 and ρ_2 are the 0 and 1 states of the chip reflection coefficient, which depends on the chip load).

An empirical model for path loss is often used in indoor environments such as RFID. It is based on a two-slope model [4]:

$$L_P(\text{dB}) = -20 \log \left(\frac{\lambda}{4\pi} \right) + n_1 10 \log(r) + (\alpha - n_1) 10 \log(1 + r/R_0) + L_{obs}(\text{dB}) \quad (2)$$

where r is the distance between tag and reader, λ is the wavelength, n_1 the path loss factor for $r < R_0$ [13] and α is the path loss factor for $r > R_0$ (for flat earth model $\alpha = 4$). L_{obs} is the loss due to diffraction and medium attenuation. In practice, for passive RFID,

$R_0 = 4h_1h_2/\lambda$ (where h_1 and h_2 are the reader and tag antenna heights, respectively) is longer than the maximum read range. Thus, model (2) can be simplified by taking into account only the first path loss term $n_1 10 \log(r)$. The path loss factor n_1 depends on the antenna's height but it has been found experimentally that for typical RFID environments it is close to 2 [4].

The tag sensitivity is defined as the minimum power needed for rectification of the incident RF power (power up process). For instance, for the commercial tag *Impinj Monza Gen 2*, sensitivity is about -11 dBm. This value is higher than reader sensibility. In consequence, readers in passive UHF systems need to transmit high power in order to power up the tags. Thus, the interference signals from other readers may be a problem in downlink communication where the backscattered signal level can be comparable to the interfering signals.

2.2. Interferences in RFID Regulations

There are two major protocols adopted by the worldwide industry in UHF passive RFID field, *EPCglobal* specifications [7] and ISO 18000-6 [14], which identify the interaction between tags and readers. In addition, to avoid harm to human health and frequency interferences, local regulations such as the definition of the electromagnetic compatibility and the radio spectrum must be implemented (*ETSI 302.208* in Europe [6] and *FCC part 15* in US [5]). The requirements in terms of modulation type and depth and transmission mask determine the UHF RFID transmitter architecture.

To meet the different RFID protocols in the uplink, the reader can use Double-SideBand Amplitude Shift Keying (DBS-ASK), Phase-Reversal ASK (PR-ASK) and Single-SideBand ASK (SSB-ASK). The EPC GEN 2 specification defines a number of options for the physical layer in both downlink and uplink and the reader uses Pulse Interval Encoding (PIE). The length of Data-0 is given in Tari, where a Tari is the time reference unit of signaling and takes values between $6.25 \mu\text{s}$ and $25 \mu\text{s}$. The length of Data-1 takes values between 1.5 and 2 Tari.

European regulations fix a Listen Before Talk access protocol; if a reader detects a signal on the channel where it intends to transmit, it switches to another free channel. Two cases could be considered: a single-reader environment or a multiple-reader environment. In the latter, the number of simultaneously operating readers is assumed to be lower than the number of available channels. When the number of operating readers is large compared to the number of available channels, the situation is defined as a dense reader environment. In such environment, certified readers must incorporate the schemes defined in the EPC GEN 2 specification to minimise

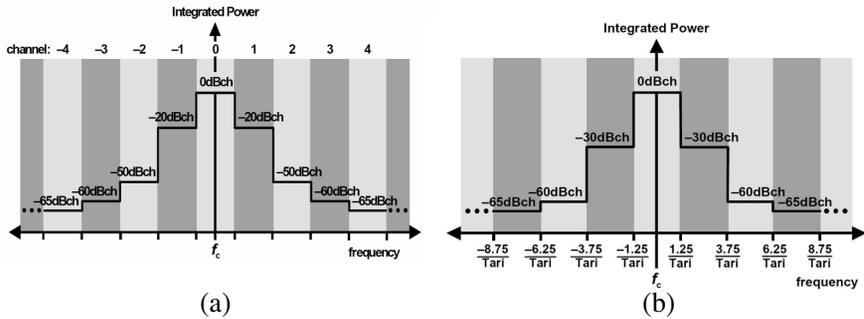


Figure 2. Interrogator transmit mask. (a) Multiple reader environment and (b) dense reader environment [7].

mutual interference. In the time-synchronized scheme, all the readers transmit together and listen simultaneously to the tag responses while maintaining their CW. In the frequency-separated scheme, readers transmit on even-numbered channels, while tags respond on odd-numbered channels. In the latter scheme, the powerful reader signals must not mask the backscattered signals at the tag, which are several dBs smaller.

Another aspect to take into account is band limitation. In North America, UHF RFID operates in the 902–928 MHz band (FCC Part 15.247 regulations) and frequency hopping between the 52×500 kHz channels is used. This is a large band compared to the 2 MHz frequency band in Europe (10×200 kHz channels between 865.6–867.6 MHz for ETSI EN 302 208 regulations).

Interrogators (readers) certified for operation according to EPC GEN2 protocol shall meet local regulations for out-of-channel and out-of-band spurious radio-frequency emissions. For a small number of readers to coexist, interrogators must confine their spurious emissions as shown in Figure 2(a) (multiple reader environments). However, for dense reader populations, the transmit mask is defined in Figure 2(b).

2.3. Bit Error Probability in Presence of Interferences

The objective of this work is to study the effect of interferences in the probability of detection (in terms of bit error probability, P_b or BER). Since path loss in the backscattered signals (downlink) is higher than in the uplink, the work is focused on the downlink.

The bit error probability P_b is a function of the signal-to-noise ratio. In a multipath fading channel, the received signal and the signal-to-noise ratio change with time. A standard deviation between

the model (2) and the measured received power of up to 4 dB was experimentally found in [4]. This value increases when the antenna height decreases. Moreover, the received signal follows different probability functions depending on the scenario. The cover range as a function of the scenario has been studied in [4].

In a multipath channel, an average signal-to-noise ratio must be taken into account to calculate the average P_b . However, in systems with interferences, if the statistical distribution of the interference can be approximated to that of Gaussian noise, the received average signal-to-interference-plus-noise power ratio (SINR) is often used instead of the average signal-to-noise ratio to calculate error probability. In those RFID systems operating according to EPC GEN2 protocol, the interference can come from spurious emissions of all interfering readers, according to the transmit mask (see Figure 2). Moreover, interferent and interfered readers are not frequency-locked to the same clock reference and they can present frequency deviations. In addition, if the readers operate in multiple reader environments or are not perfectly synchronized in dense reader environments, the interfering signals are spurious and residual out-of-band modulated signals of the uplink. By applying the Central Limit Theorem to the interference, it can be approximated as added Gaussian noise. Thus, the interfering signals are uncorrelated with the backscattered signal at the tag and noise, and then the effective average signal-to-interference-plus-noise ratio (or SINR) $\bar{\gamma}$ is given by [15]:

$$\bar{\gamma} = \frac{S}{N + I} = \frac{1}{\frac{1}{SNR} + \frac{1}{CIR}} \quad (3)$$

where S is the average signal power, N is the noise power and I is the average interference power. SNR is the average signal to noise ratio in an AWGN channel and CIR is the carrier-to-interference ratio (or SIR, signal-to-interference ratio). The effective average SINR (3) is the hyperbolic average between the signal-to-noise ratio and the signal-to-interference ratio. It is approximately equal to CIR in an interference-dominated scenario.

The CIR can be calculated from the difference between the power received by the reader from the tag (1) and the interfering power P_I , which can be calculated from:

$$P_I(\text{dBm}) = P_{reader,int}(\text{dBm}) - ACPR(\text{dB}) + G_{reader,int}(\text{dB}) \\ + G_{reader}(\text{dB}) - L_{P,int}(\text{dB}) \quad (4)$$

where $P_{reader,int}$ and $G_{reader,int}$ are the power transmitted by the interfering reader and its antenna gain in the direction of the interfered reader, respectively. In (4), ACPR is the adjacent channel power ratio

and it is determined by the transmission mask (see Figure 2). The path loss between the interfering reader and the interfered reader $L_{P,int}$ is given by (2) but using the reader-to-reader distance. Fortunately, in this case, this distance can be larger than R_0 and the path loss may be considerably high. In addition, losses due to obstacles may be very important and can also reduce reader-to-reader interference.

The uplink data rate is partially determined by the downlink preamble and partially by a bit field set in the query command which starts each query round [7]. These settings allow for an uplink data rate ranging from 40 kbps to 640 kbps. The reader sets the uplink frequency and also sets one of the four uplink encodings, namely FM0, Miller-2, Miller-4 or Miller-8 (tag communicates with reader using either FM0 or Miller sub-carrier encoding). When using FM0, one bit is transmitted during each cycle and a phase inversion occurs at the boundary between symbols while Data-0 has a mid-symbol phase inversion. FM0 is highly susceptible to noise and interferences and this motivated the addition of the Miller encodings. While these are more robust to errors with the increase of the number, their link rates are reduced by a factor of 2, 4 or 8, depending on the encoding. Reference [16] derives an expression for bit error rate (BER) for FM0 and Miller encoding. This result is only valid for an AWGN channel. If a symbol-by-symbol detection is applied, it is not optimal but it is easy to implement compared to differential detection. When using a differential decoder a 3-dB improvement is obtained [16]. The symbol error rate (SER) (or, equivalently, the BER) is given by [16]:

$$P_b = 2Q \left(\sqrt{\frac{ME_S}{N_0}} \right) \left[1 - Q \left(\sqrt{\frac{ME_S}{N_0}} \right) \right] \quad (5)$$

where E_S is the symbol energy, $N_0/2$ is the noise power spectrum density of an AWGN channel, M is the Miller-code order, and $Q(x)$ is the Q -function [17]. From the E_S/N_0 ratio, it can be easily obtained the signal-to-noise ratio γ assuming that noise bandwidth is approximately equal to $1/T_S$ (where T_S is the duration of a symbol):

$$\gamma = S/N \approx \frac{\frac{E_S}{T_S}}{\frac{N_0}{T_S}} = \frac{E_S}{N_0} \quad (6)$$

However, (5) is not generally valid in RFID environments, since due to multipath propagation, the signals follow a Rayleigh distribution in the worst case. Then, the average error probability \bar{P}_b is computed by integrating the error probability in AWGN over the fading distribution:

$$\bar{P}_b = \int_0^\infty P_b(\gamma) f_\gamma(\gamma) d\gamma \tag{7}$$

where $P_b(\gamma)$ is the probability of symbol error in AWGN with SNR γ , which can be obtained from (5) and $f_\gamma(\gamma)$ the probability density for a Rayleigh distribution of fading amplitude, which can be computed from:

$$f_\gamma(\gamma) = \frac{1}{\bar{\gamma}} e^{-\gamma/\bar{\gamma}} \tag{8}$$

where $\bar{\gamma}$ is the effective average SINR (3). To evaluate the integral (7), the $Q(x)$ function and $Q^2(x)$ can be written as [15]:

$$Q(x) = \frac{1}{\pi} \int_0^{\pi/2} e^{-\frac{x^2}{2 \sin^2 \phi}} d\phi \tag{9}$$

$$Q^2(x) = \frac{1}{\pi} \int_0^{\pi/4} e^{-\frac{x^2}{2 \sin^2 \phi}} d\phi \tag{10}$$

Then, using (9),(10), the following new compact expression has been obtained for the mean bit error rate in a Rayleigh channel:

$$\bar{P}_b(\bar{\gamma}) = \frac{1}{2} - \frac{1}{\sqrt{1 + 2/(M\bar{\gamma})}} + \frac{2}{\pi} \frac{\tan^{-1} \left(\sqrt{1 + 2/(M\bar{\gamma})} \right)}{\sqrt{1 + 2/(M\bar{\gamma})}} \approx \frac{1}{2M\bar{\gamma}} \tag{11}$$

where the approximation holds for large $\bar{\gamma}$; in this case, (11) is inversely proportional to $\bar{\gamma}$, identical to the BPSK case [15]. In addition, if a differential decoder is used, (11) tends to the same limit as the BPSK case ($1/4\bar{\gamma}$).

Figure 3 compares the BER performance of FM0 and Miller codes in ideal AWGN and Rayleigh channels. It is clear that for large signal-to-noise ratios the BER decreases faster in an AWGN channel than in a Rayleigh channel. A SNR of approximately 12 dB is required to maintain a 10^{-3} bit error rate in AWGN while a SNR of approximately 25 dB is required in a Rayleigh channel when using FM0 encoding. It can also be deduced from (11) that the BER decreases with the increase of the Miller sub-carrier order, but here the disadvantage is the reduction in the data rate. From Figure 3 it is also clear that a technique is required to maximize the read range and remove the effects of fading. Next section proposes antenna diversity to overcome these limitations. It must be noted that Rayleigh fading is one of the worst-case scenarios.

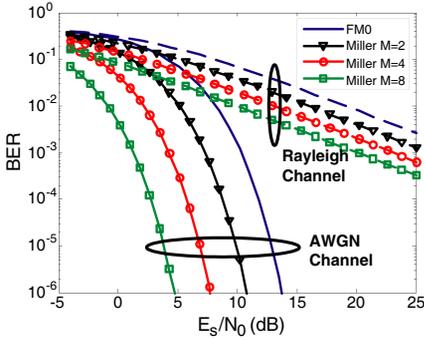


Figure 3. BER as a function of E_S/N_0 for different encoding modulations in AWGN and Rayleigh channels.

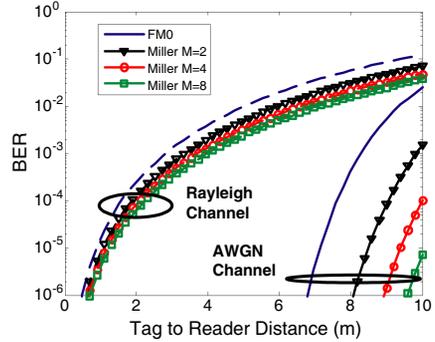


Figure 4. BER as a function of tag-to-reader distance; reader $CIR = 20$ dB in AWGN and Rayleigh channels.

The lower bound of the reader dynamic range is limited by the noise of its front-end. Since the strength range of the backscattered signals is extremely wide (about 80 dB, that is, from -75 dBm to 5 dBm), an input attenuator is required to avoid the saturation of the amplifier stages. In consequence, the noise figure is relatively high (about 22 dB). In addition, the oscillator phase noise also increases the noise floor, since the local oscillator phase noise is down-converted in the received band. Commercial readers specify a sensitivity of $S_{\min} = -70$ dBm; assuming a noise figure of $NF = 22$ dB and a maximum receiver bandwidth of $BW = 1.6$ MHz (using a DSB modulation scheme at 640 kHz and 22% bit rate tolerance) SNR can be calculated:

$$SNR = S_{\min}(\text{dBm}) - (NF(\text{dB}) + 10 \log(BW) - 174) = 20 \text{ dB} \quad (12)$$

And the maximum phase noise (PN) permitted can be calculated from [18]:

$$PN(\text{dBc}/\text{Hz}) = S_{\min} + ACPR(\text{dB}) - SNR(\text{dB}) - 10 \log(CBW) \quad (13)$$

Assuming an adjacent channel power ratio $ACPR = 30$ dB (see Figure 2(b), the SNR obtained in (12) and a channel bandwidth of $CBW = 250$ kHz, the phase noise is $PN = -96$ dBc/Hz@250 kHz, which is feasible to achieve in practice.

In order to study the influence of interferences, the limit case with signal-to-interference ratio $CIR = 20$ dB is considered. Figure 4 shows the probability of error as a function of the distance between reader and tag. This figure shows that in a Rayleigh channel the read range

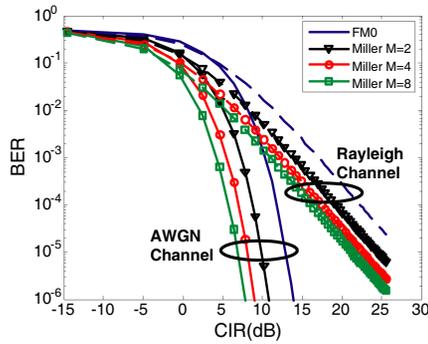


Figure 5. BER as a function of CIR for a tag placed 2 m away from the reader, considering an $ACPR = 30$ dB for AWGN and Rayleigh channels.

is limited by the downlink (tag to reader) because for a given BER, e.g., $BER = 10^{-3}$, the distance is limited to 2–3 m, depending on the encoding. In case of an AWGN channel, the read range is limited by the uplink, where the power received at the tag must be higher than its sensitivity. In free-space conditions, this distance is higher than 4–6 m (depending on the transmitted power), but it decreases to 2–3 m when Rayleigh fading is considered [4].

Figure 5 studies the BER as a function of CIR for a tag placed 2 m away from the reader considering an $ACPR = 30$ dB for AWGN and Rayleigh channels. For a typical BER limit (e.g., 10^{-3}) the required SNR in AWGN is very low (see Figure 3), thus the effective SINR $\bar{\gamma}$ is equal to SNR for a $CIR > 10$ dB (3). However, in a Rayleigh channel the effective SINR is approximately equal to CIR. Then, following (11), the BER decreases as $1/CIR$. In consequence, the BER decreases much more slowly in a Rayleigh channel than in an AWGN channel with the increase of CIR. An important improvement is obtained when Miller codes are used over FM0 encoding.

3. ANTENNA DIVERSITY

One of the most powerful techniques to mitigate the effects of fading is to use diversity-combining of independently-fading signal paths [19, 20]. This section focuses on common techniques at the transmitter and receiver to achieve diversity. Diversity-combining relies on the fact that independent signal paths have a low probability of experiencing deep fading simultaneously. Thus, the idea behind diversity is to send the same data over independent-fading paths.

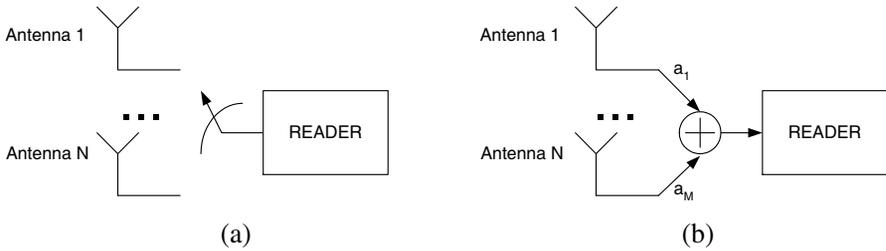


Figure 6. Combining diversity techniques: (a) Selection Combining (SC), (b) Maximum Ratio Combining (MRC) and Equal Gain Combining (EGC).

These independent paths are combined in such a way that the fading of the resultant signal is reduced. For example, let us consider a system with two antennas at either the transmitter or the receiver that experience independent fading. If the antennas are spaced sufficiently far apart, it is unlikely that they both experience deep fading at the same time. By selecting the antenna with the strongest signal, known as selection combining (SC), a much larger signal than the case with just one antenna is obtained (see Figure 6(a)). Other diversity techniques that have potential benefits over this scheme in terms of performance or complexity are discussed next (see Figure 6(b)). In maximum ratio combining (MRC) [15], the branch signals are weighted and combined so as to yield in the highest instantaneous SNR possible with any linear combining technique. In equal gain combining (EGC) all of the weights have the same magnitude but an opposite phase to that of the signal in the respective branch. However, MRC or EGC diversity techniques require important modification in commercial readers.

There are many ways of achieving independent fading paths in a wireless system. One method is to use multiple transmit or receive antennas, known as antenna array, where the elements of the array are separated in distance. This type of diversity is referred to as space diversity. Another method consists in frequency diversity. In this case, the independent paths are performed using uncorrelated frequency channels. However, the minimum frequency offset between two channels to be considered uncorrelated must be higher than the coherence bandwidth. The measured coherence bandwidth in a typical RFID environment is shown in [4]. The typical coherence bandwidth in UHF RFID is higher than in ISM-band RFID. Thus, frequency diversity could not be applied to combat multipath fading because all the channels are correlated.

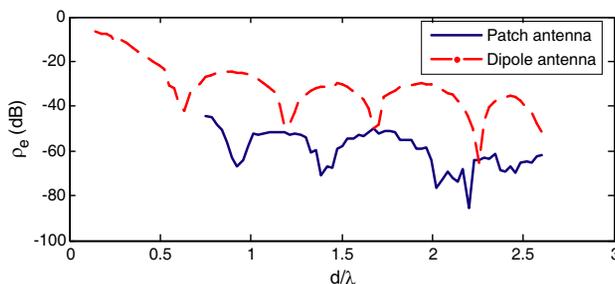


Figure 7. Measured envelope correlation coefficient as a function of the normalized distance between dipole and dual-polarized patch antennas.

Space diversity requires a separation between antennas in such a way that the fading amplitudes corresponding to each antenna are approximately independent. The necessary antenna separation for a two-antenna system can be found by using the envelope correlation coefficient. It can be proved that if it is assumed that the angles of arrival have equal probability, the envelope correlation coefficient ρ_e can be expressed using the S-parameters and is given by [21]:

$$\rho_e = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{\left(1 - (|S_{11}|^2 + |S_{21}|^2)\right) \cdot \left(1 - (|S_{22}|^2 + |S_{12}|^2)\right)} \quad (14)$$

Expression (14) allows for a fast characterization of the envelope correlation coefficient including mutual coupling. Figure 7 shows the measured envelope correlation as a function of distance between antennas for two cases: 1/ two dipoles with a ground plane as a reflector and 2/ two commercial dual-polarized patch antennas (model FEIG250). This figure shows that the envelope correlation coefficient presents minimums separated a distance $\lambda/2$ in both antennas. However, the envelope correlation coefficient is considerably lower for the patch antenna, since this topology presents a null in the direction of the ground plane.

In conclusion, the antennas frequently used in RFID doors can be placed very close from each other, since they are practically uncorrelated. This can also be taken into account when space diversity is considered. However, conventional patch antennas are not suitable for portable readers due to their size. Here, compact topologies such as dipole-like antennas are needed. Then, two dipoles will be considered uncorrelated if the distance is higher than 0.7λ . Since this separation could be prohibitive in a portable reader, the antennas could also be uncorrelated by using special interface circuits [22].

After the study of practical viability of space diversity in UHF RFID systems, the performance of selecting combining technique is investigated. In selection combining, the combiner outputs the signal on the branch with the highest SNR. Assuming a stationary scenario, for a N -branch diversity, the Complementary Distribution Function (CDF) of the average signal-to-noise-ratio γ_Σ is given by [15]:

$$P_{\gamma_\Sigma}(\gamma) = p(\gamma_\Sigma < \gamma) = p(\max[\gamma_1, \gamma_2, \dots, \gamma_N] < \gamma) = \prod_{i=1}^N p(\gamma_i < \gamma) \quad (15)$$

Defining the average SNR in the i th branch as $\bar{\gamma}_i = E[\gamma_i]$, the SNR distribution is exponential and it is given by (8) with $\bar{\gamma} = \bar{\gamma}_i$. If the average SNR for all the branches is the same $\bar{\gamma} = \bar{\gamma}_i$, then (15) reduces to:

$$P_{\gamma_\Sigma}(\gamma) = p(\gamma_\Sigma < \gamma) = \prod_{i=1}^N (1 - e^{-\gamma/\bar{\gamma}_i}) = (1 - e^{-\gamma/\bar{\gamma}})^N \quad (16)$$

Differentiating (16) relative to $\bar{\gamma}$ yields the probability distribution function for γ_Σ :

$$f_{\gamma_\Sigma}(\gamma) = \frac{N}{\bar{\gamma}} [1 - e^{-\gamma/\bar{\gamma}}]^{N-1} e^{-\gamma/\bar{\gamma}} \quad (17)$$

Then, the mean error probability in selection combining diversity $\bar{P}_{b,SC}$ can be calculated using:

$$\bar{P}_{b,SC} = \int_0^\infty P_b(\gamma) f_{\gamma_\Sigma}(\gamma) d\gamma \quad (18)$$

Finally, using (9), (10), a new compact expression for (18) is obtained:

$$\bar{P}_{b,SC} = N \sum_{n=0}^{N-1} \frac{(-1)^n}{n+1} \binom{N-1}{n} \bar{P}_b \left(\frac{\bar{\gamma}}{n+1} \right) \quad (19)$$

where the function \bar{P}_b is given by the average Rayleigh error probability (11). Equation (19) has been checked by means of numerical integration.

Figures 8, 9 study the effects of diversity in presence of interference by calculating the BER as a function of distance between the interfering reader and the interfered reader for an AWGN channel, a Rayleigh channel and a Rayleigh channel with antenna diversity of order $N = 2$. The tag is located 2 m away from the interfered reader. According to the transmit mask for dense reader environment (Figure 2(b)), it is

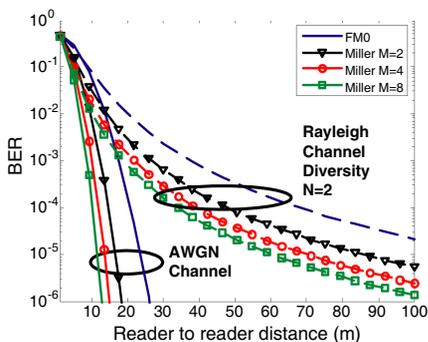


Figure 8. BER as a function of reader-to-reader distance for an AWGN channel and a Rayleigh channel using antenna diversity of order 2, with interference and considering an ACPR of 30 dB.

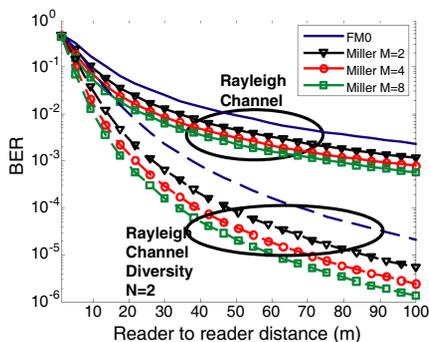


Figure 9. BER as a function of reader-to-reader distance for a Rayleigh channel and a Rayleigh channel using antenna diversity of order 2, with interference and considering an ACPR of 30 dB.

assumed that in the worst case the interference falls just at the adjacent channel, the ACPR in (4) amounts to 30 dB and the reader antennas are one in front of the other. In this case, for an error probability of 10^{-4} , the minimum reader-to-reader distance can be up to 10–25 m in an ideal AWGN channel; however, in a Rayleigh channel, readers as far as 100 m could degrade the BER in RFID systems. Using antenna diversity with only 2 branches, this minimum distance can be reduced down to about 30 m (using Miller encoding). It can be concluded that a diversity technique as simple as SC with two branches aids to solve the problem of interferences.

Figures 10,11 show the BER as a function of CIR for an AWGN channel, a Rayleigh channel and a Rayleigh channel with antenna diversity considering an ACPR of 30 dB and a tag 2 m away from the interfered reader. These figures, as well as Figures 8,9, demonstrate that the utilization of an antenna diversity technique as simple as selection combining is fundamental to achieve high-detection probability in dense reader environments. An increase in the CIR could be obtained by blocking the interference with absorbing materials or metallic walls. This extra increase in the path attenuation would allow reducing the reader-to-reader distance below 30 m. However, this seems to be a very unpractical solution. A CIR reduction of about 5–6 dB could be achieved by increasing the number of antennas from 2 to 4, which corresponds to a reduction to a half of the reader-to-reader minimum distance.

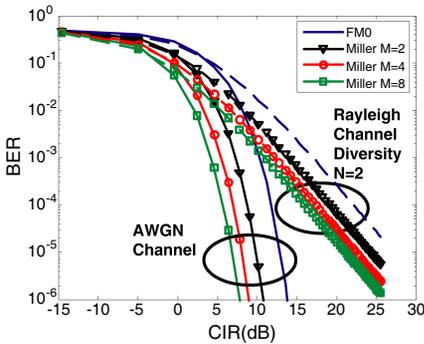


Figure 10. BER as a function of CIR for an AWGN channel and a Rayleigh channel with antenna diversity of order 2.

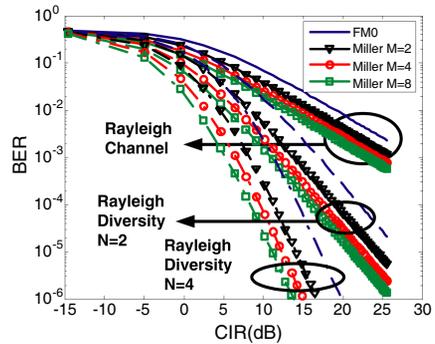


Figure 11. BER as a function of CIR for a Rayleigh channel without antenna diversity and a Rayleigh channel with antenna diversity of order 2 and 4.

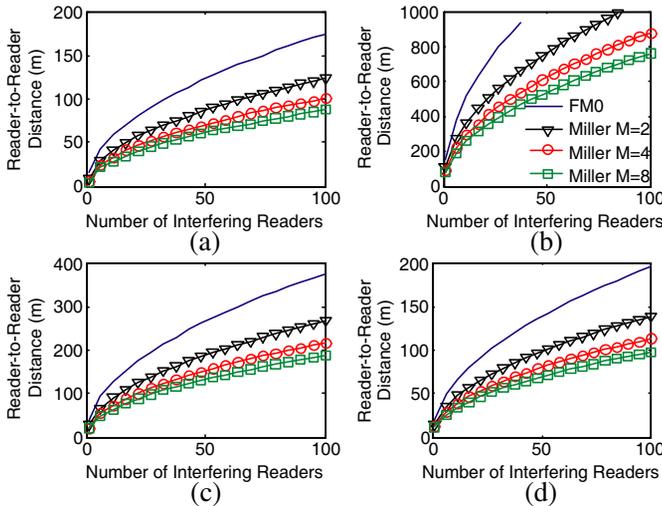


Figure 12. Minimum reader-to-reader distance as a function of the number of interfering readers for a $BER = 10^{-3}$ using FM0, Miller $M = 2$, Miller $M = 4$ and Miller $M = 8$ encodings: (a) AWGN channel, (b) Rayleigh channel, (c) Rayleigh channel with diversity order $N = 2$ and (d) Rayleigh channel with diversity order $N = 4$.

Using the model previously presented, the effect of the number of interfering readers in a dense scenario can be estimated. Assuming the extreme case where all the interfering readers are active and located at the same distance from the interfered reader, Figure 12 compares the

minimum reader-to-reader distance permitted to obtain a bit error rate ($BER = 10^{-3}$) using FM0, Miller $M = 2$, Miller $M = 4$ and Miller $M = 8$ encodings. From these results, it is clear that the minimum permitted reader-to-reader distance decreases with the increase of the encoding order M . It is also clear that, by increasing the antenna diversity order, minimum reader-to-reader distances in a Rayleigh channel similar to the ones in an AWGN channel can be recovered.

4. CONCLUSIONS

In this paper, the effect of reader-to-reader interference in RFID systems has been studied. Indoor wireless systems, such as RFID systems, are seriously affected by fadings due to multipath propagation. In these scenarios the channel is far from an ideal AWGN channel. The received power changes with time and follows a Rayleigh distribution. In this paper, expressions to evaluate the error probability for FM0 and Miller codes (the ones used in RFID) in Rayleigh channels have been derived. Then, the effects of interferences in (ideal) AWGN and (real) Rayleigh channels are compared. The use of antenna diversity schemes has been proposed in order to mitigate the read range reduction due to reader-to-reader interference. In those RFID applications where the tag position is not known (for instance, dock doors), space diversity is often used. By using several reader antennas, it is possible that one antenna is in line-of-sight with the tag and, in consequence, signal blocking is avoided. In addition, selection combining is often used in RFID systems to increase the number of tag reads. However, in this paper the concept of antenna diversity has been introduced to increase the probability of detection in presence of interferences. To this end, a new compact expression to model the probability of error for FM0 and Miller codes in a Rayleigh channel has been derived. It has been demonstrated that antenna diversity allows reducing considerably the reader-to-reader distance considering a Rayleigh channel up to a minimum distance close to the ideal AWGN channel case. Finally, the correlation distance between two typical RFID antennas has been studied, demonstrating the viability of using N -branch diversity in most RFID applications to combat reader-to-reader interference.

The design considerations and expressions given in this paper for the calculation of bit error probability using FM0 and Miller encoding and considering a Rayleigh channel can be applied to develop tools and simulators for prevision of interferences in dense-reader environments, serving as a useful guideline for RFID system-level designers or engineers.

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