Spatial Fading in Backscatter Channels: Theory and Models

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IEEE Consumer Communications & Networking Conference, 2019

About Us

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Director

RFID
- Channel Modeling
- Microwave Structures
- Channel Coding
- Energy Harvesting
- Localization

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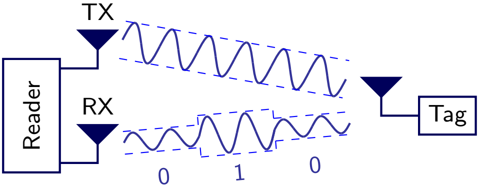
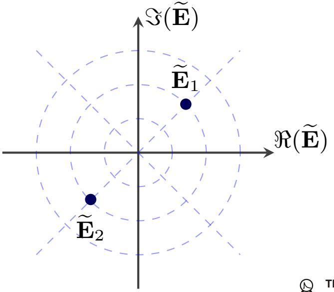
Table of Contents

System Overview

Fact

RFID systems communicate by means of *backscattered* fields

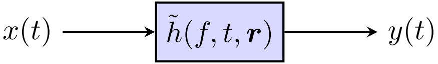




- "0" bit $\longrightarrow$ $\widetilde{\mathbf{E}}_1$
- "1" bit $\longrightarrow$ $\widetilde{\mathbf{E}}_2$

General Overview

The envelope of the signal fades with *time*, *frequency*, and *space*



- $f \longleftrightarrow \tau$ (delay)
- $t \longleftrightarrow w$ (Doppler)
- $\boldsymbol{r} \longleftrightarrow \boldsymbol{k}$ (wavenumber)

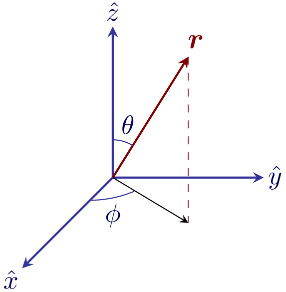
Spatial Fading

- Spatial Fading; $\frac{\partial \tilde{h}}{\partial f} = 0, \ \frac{\partial \tilde{h}}{\partial t} = 0$
- $\boldsymbol{r} = (r, \theta, \phi) \longrightarrow r$

Spatial Fading is the building block for frequency fading

$$\tilde{h}(t) = \sum_{\ell=0}^{L} \gamma_\ell \delta(t - \tau_\ell) \quad \text{(CIR)}$$

γ_ℓ determined from $\tilde{h}(r)$



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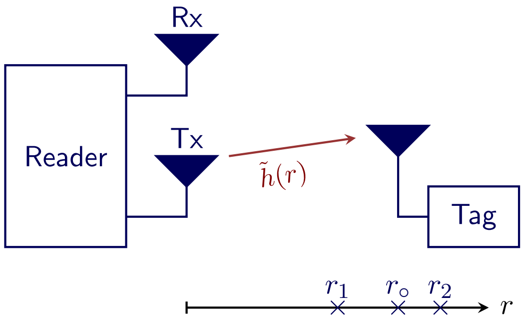
One-Way Channel Model I

At the tag: $$\tilde{h}(r) = \underbrace{\alpha_1(r)\exp\left[j\Phi_1(r)\right]}_{\text{Line-of-sight}} + \underbrace{\sum_{i=2}^{N}\alpha_i(r)\exp\left[j\Phi_i(r)\right]}_{\text{Non-Line-of-sight}}$$



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One-Way Channel Model II

At the tag: $$\tilde{h}(r) = \underbrace{\alpha_1(r)\exp\left[j\Phi_1(r)\right]}_{\text{Line-of-sight}} + \underbrace{\sum_{i=2}^{N}\alpha_i(r)\exp\left[j\Phi_i(r)\right]}_{\text{Non-Line-of-sight}}$$

Two cases:

1. $\alpha_1^2(r) << \sum_{i=2}^{N}\alpha_i^2(r)$ (e.g., $\alpha_1(r) = 0$)
2. $\alpha_1^2(r)$ is *comparable* to $\sum_{i=2}^{N}\alpha_i^2(r)$

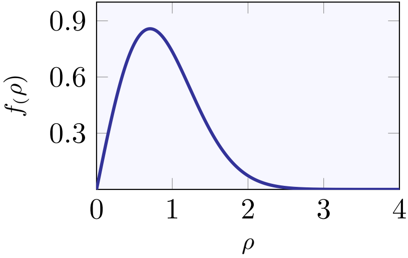
One-Way Channel Model: Rayleigh Fading

First case: $\alpha_1^2(r) << \sum_{i=2}^{N} \alpha_i^2(r)$ (e.g., $\alpha_1(r) = 0$)

$$\sum_{i=1}^{N} \alpha_i(r) \exp\left[j\Phi_i(r)\right] \sim \mathcal{CN}(0, \sigma^2)$$

The envelope (magnitude)

$$f(\rho) = \frac{2\rho}{\sigma^2} \exp\left(-\frac{\rho^2}{\sigma^2}\right)$$



One-Way Channel Model: Rician Fading

Second case: $\alpha_1^2(r)$ is *comparable* to $\sum_{i=2}^{N} \alpha_i^2(r)$

$$\alpha_1(r)\exp\left[j\Phi_1(r)\right] + \mathcal{CN}(0,\sigma^2)$$

$$f(\rho) = \frac{2\rho}{\sigma^2}\exp\left(-\frac{(\rho^2+\alpha_1^2)}{\sigma^2}\right) I_0\left(\frac{2\rho\alpha_1}{\sigma^2}\right)$$

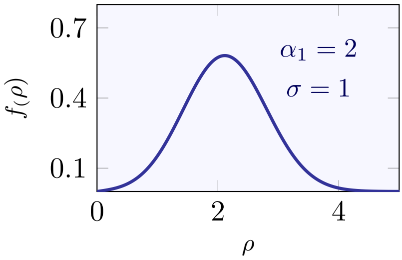
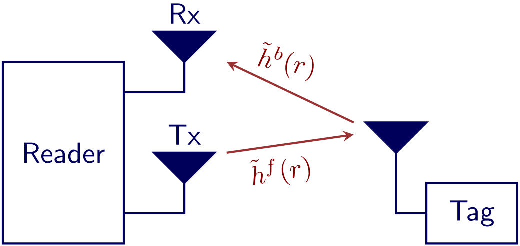
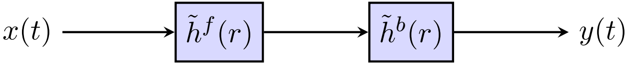


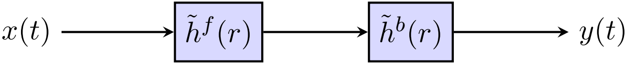
Table of Contents

Physical Model





System Architecture



Three possible configurations:

1. *Monostatic*; Tx $=$ Rx; hence, $\tilde{h}^f(r) = \tilde{h}^b(r)$
2. *Co-located Bistatic*; Tx$\neq$ Rx; but $\tilde{h}^f(r)$ and $\tilde{h}^b(r)$ are correlated
3. *Dislocated Bistatic*; Tx$\neq$ Rx; but $\tilde{h}^f(r)$ and $\tilde{h}^b(r)$ are independent

Facts

First Fact

Backscatter channels are the product of two one-way channels

Second Fact

Severity of fading increases with the correlation between the forward and backward channel

We want to study the two extreme cases, monostatic (fully correlated) and dislocated bistatic (independent; hence, uncorrelated)

Monostatic Channels

Recall:

- $\tilde{h}^f(r) = \sum_{i=1}^{N} \alpha_i(r) \exp\left[j\Phi_i(r)\right]$, and $\tilde{h}^b(r) = \sum_{i=1}^{M} \beta_i(r) \exp\left[j\Psi_i(r)\right]$
- Monostatic implies $\tilde{h}^f(r) = \tilde{h}^b(r) \longrightarrow \tilde{h}(r) = \left(\tilde{h}^f(r)\right)^2$

Under the same environment, if X is a random variable that describes fading in a **one-way** channel, then $Y = X^2$ is the random variable that describes fading in a **monostatic backscatter** channel

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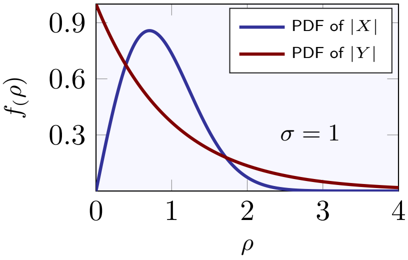
Monostatic Channels: Rayleigh Fading

- $X \sim \mathcal{CN}(0, \sigma^2)$, $|X|$ is Rayleigh
- $Y = X^2$, $|Y| = |X|^2$ is double Rayleigh



$$f_{|X|}(\rho) = \frac{2\rho}{\sigma^2} \exp\left(-\frac{\rho^2}{\sigma^2}\right), \qquad f_{|Y|}(\rho) = \frac{1}{\sigma^2} \exp\left(-\frac{\rho}{\sigma^2}\right)$$

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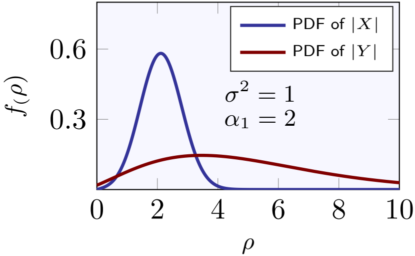
Monostatic Channels: Rician Fading

- $X \sim \mathcal{CN}(0, \sigma^2) +$ UDP, $|X|$ is Rician
- $Y = X^2$, $|Y| = |X|^2$ is double Rician



$$f_{|X|}(\rho) = \frac{2\rho}{\sigma^2} \exp\left(-\frac{(\rho^2 + \alpha_1^2)}{\sigma^2}\right) I_0\left(\frac{2\rho\alpha_1}{\sigma^2}\right),$$

$$f_{|Y|}(\rho) = \frac{1}{\sigma^2} \exp\left(-\frac{(\rho + \alpha_1^2)}{\sigma^2}\right) I_0\left(\frac{2\sqrt{\rho}\alpha_1}{\sigma^2}\right)$$

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Monostatic Channels: Weibull Fading I

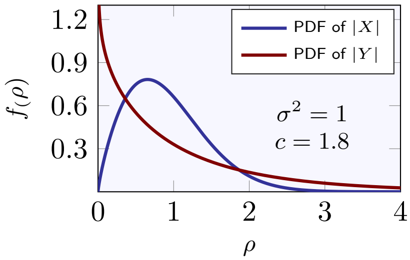
- Sometimes, Rayleigh and Rice distributions do not fit!
- We look for a distribution that fits!
- At UHF, Weibull distribution is a good choice!

Weibull PDF

$$f(\rho) = \frac{c\rho^{c-1}}{\eta} \exp\left(\frac{-\rho^{c}}{\eta}\right), \ \eta = \left(\frac{\Gamma(1+2/c)}{\sigma^2}\right)^{-c/2}$$

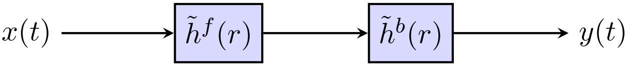
Monostatic Channels: Weibull Fading II

- Most RFID systems operate at UHF
- $|X|$ is Weibull
- $Y = X^2$, $|Y| = |X|^2$ is double Weibull



$$f_{|X|}(\rho) = \frac{c\rho^{c-1}}{\eta}\exp\left(\frac{-\rho^c}{\eta}\right), \qquad f_{|Y|}(\rho) = \frac{c\rho^{c/2-1}}{2\eta}\exp\left(\frac{-\rho^{c/2}}{\eta}\right)$$

Dislocated Bistatic Channels: Overview



- $\tilde{h}^f(r)$ and $\tilde{h}^b(r)$ are independent
- $X \sim \tilde{h}^f(r)$ and $Y \sim \tilde{h}^b(r)$
- $Z = XY \sim \tilde{h}(r) = \tilde{h}^b(r)\tilde{h}^f(r)$

Dislocated Bistatic Channels: Rayleigh, Rice, & Weibull

In terms of the CDF

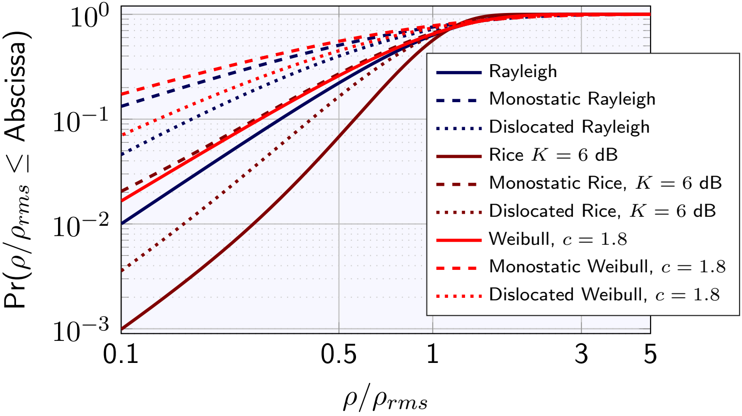


Table of Contents

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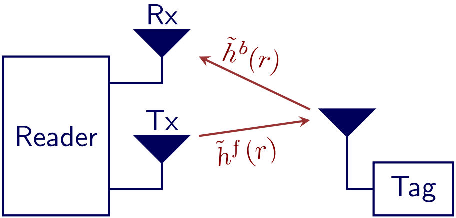
Motivation I

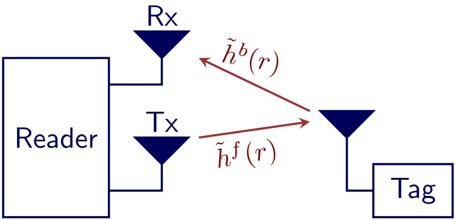
So far:

- Three RFID Configurations



- The severity of fading increases with correlation

Motivation II



- Statistically:
  1. Monostatic $\longrightarrow$ R.V. squared $\longrightarrow$ easiest to compute
  2. Dislocated $\longrightarrow$ Product of 2 indep. R.V. $\longrightarrow$ easy to compute
  3. Co-located $\longrightarrow$ Product of 2 dep. R.V. $\longrightarrow$ hard to compute

Question & Answer

Is there a way to get a rough estimate of #3 statistics ?

Observable Fact

Experimentally, the statistics of a co-located bistatic channel fall between that of monostatic and dislocated bistatic

- Strong correlation $\longrightarrow$ closer to monostatic
- Weak correlation $\longrightarrow$ closer to dislocated bistatic

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BER Definition

Mathematically:

$$P_b(\bar{\gamma}) = \int_0^{\infty} P_{\text{AWGN}}(\gamma) f(\gamma)\ \mathrm{d}\gamma$$

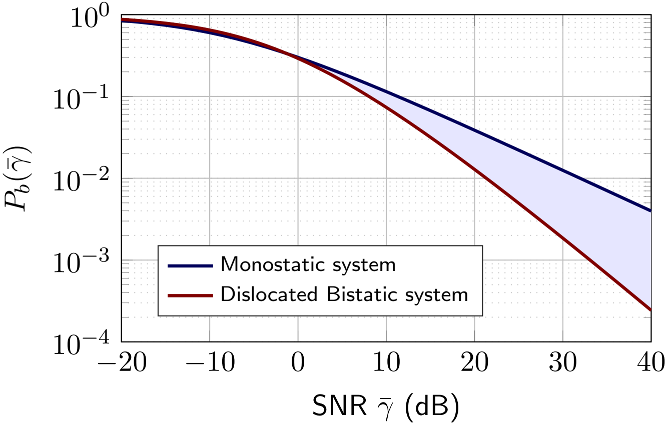
- $\bar{\gamma}$: Average SNR per bit per unit RMS
- γ: Instantaneous SNR per bit
- AWGN: Additive White Gaussian Noise
- $P_{\text{AWGN}}(\gamma)$ depends on modulation
- $f_\gamma(\gamma) = \frac{1}{2\sqrt{\gamma\bar{\gamma}}} f_\rho\left(\sqrt{\frac{\gamma}{\bar{\gamma}}}\right)$

BER of BPSK

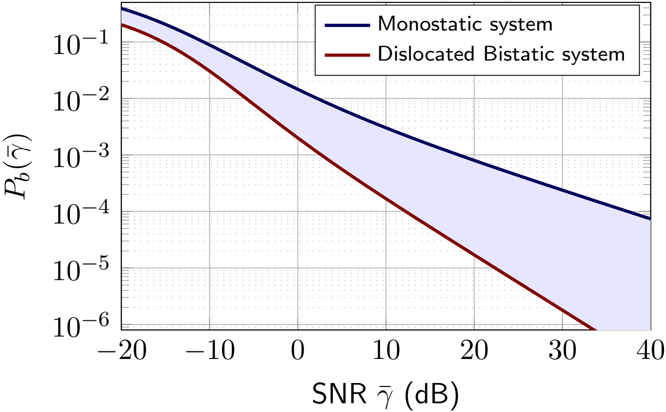
$$P_b(\bar{\gamma}) = \int_0^\infty P_{\text{AWGN}}(\gamma) f(\gamma)\, \mathrm{d}\gamma$$

- Most RFID systems use binary modulation
- Passive RFID $\longrightarrow$ OOK
- Semi-passive RFID $\longrightarrow$ BPSK
- For BPSK; $P_{\text{AWGN}} = Q(\sqrt{2\gamma})$

BER of Rayleigh Channels



BER of Rician Channels



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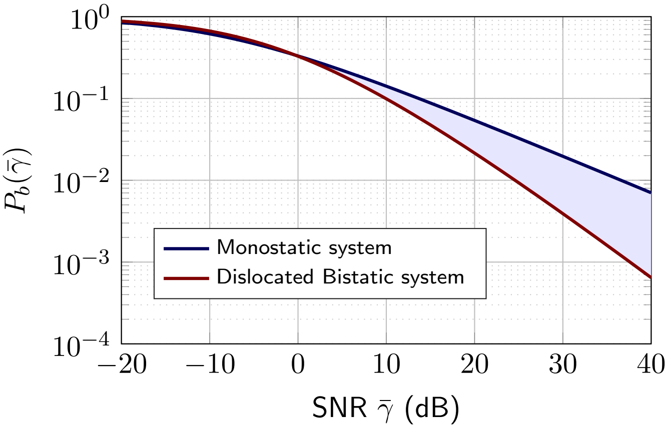
BER of Weibull Channels



Summary

To sum up,

- The statistics of RFID systems strongly depend on the correlation between the forward and backward channel
- Fading is less sever when these channels are weakly correlated
- Independent and identical channels are the two extreme cases