



CS649
Sensor Networks
Lectures 7-8: Physical Layer Characterization

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<http://hinrg.cs.jhu.edu/wsn06/>

Outline

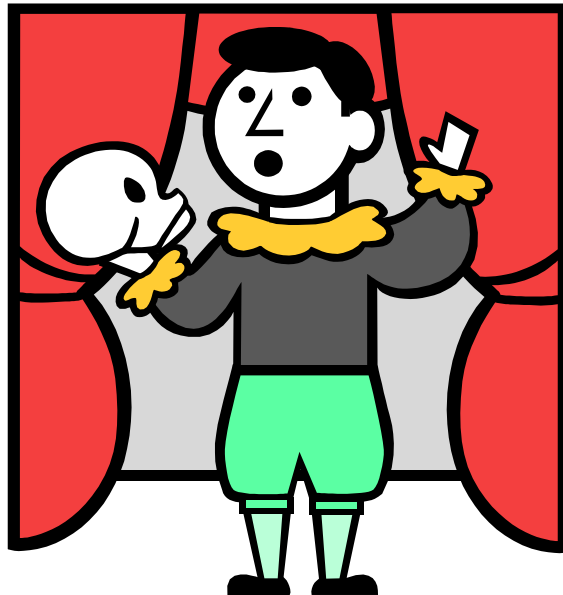
- (Simple) Radio Power loss models
- Reality
- (More) Radio Power loss models

Motivation

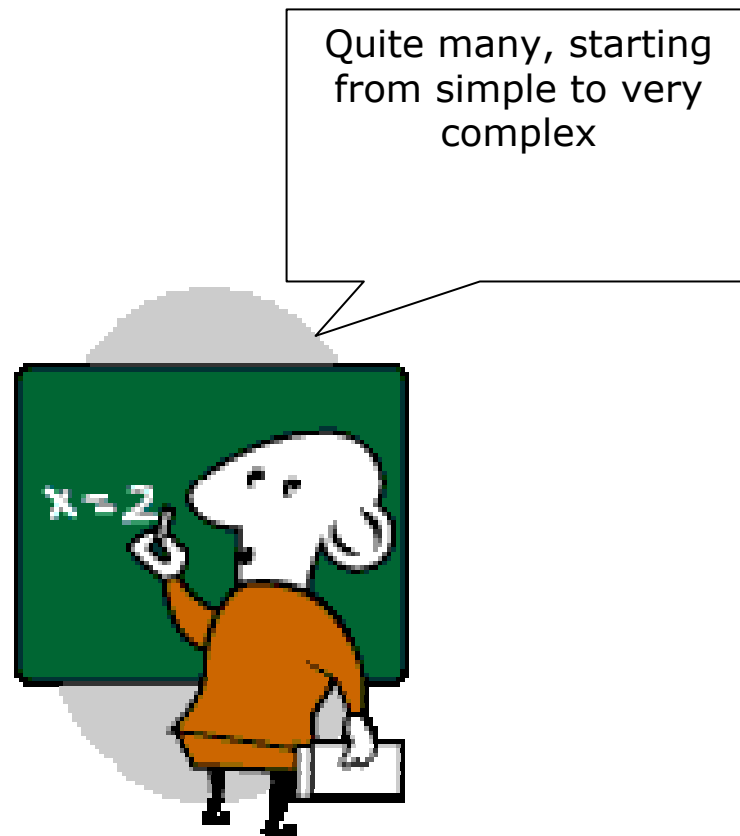
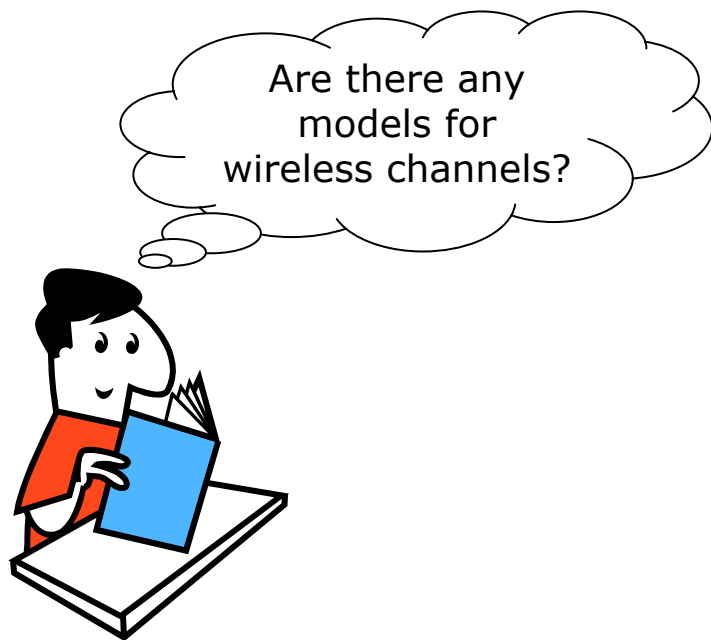
- Communication between nodes over wireless channel
- Characteristics of wireless channel have impact on all upper layer protocols
 - Transmission range
 - Loss rate (BER is determined by SNR at the receiver)
- Would like to model those characteristics
 - Guide design of future systems
 - Help analysis of future systems

We are Computer Scientists

- EE “stuff” has a lot of math
- Math is hard!
- Presented as a play with three acts



First Act



Friss Free-Space Propagation Model

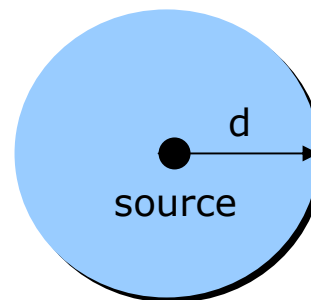
$$\frac{P_R}{P_T} = G_T G_R \left(\frac{\lambda}{4\pi d} \right)^2$$

P_T and P_R - power values at the receiving and transmitting antennas (in watts)

G_T and G_R are the power gains for the transmitting and receiving antenna

λ - wavelength in meters

d - distance between receiver and transmitter

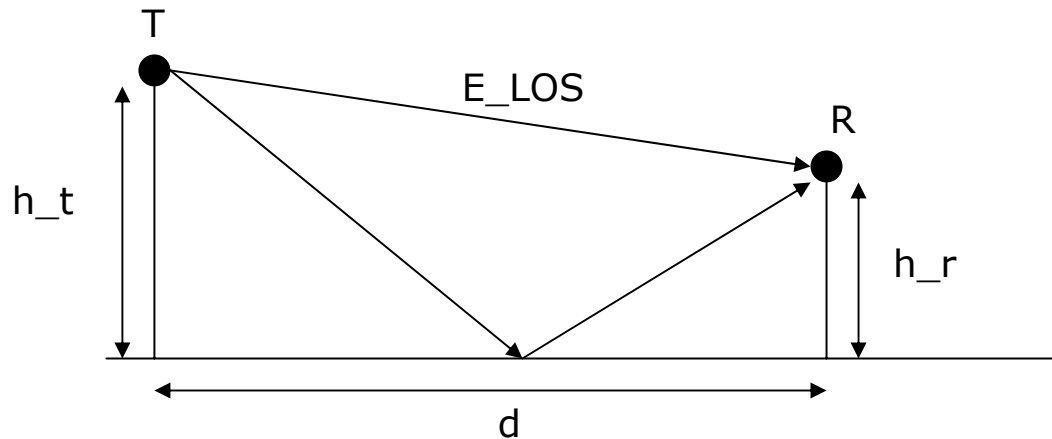


- Models **average power** received
- Assume no obstructions between source and receiver (LOS path)
- Isotropic antennas
- Perfect Power match

Propagation Mechanisms in Space with Objects

- Reflection
 - Radio wave impinges on an object $\gg \lambda$ (30 cm @1 GHz)
 - Earth surface, walls, buildings, atmospheric layers
- Diffraction
 - Radio path is obstructed by an impenetrable surface with sharp irregularities (edges)
 - Secondary waves “bend” around the obstacle
 - Explains how RF energy can travel without LOS
- Scattering
 - When medium has large number of objects $< \lambda$ (30cm @1 GHz)
 - Similar principles as diffraction, energy reradiated in many directions
 - Rough surfaces, small objects (e.g. foliage, lamp posts, street signs)
- Other: Fading and multi-path

Example: Ground Reflection (2-Ray) Model



- Model found to be good predictor for large-scale signal strength over distances of several kilometers for mobile systems with tall towers ($h > 50\text{m}$)
- Can show that for large d $d \gg \sqrt{h_t h_r}$

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}$$

Log-distance Path Loss Model

- Assume average power (in dB) decreases proportional to the *log* of distance

$$\overline{PL}(d) = \overline{PL}(d_o) + 10n \log\left(\frac{d}{d_o}\right)$$

- Path-loss exponent n , depends on propagation environment

Environment	n
Free Space	2
Urban Area	2.7-3.5
Shadowed Urban	3-5
In-building LOS	1.6 to 1.8
Obstruction in building	4 to 6
Obstruction in factories	2 to 3

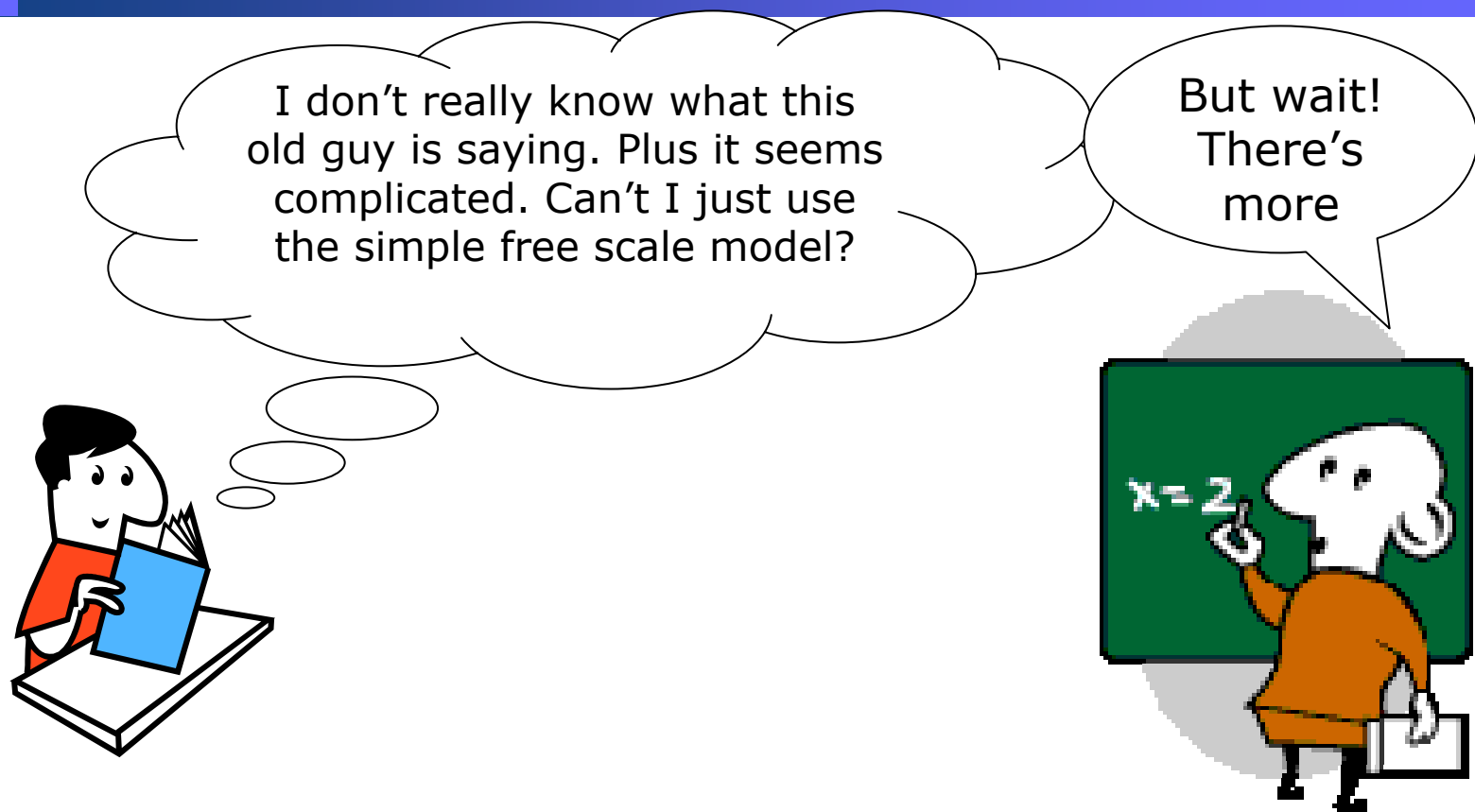
A more realistic model: Log-Normal Shadowing Model

$$\overline{PL}(d) = \overline{PL}(d_o) + 10n \log\left(\frac{d}{d_o}\right) + X_\sigma$$

X_σ is zero - mean Gaussian r.v (in dB) with standard deviation σ (in dB)

- Statistically describes random shadowing effects
 - values of n and σ are computed from measured data using linear regression
- Model typically derived from measurements
- Log normal model found to be valid in indoor environments
- All these models describe signal strength variations over large distances and large time scales

Back in the class...



Second Act

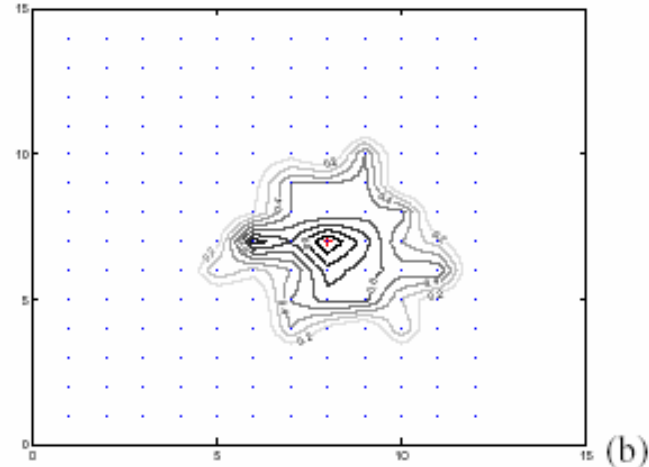
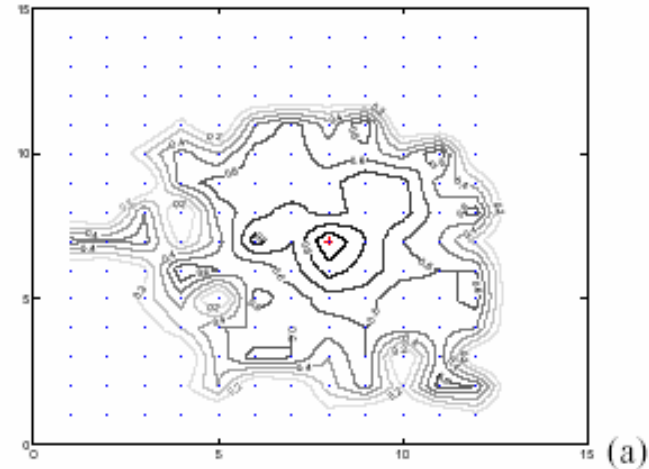
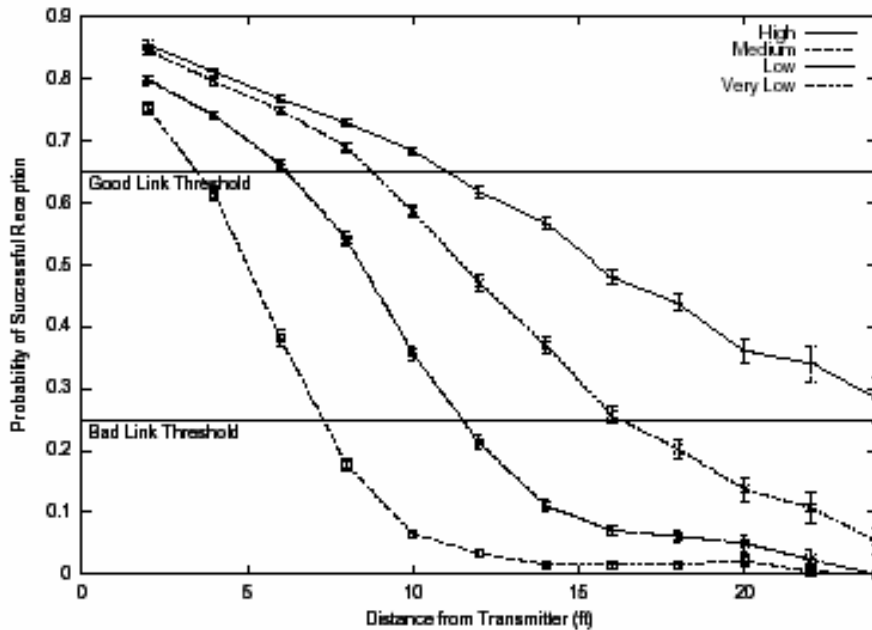
- Assuming that the old guy is exaggerating about the need of extra models, our friend sets out to verify that experimental results match the simple model

Complex Behavior at Scale: An Experimental Study of Low-Power Sensor Networks

- Motivating Scenario
 - Expected vs. Obtained results
- Platform
- Methodology

Packet Reception Statistics

- Radio range is not uniform
 - Why?
- 10%-15% of links are asymmetric
 - Why?



Radio Channel Features

- Asymmetrical links: the connectivity of node a to node b ($a \rightarrow b$) might be significantly different than from node b to node a ($b \rightarrow a$).
- Non-isotropical connectivity: the connectivity is not necessary the same in all the directions (same distance) from the source.
- Non-monotonical distance decay: nodes that are geographically far away from the source may get better connectivity than nodes that are geographically closer.

Parameters

- **Transmission gain control:** most of the low power radios used in sensor networks have some form TX gain control.
- **Antenna height:** the relative distance of the antenna with respect to the reference ground.
- **Radio frequency and modulation type:** as defined by the radio hardware used.
- **Packet size:** the number of bits transmitted per packet can affect the likelihood of receiving the packet with no errors.
- **Data rate:** the number of packet per second transmitted.
- **Environment type:** difficult to completely classify. We could differentiate between indoors or outdoors, with or w/o LOS, different levels of physical interference (furniture, walls, trees, etc.), and different materials (sand, grass, concrete, etc.).



SCALE: A tool for Simple Connectivity Assessment in Lossy Environments

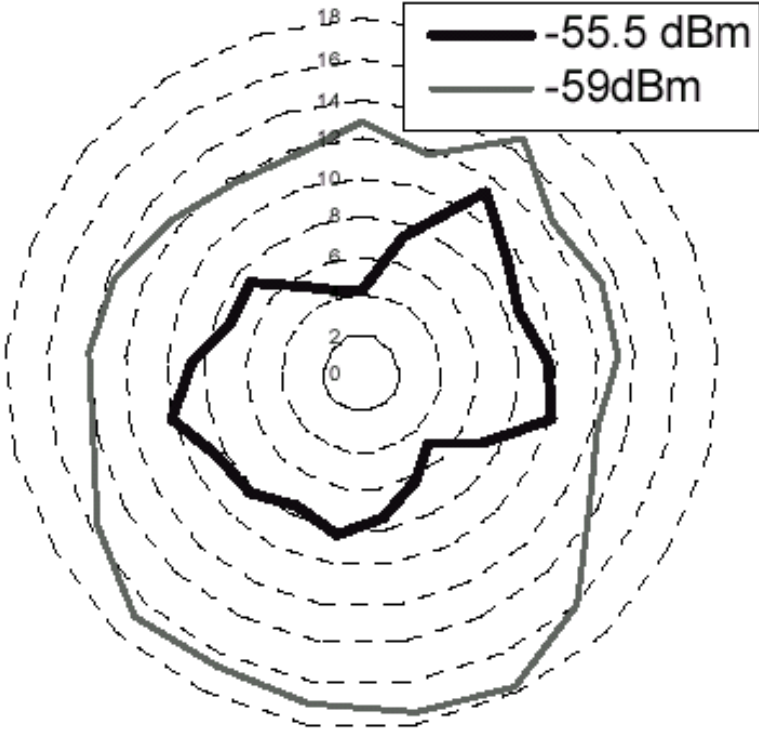
Alberto Cerpa, Naim Busek and Deborah Estrin

Locations

- Outdoors Forest: Will Rogers Park. Dense vegetation and trees with open area in a valley.
- Outdoors Urban: Boelter Hall Court Yard. Open area with some vegetation surrounded by buildings.
- Indoors: LECS Ceiling and Lab. Office type of environment with cubicles, desks, etc.

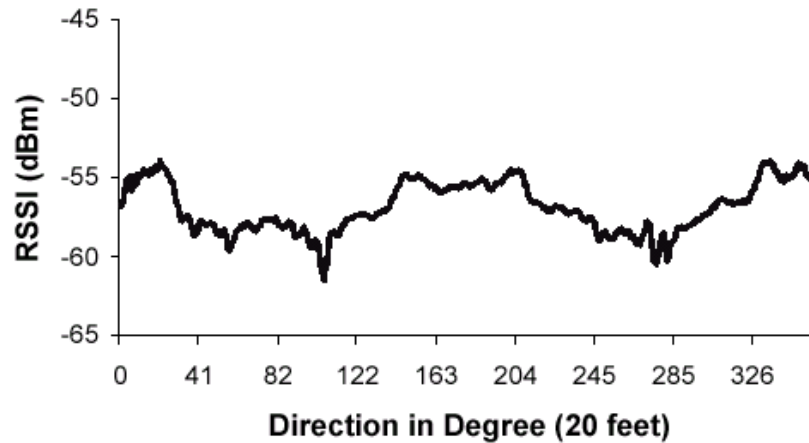
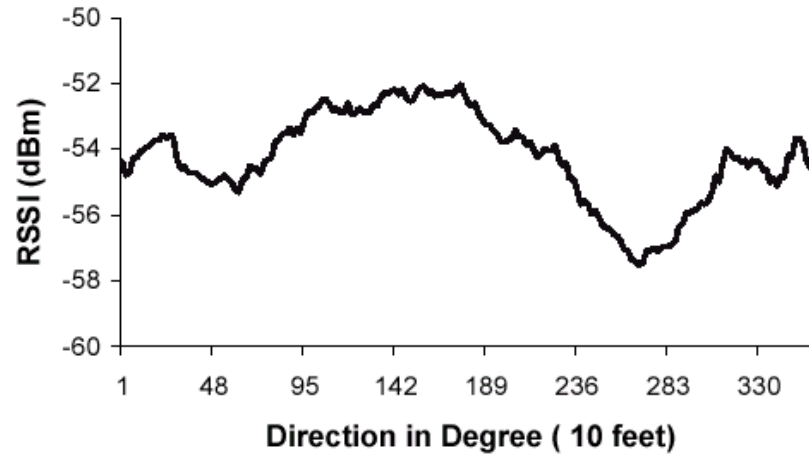


Non-isotropic connectivity



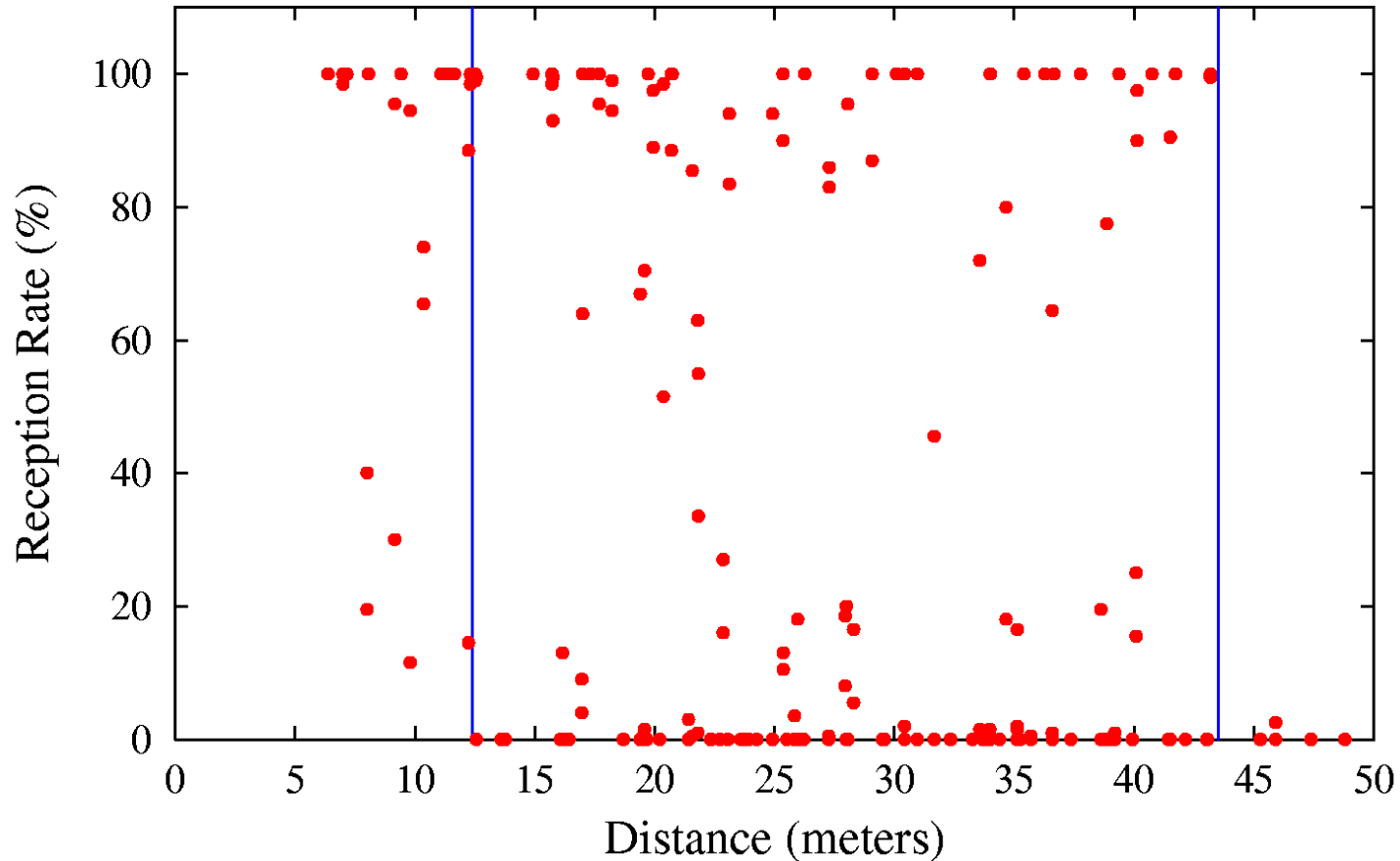
Received Signal Strength

Another view of directionality

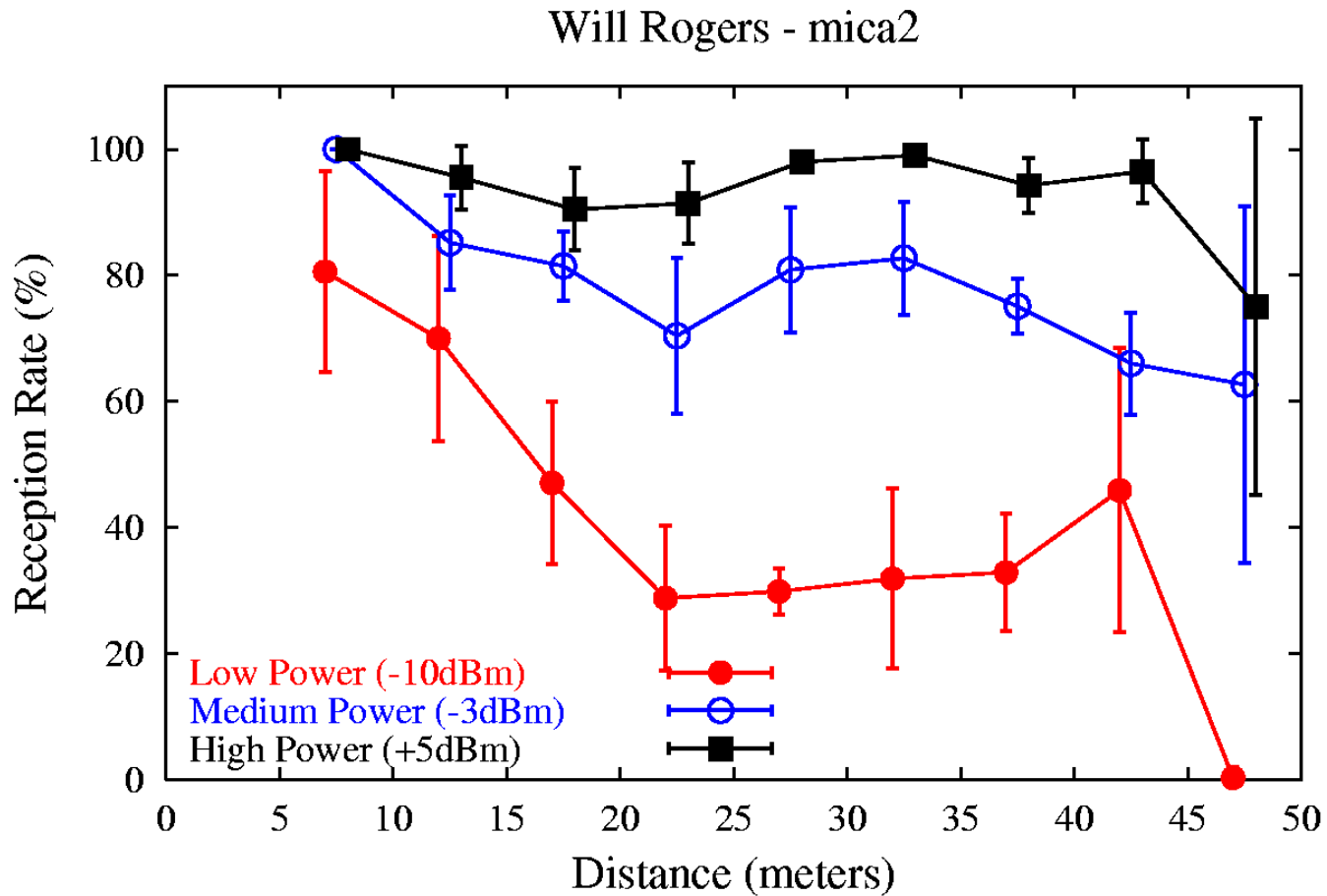


Reception rate as a function of distance (low power)

Will Rogers Outdoor Habitat - Mica 2



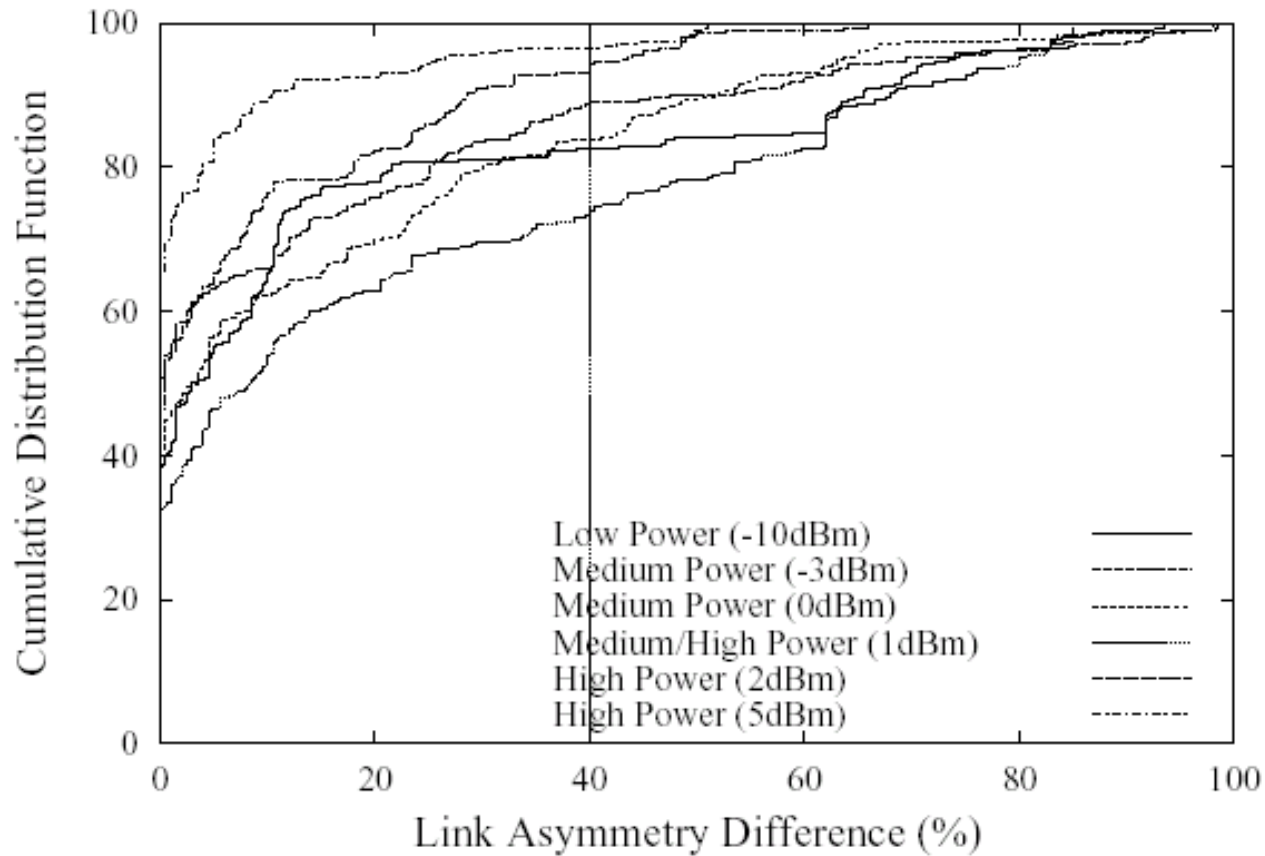
Effect of tx power on link quality



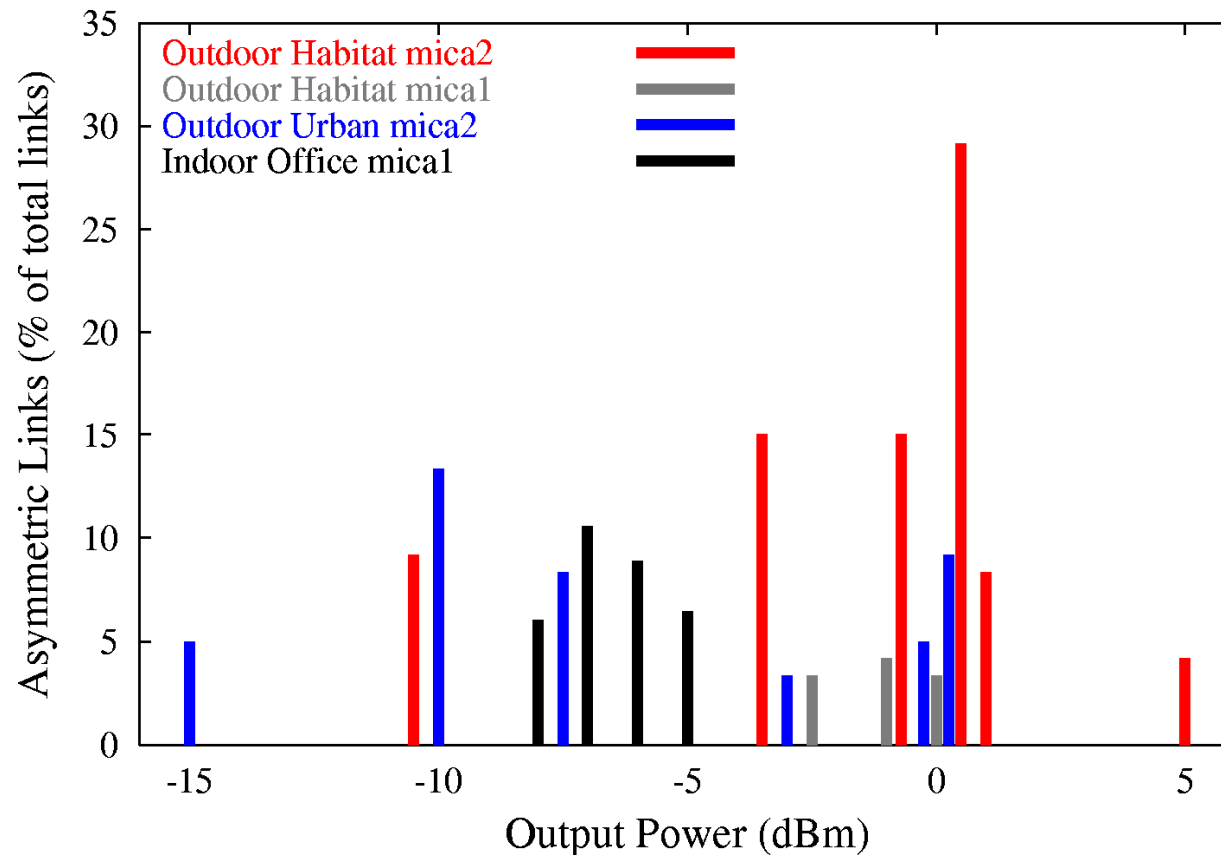
Spatial Characteristics

- Great variability over distance (50 to 80% of radio range)
 - Reception rate is not normally distributed around the mean and std. dev. (more later)
 - Real communication channel is not isotropic
- Low degree of correlation between distance and reception probability; lack of monotonicity and isotropy
- The region of highly variable reception rates is 50% or more of the radio range, and it is not confined to the limit of the radio range (explain)

Link Asymmetries

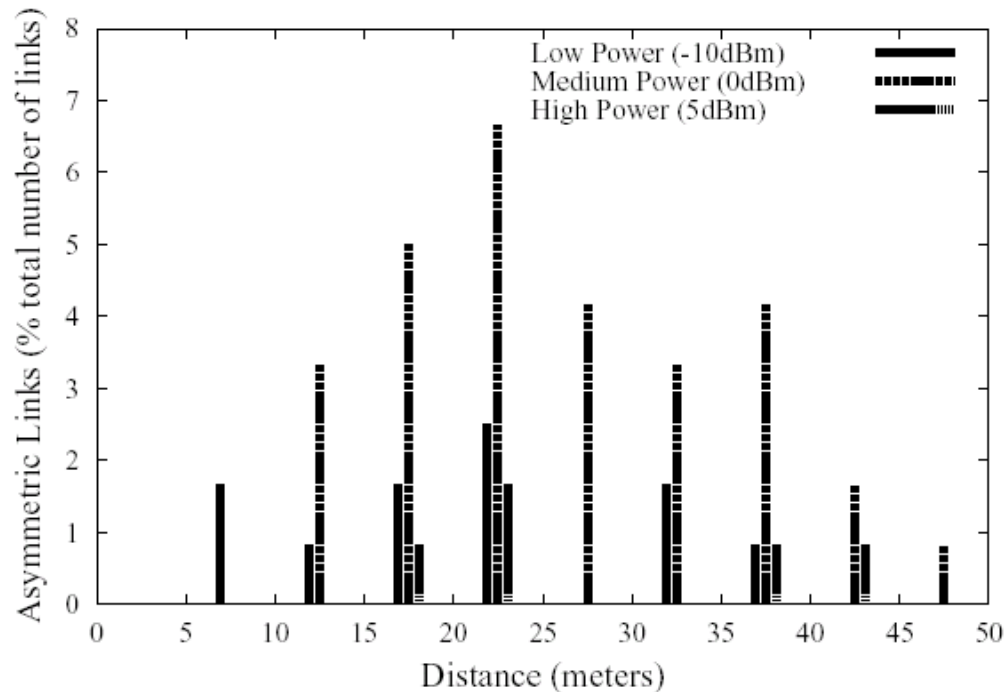


Percentage of asymmetric links as a function of tx power



- No correlation between power setting and asymmetry

Percentage of asymmetric links as a function of distance



(a) Outdoor Habitat, Mica 2

- No clear correlation between distance and existence of asymmetric links

Asymmetric Links

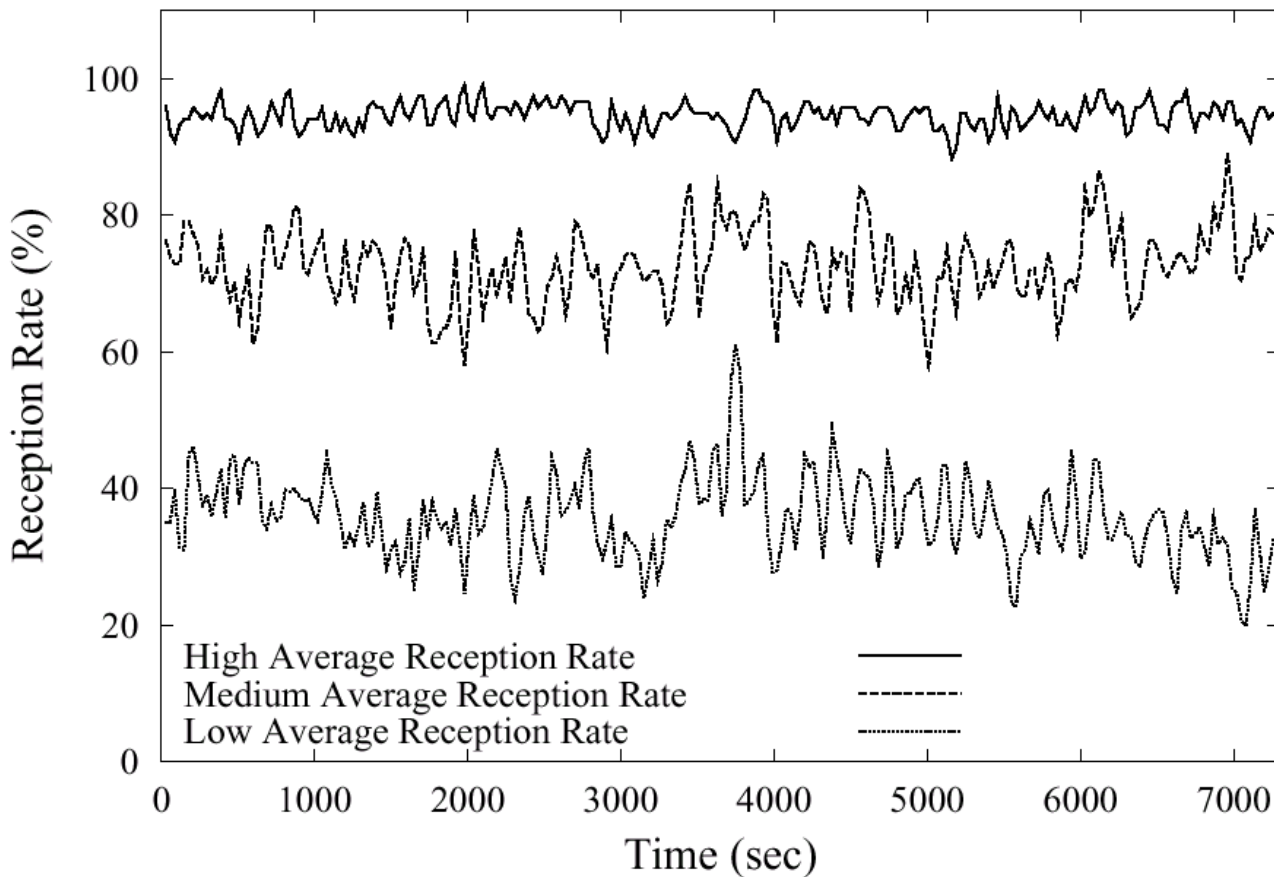
- Found 5 to 30% of asymmetric links
- No simple correlation between asymmetric links and distance or TX output power
- They tend to appear at multiple distances from the radio range, not at the limit.

What is the main cause of asymmetric links?

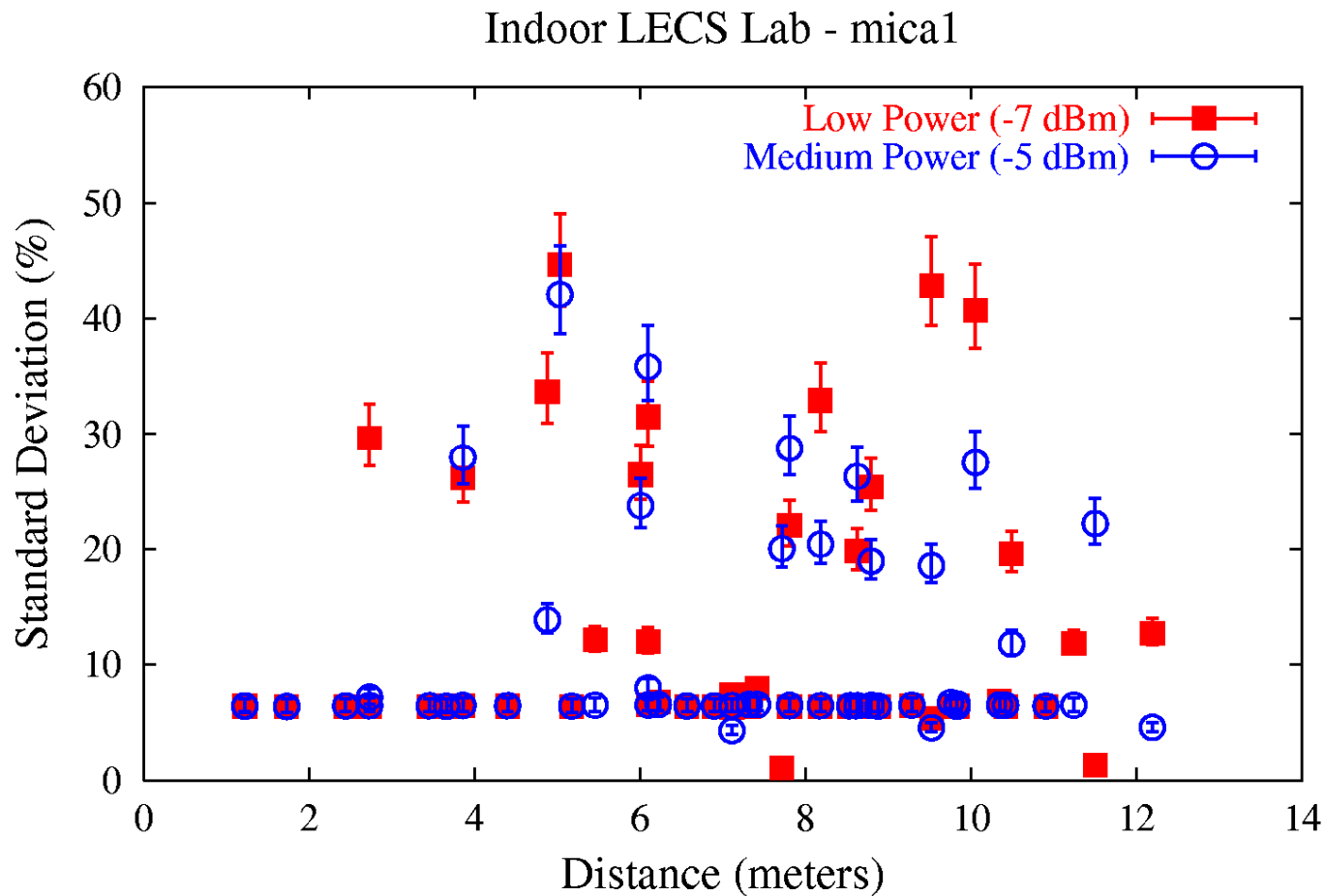
Node Type	Location Type	Asymmetric link-pairs <i>before</i> swapping	Inverted link-pairs <i>after</i> swapping
Mica 2	Outdoor Urban	11	10
Mica 2	Indoor Office	10	9
Mica 1	Indoor Office	24	22

- When swapping the asymmetric links node pairs, the asymmetric links were **inverted** ($91.1\% \pm 8.32$)
- Link asymmetries are primarily caused by differences in **hardware calibration**.

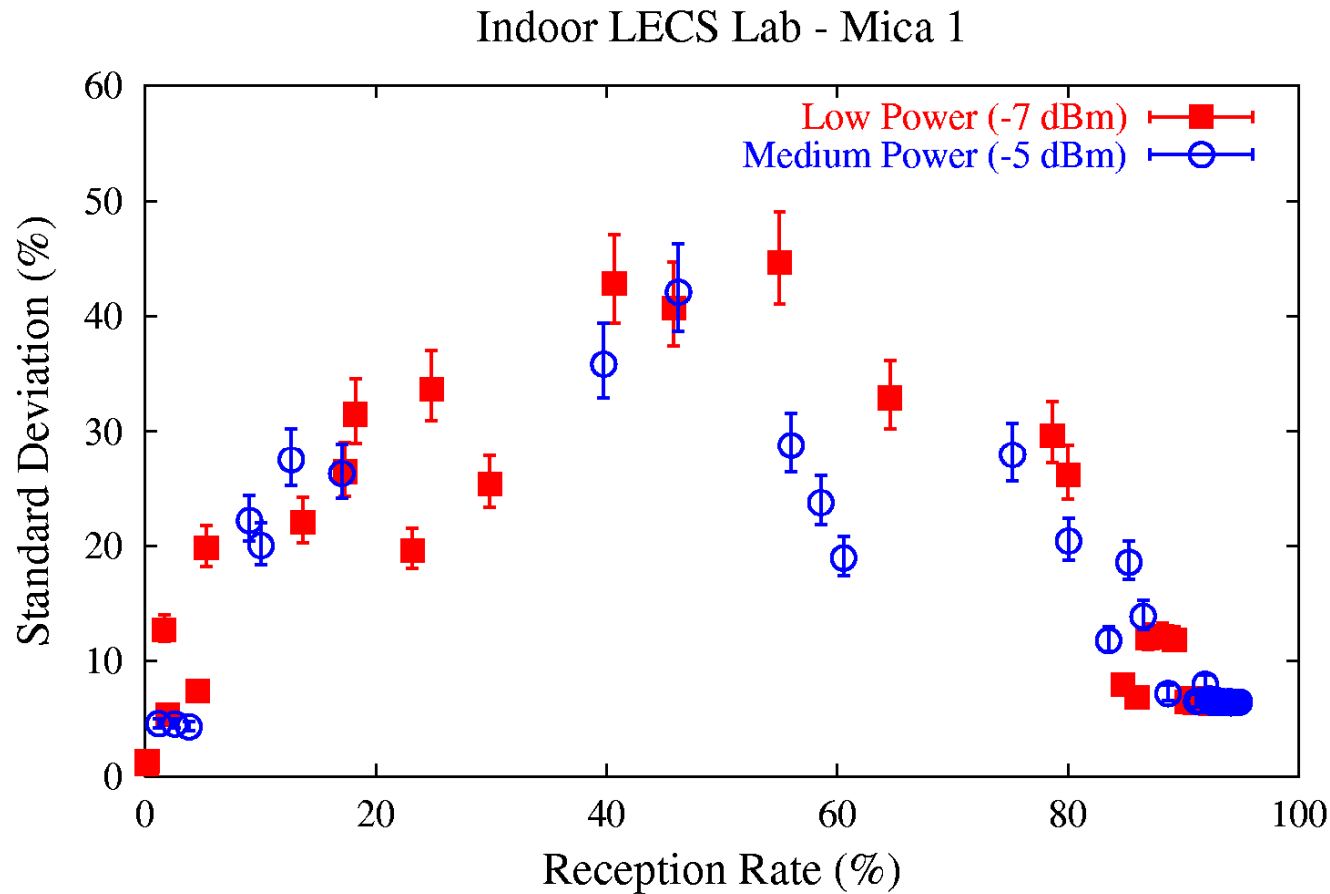
Temporal signal variation



Variation in reception rate is weakly correlated to distance



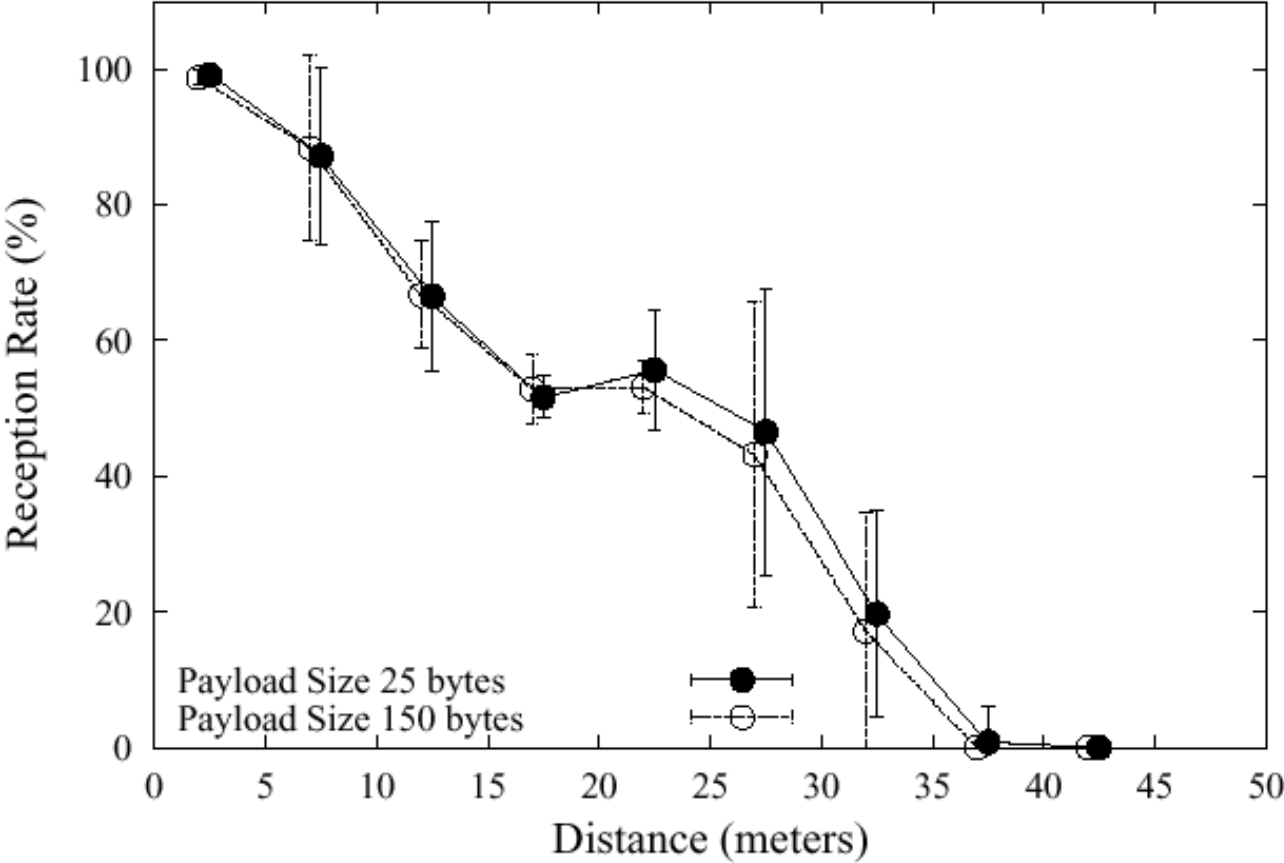
Correlation between avg reception rate and reception rate variation



Temporal Characteristics

- Time variability is correlated with mean reception rate
- Time variability is not correlated with distance from the transmitter

Effect of packet size on reception rate

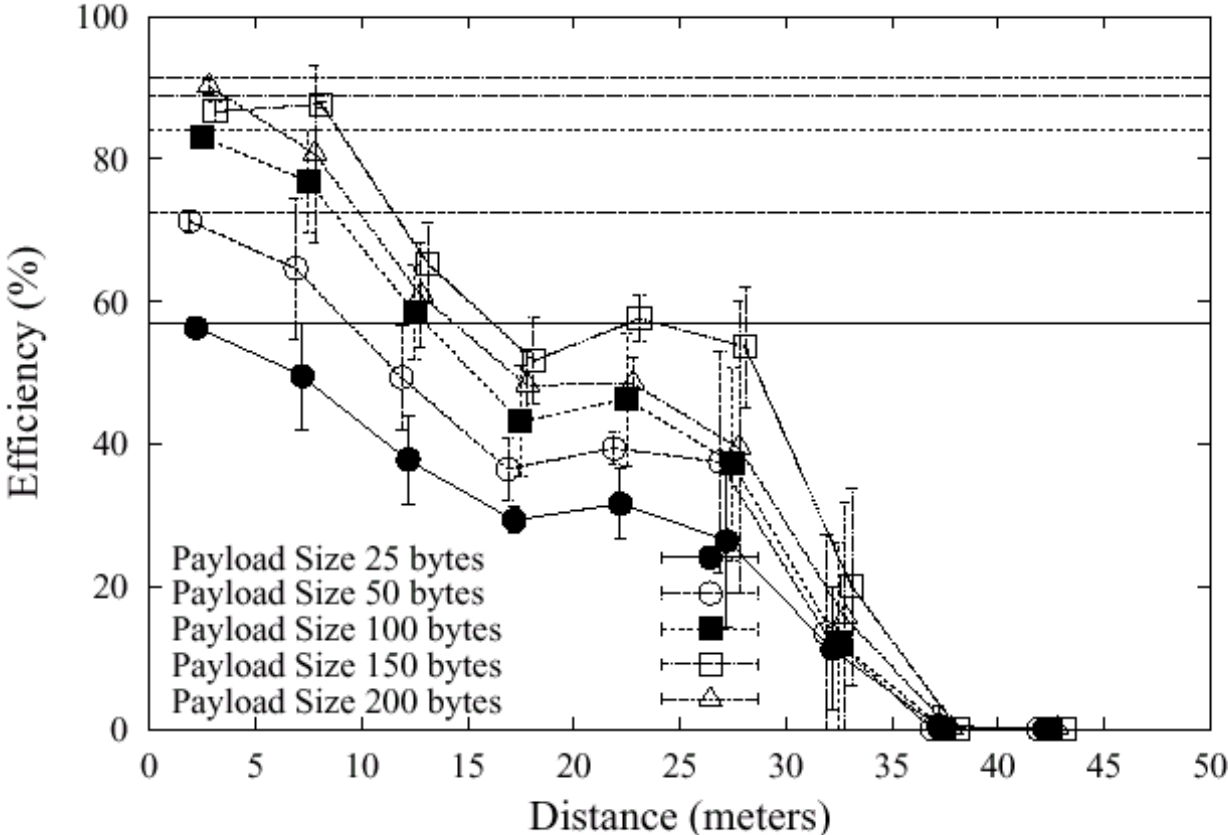


Optimal Packet Size?

- Larger packets produce a slight decrease in reception rate...
- ...BUT, larger packets reduce start symbol and header overhead.
- Efficiency:

$$\frac{UsefulBitRX}{TotalBitTX} = \frac{PayloadSize_i}{TotalPacketSize_i} \times P_i(s)$$

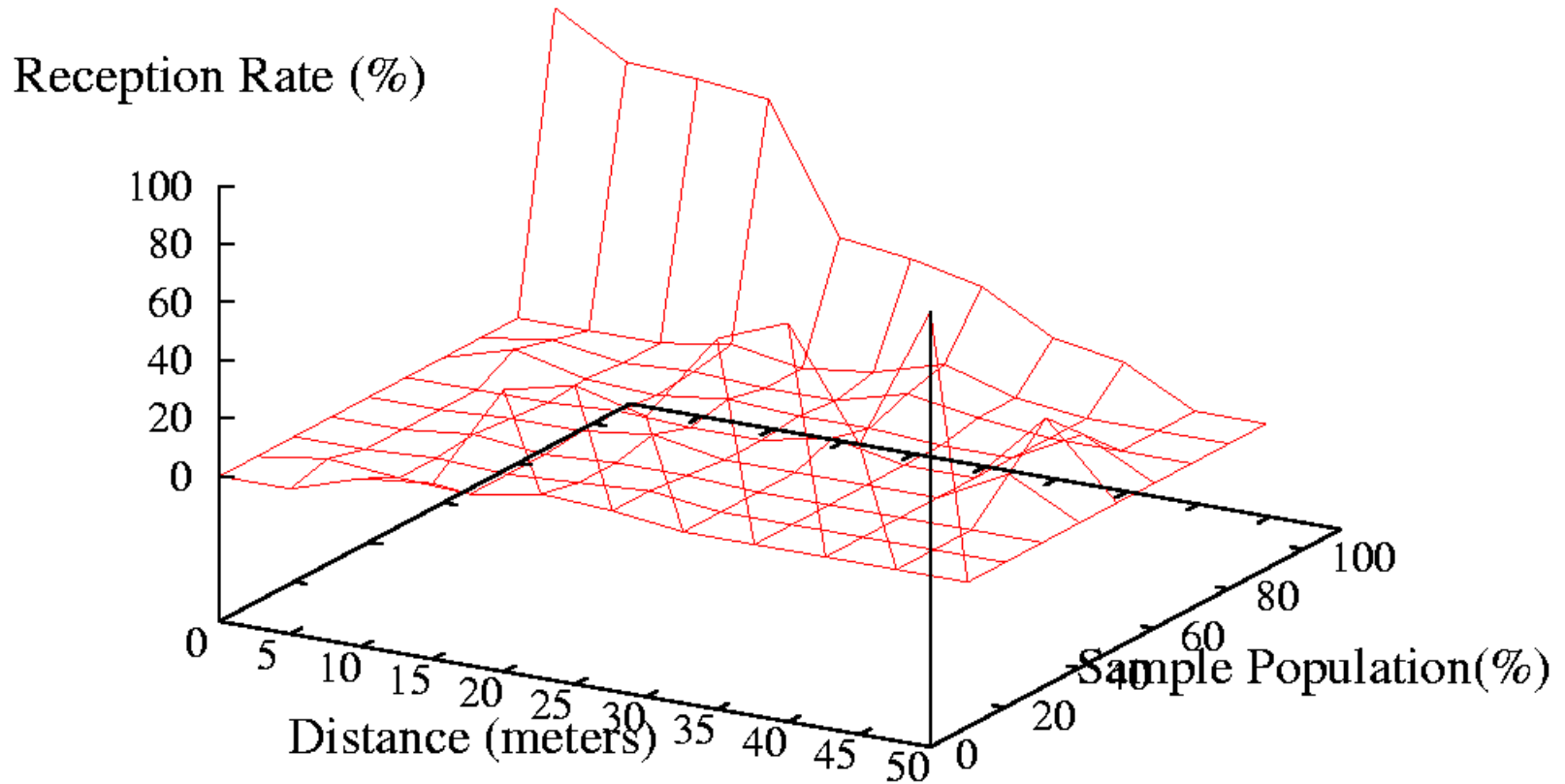
Efficiency Metric



In a Nutshell

- Great variability over distance (50 to 80% of radio range)
 - Reception rate is not normally distributed around the mean and std. dev.
 - Real communication channel is not isotropic
- Found 5 to 30% of asymmetric links
 - Not correlated with distance or transmission power
 - Primary cause: differences in hardware calibration (rx sensitivity, energy levels)
- Time variability is correlated with mean reception rate and not correlated with distance from the transmitter
- It is possible to optimize your performance by adjusting the coding schemes and packet sizes to the operating conditions

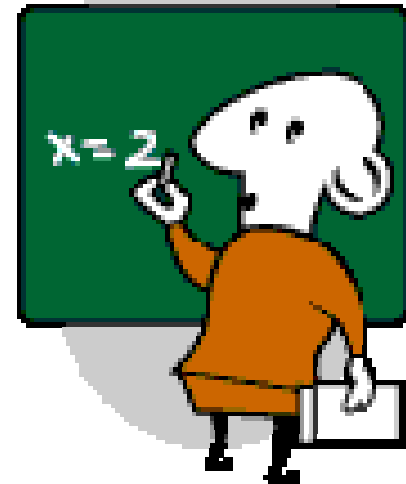
Underlying distribution looks like?



Third act

So the simple model is obviously insufficient. The log-normal shadow model can explain variations in space, but what about variations in time?

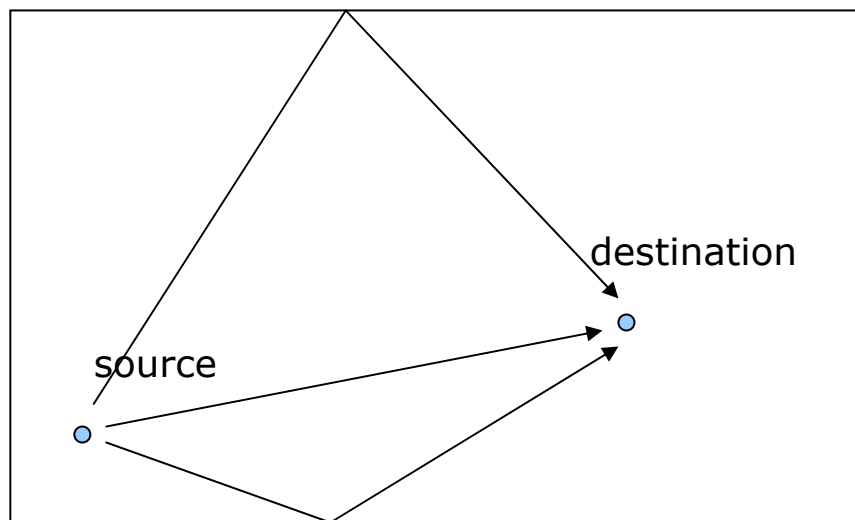
If only you would have let me finish



Small scale effects

- Variation of the received signal strength about a local mean over small travel distances (few λ 's) and short time intervals.
- Due to Fading
 - Multipath propagation
 - Speed of node and surroundings

Multipath Propagation



- Radio channel impulse response is the sum of all the paths the rays take:

$$h(t) = \sum_{i=1}^k a_i e^{g_i} \delta(t - \tau_i)$$

- Result is **Rayleigh** distribution (NLOS)

$$f(x) = \frac{x}{\alpha^2} e^{-x^2/2\alpha^2}, x \geq 0, \alpha \geq 0$$

or **Rician** distribution (LOS)