Interference and Spatial Modeling in Wireless Networks

Matthew C. Valenti

West Virginia University

May 28, 2013
Acknowledgements

Collaborators:
- Dr. Don Torrieri (Army Research Laboratory).
- Mr. Salvatore Talarico (WVU Ph.D. student).

Sponsors:
- National Science Foundation.
  
  *Award No. CNS-0750821*

- Army Research Laboratory.
  
  *Award No. W911NF-10-0109*

- Office of Naval Research.
  
  *Award No. N00014-09-1-1189*

The views expressed in this presentation do not necessarily reflect those of the sponsoring agencies.
1. Introduction

2. Outage Analysis of Interference Networks

3. Spatial Modeling

4. Transmission Capacity

5. Optimization of Frequency-Hopping Networks

6. Analysis of Cellular Networks

7. Conclusions
1. Introduction

2. Outage Analysis of Interference Networks

3. Spatial Modeling

4. Transmission Capacity

5. Optimization of Frequency-Hopping Networks

6. Analysis of Cellular Networks

7. Conclusions
Introduction

Sources of randomness in a wireless network:
1. Fading and noise.
2. Random transmitter activity (buffer status).
3. Effect of interference-avoidance protocols.
4. Shadowing.
5. Location of interfering transmitters (topology).

The above effects work at different timescales.
- Suggests a hierarchical approach to analysis.
  - Fix the locations of the interferers and amount of shadowing; determine the corresponding *conditional* outage probability.
  - Then consider the effect of node location and shadowing distribution.

Averages are more appropriate for faster phenomena (fading).
- Closed-form expressions can be obtained for the outage probability of a given network topology.

For slower phenomena (network topology), cdf of performance metrics (outage, rate) are more meaningful.
Outline

1. Introduction
2. Outage Analysis of Interference Networks
3. Spatial Modeling
4. Transmission Capacity
5. Optimization of Frequency-Hopping Networks
6. Analysis of Cellular Networks
7. Conclusions
Network Model

- Transmitters are arbitrarily placed in a 2-D finite region.
- A reference receiver is located at the origin.
- $X_i$ represents the $i^{th}$ transmitter and its location.
  - $X_0$ is location of the reference transmitter.
  - $M$ interfering transmitters, $\{X_1, ..., X_M\}$.
  - $|X_i|$ is distance from $i^{th}$ transmitter to the reference receiver.
- Network may be *cellular* or *ad hoc* (infrastructureless).
- Later, we will consider models governing the placement of the radios.
Signal from $X_i$ to the reference receiver undergoes fading, shadowing, and path loss.

At the reference receiver, $X_i$’s signal is received with power:

$$\rho_i = P_i g_i 10^{\xi_i/10} \left( \frac{|X_i|}{d_0} \right)^{-\alpha}$$

where:

- $P_i$ is the transmitted power.
- $g_i$ is the power gain due to fading.
- $\xi_i$ is the dB shadowing factor.
- $\alpha$ is the path-loss exponent.
- $d_0$ is a reference distance.
The performance at the reference receiver is characterized by the signal-to-interference and noise ratio (SINR), given by:

$$\gamma = \frac{\rho_0}{N + \sum_{i=1}^{M} I_i \rho_i} = \frac{g_0 \Omega_0}{\Gamma^{-1} + \sum_{i=1}^{M} I_i g_i \Omega_i} \quad (1)$$

where:

- $N$ is the noise power.
- $I_i$ is a Bernoulli indicator with $P[I_i] = p_i$.
  - Probability that $X_i$ collides with $X_0$.
- $\Gamma = P_0/N$ is the SNR.
- $\Omega_i = \frac{P_i}{P_0} 10^{\xi_i/10} |X_i|^{-\alpha}$ is the normalized average received power.
  - Normalized with respect to $P_0$
  - Accounts for shadowing and path loss, but not fading.
Outage Probability

- An outage occurs when $\gamma \leq \beta$, where $\beta$ is an SINR threshold.
  - The value of $\beta$ depends on the choice of modulation and coding.
- From (1), the outage probability is

$$
\epsilon = P \left[ \frac{g_0 \Omega_0}{\gamma + \sum_{i=1}^{M} I_i g_i \Omega_i} \leq \beta \right]
$$

$$
= P \left[ \beta^{-1} g_0 \Omega_0 - \sum_{i=1}^{M} I_i g_i \Omega_i \leq \Gamma^{-1} \right]
$$

$$
= P \left[ Z \leq \Gamma^{-1} \right] = F_Z(\Gamma^{-1}).
$$

- The outage probability is the cdf of $Z$, $F_Z(z)$ evaluated at $z = \Gamma^{-1}$.
  - Since $\{\Omega_i\}$ are fixed, we can also write as the conditional cdf $F_Z(z|\Omega)$. 
Rayleigh Fading

- When the $g_i$ are i.i.d. exponential, the outage probability conditioned on the network geometry is:

$$F_Z(z|\Omega) = 1 - e^{-\beta \Omega_0^{-1} z} \prod_{i=1}^{M} \left[ \frac{(1 - p_i) \beta \Omega_0^{-1} + \Omega_i^{-1}}{\beta \Omega_0^{-1} + \Omega_i^{-1}} \right]$$  \hspace{1cm} (2)

Example #1:
- $X_0 = 1$.
- $M = 50$ interferers, with $0.25 \leq |X_i| \leq 2, \forall i > 0$.
- $\alpha = 3$ and no shadowing.
- $p_i = 0.005$.
- Analytical curves are solid, while • represents simulated values.
Nakagami Fading\(^1\)

If the amplitude gain from the \(i^{th}\) transmitter to the receiver is Nakagami-\(m\) with parameter \(m_i\), then the outage probability conditioned on the network geometry is:

\[
F_Z (z | \Omega) = 1 - e^{-\beta_0 z} \sum_{j=0}^{m_0-1} (\beta_0 z)^j \sum_{k=0}^{j} \frac{z^{-k}}{(j-k)!} \sum_{\ell_i \geq 0} \prod_{i=1}^{M} G_{\ell_i}[i] \quad (3)
\]

where \(m_0\) is an integer, \(\beta_0 = m_0 \beta / \Omega_0\), the summation in (3) is over all sets of positive indices that sum to \(k\),

\[
G_{\ell}[i] = (1 - p_i) \delta[\ell] + \frac{p_i \Gamma(\ell + m_i)}{\ell! \Gamma(m_i)} \left( \frac{\Omega_i}{m_i} \right)^\ell \left( \frac{m_i}{\beta_0 \Omega_i + m_i} \right)^{m_i + \ell} \quad (4)
\]

and \(\delta[\ell]\) is the Kronecker delta function.

Nakagami Fading Example

Example #2:
- $X_0 = 1$.
- $M = 50$ interferers, with $0.25 \leq |X_i| \leq 4, \forall i > 0$.
- $\alpha = 3$ and no shadowing.
- $p_i = 0.005$.
- $\beta = 3.7$ dB.
- Fading types:
  - Rayleigh: $m_i = 1, \forall i$.
  - Nakagami: $m_i = 4, \forall i$.
  - Mixed: $m_0 = 4$, $m_i = 1, \forall i > 0$.

Figure: Outage probability $\epsilon_\Omega$ conditioned on $\Omega$ as a function of SNR $\Gamma$. Analytical curves are solid, while • represents simulated values.
Interference may be controlled through signal and protocol design.

Spread spectrum signaling reduces interference.
  - Direct sequence (DS).
  - Frequency hopping (FH).
  - Hybrid DS/FH.

Interference avoidance protocols reduce interference.
  - CSMA/CA.
Direct Sequence Spread Spectrum

- Spread bandwidth of each signal by a spreading factor $G = B/W$.
- Effectively reduces the power of each interferer.
- $G$ is also called the *processing gain* and is the amount of reduction in interference power.
- Can be handled by dividing normalized powers of the interferers by $G$

$$\Omega_i = \left( \frac{1}{G} \right) \frac{P_i}{P_0} 10^{\xi_i/10} |X_i|^{-\alpha}, \forall i > 0$$

- Interference averaging.
- If transmissions are asynchronous a *chip factor* can further reduce the interference power.
Frequency Hopping

Transmitters randomly pick from among $L$ frequencies.

$I_i$ is a Bernoulli random variable with probability $p_i = 1/L$.

Interference *avoidance*.
Hybrid DS/FH

- Spread bandwidth of each signal by a factor $G$.
- Transmit DS-spread signal over randomly selected frequency.
- $G > 1$ and $p_i < 1$. 
Guard Zones

- Interference-avoidance protocols may be used to prevent close interferers.
  - Carrier-sense multiple access with collision avoidance (CSMA-CA).
  - If one transmitter is too close to another, it will deactivate.
    - Each transmitter is surrounded by a circular guard zone of radius $r_{\text{min}}$.
    - Other nodes in the guard zone are forbidden to transmit ($p_i = 0$).
- Equivalent to Matern thinning of the spatial model.

Guard Zones Reduce the Outage Probability

Figure: By using a guard zone with $r_{\text{min}} = 1$, the number of potential interferers decreases to 21.

Figure: Outage probability $\epsilon$ over the mixed fading channel of Example #2 when a guard zone of radius $r_{\text{min}}$ is imposed.
Outline

1. Introduction
2. Outage Analysis of Interference Networks
3. Spatial Modeling
4. Transmission Capacity
5. Optimization of Frequency-Hopping Networks
6. Analysis of Cellular Networks
7. Conclusions
So far, the outage probability has been conditioned on the *network geometry*. The locations of potential interferers and the shadowing realization are fixed. Only the fading and node activity are random.

May want to remove the conditioning on network geometry. Allow the transmitter locations and shadowing factors to randomly vary. Particularly important for considering guard zones, which cause the locations of potential interferers to change.

Should take into account the spatial model, which is a point process. Binary point process (BPP). Poisson point process (PPP). Uniform clustering model. Matern thinning.
Spatial Averaged Outage Probability

The cdf conditioned on the network geometry, $\Omega$:

$$\epsilon_\Omega = P \left[ \gamma \leq \beta \mid \Omega \right] = F_Z(\Gamma^{-1} \mid \Omega)$$
Spatially Averaged Outage Probability

The cdf conditioned on the network geometry, $\Omega$:
$$\epsilon_\Omega = P \left[ \gamma \leq \beta \mid \Omega \right] = F_Z(\Gamma^{-1} \mid \Omega)$$

The cdf conditioned on the number of interferers, $M$:
$$\epsilon_M = \mathbb{E} [\epsilon_\Omega] = F_{Z_M}(\Gamma^{-1}) = \int f_\Omega(\omega) F_Z(\Gamma^{-1} \mid \omega) d\omega$$

$$f_\Omega(\omega) = \prod_{i=1}^{M} f_{\Omega_i}(\omega_i)$$

is the pdf of $\Omega$
Spatially Averaged Outage Probability

The cdf conditioned on the network geometry, $\Omega$:
$$
\epsilon_\Omega = P[\gamma \leq \beta | \Omega] = F_Z(\Gamma^{-1} | \Omega)
$$

The cdf conditioned on the number of interferers, $M$:
$$
\epsilon_M = E[\epsilon_\Omega] =
F_{Z_M}(\Gamma^{-1}) = \int f_{\Omega}(\omega) F_Z(\Gamma^{-1} | \omega) d\omega
$$

The unconditional cdf:
$$
\epsilon = E[\epsilon_M] =
F_Z(\Gamma^{-1}) = \sum_{m=0}^{\infty} p_M(m) F_{Z_m}(z)
$$

$f_{\Omega}(\omega) = \prod_{i=1}^{M} f_{\Omega_i}(\omega_i)$
is the pdf of $\Omega$

$p_M(m)$
is the pmf of $M$
Average Outage Probability for a BPP: Results

- In a binomial point process (BPP), a fixed number of interferers are independently placed according to a uniform distribution.
- The cdf with a BPP network with interferers uniformly distributed on an annulus with inner radius $r_{\text{ex}}$ and outer radius $r_{\text{net}}$ is:

$$F_{Z_M}(z) = \int f_{\Omega}(\omega) F_Z(z|\omega) d\omega$$

where

$$f_{\Omega_i}(\omega) = \frac{2\omega^{2-\alpha}}{\alpha (r_{\text{net}}^2 - r_{\text{ex}}^2)}$$

for $r_{\text{ex}}^\alpha \leq \omega \leq r_{\text{net}}^\alpha$.

Substituting (2) into (5), the cdf of $Z_M$ in Rayleigh fading is

$$F_{Z_M}(z) = 1 - \exp \left\{ -\beta \Omega_0^{-1} z \right\} \left[ \frac{\Psi \left( r_{\text{net}}^\alpha \right) - \Psi \left( r_{\text{ex}}^\alpha \right)}{r_{\text{net}}^2 - r_{\text{ex}}^2} \right]^M$$

where $p_i = p, \forall i$, and

$$\Psi(x) = x^{2\alpha} \left[ 1 - p + \frac{2p}{\alpha + 2} \cdot \frac{x^{2+\alpha}}{\beta \Omega_0^{-1}} \cdot 2F_1 \left[ \left\{ \frac{\alpha + 2}{\alpha} \right\}; \frac{2\alpha + 2}{\alpha}, -\frac{x}{\beta \Omega_0^{-1}} \right] \right].$$
Average Outage Probability for a BPP: Example

Example:
- \( r_{\text{ex}} = 0.25 \).
- \( r_{\text{net}} = 2 \).
- \( \alpha = 3 \).
- \( \beta = 3.7 \) dB.
- \( \Gamma = 10 \) dB.

Figure: Outage probability \( \epsilon_M \) as a function of \( M \) for five values of \( p \) when the location of the nodes is drawn from a BPP. Analytical curves are solid, while the ⋄ were generated by randomly placing interferers and averaging the resulting conditional outage probabilities.
In a Poisson point process (PPP), the number of interferers $M$ is a Poisson variable.

The cdf with a PPP network is:

$$F_Z(z) = \sum_{m=0}^{\infty} p_M(m) F_{Z_m}(z) = \sum_{m=0}^{\infty} \frac{(\lambda A)^m}{m!} e^{-\lambda A} F_{Z_m}(z) \quad (7)$$

where

- $\lambda$ is the density of the interferers per unit area;
- $A = \pi (r_{\text{net}}^2 - r_{\text{ex}}^2)$ is the area of the network;

substituting (6) into (7), the average outage probability is:

$$F_Z(z) = 1 - e^{-\beta \Omega_0^{-1} z} e^{-\pi \lambda \cdot \{r_{\text{net}}^2 - r_{\text{ex}}^2 - [\Psi(r_{\text{net}}^\alpha) - \Psi(r_{\text{ex}}^\alpha)]\}} \quad (8)$$

When $r_{\text{net}} \to \infty$, $r_{\text{ex}} = 0$, and $p = 1$:

$$F_Z(z) = 1 - e^{-\beta_0 z} e^{-\frac{2\pi \lambda \beta_0^\frac{2\alpha}{\alpha}}{\alpha} \Gamma\left(\frac{2}{\alpha}\right) \Gamma\left(1-\frac{2}{\alpha}\right)}$$

Baccelli et al. obtained same expression by using stochastic geometry.
Average Outage Probability for a PPP: Examples\textsuperscript{3}

Figure: Parameters: SINR threshold $\beta = 3.7$ dB, SNR $\Gamma = 10$, inner radius $r_{ex} = 0.25$, and outer radius $r_{net} = 2$. [Diagram 1]

Figure: Parameters: SINR threshold $\beta = 3.7$ dB, SNR $\Gamma = 10$, inner radius $r_{ex} = 0$, $\alpha = 3$, and $p = 1$. [Diagram 2]

Transmission Capacity: Definition

- Reducing \( \lambda \) reduces \( \epsilon \), which improves the per-link throughput.
  - However, fewer links are supported, so less total data might be transmitted within the network.
- *Transmission capacity* is a metric that quantifies this tradeoff.
- If there are \( \lambda \) transmitters per unit area, then the number of successful transmissions per unit area is
  \[
  \tau = \lambda (1 - \epsilon)
  \]
- If the outage probability \( \epsilon \) is constrained to not exceed \( \zeta \), then the transmission capacity is
  \[
  \tau_c(\zeta) = \epsilon^{-1}(\zeta)(1 - \zeta)
  \]
  where \( \epsilon^{-1}(\zeta) \) is the maximum mobile density such that \( \epsilon \leq \zeta \).
For the BPP case, \( \epsilon^{-1}(\zeta) \) is found by solving \( \epsilon = F_{ZM}(\Gamma^{-1}) = \zeta \) for \( \lambda = M/A \) and then substituting into (9):

\[
\tau_c(\zeta) = \frac{(1 - \zeta) \left[ \log (1 - \zeta) + \beta \Omega_0^{-1} \Gamma^{-1} \right]}{A \log \left\{ \left( r_{\text{net}}^2 - r_{\text{ex}}^2 \right)^{-1} \left[ \Psi (r_{\text{net}}^\alpha) - \Psi (r_{\text{ex}}^\alpha) \right] \right\}}.
\]

In the PPP case, \( \epsilon^{-1}(\zeta) \) is found by solving \( \epsilon = F_Z(\Gamma^{-1}) = \zeta \) for \( \lambda \) and then substituting into (9):

\[
\tau_c(\zeta) = \frac{(1 - \zeta) \left[ \log (1 - \zeta)^{-1} - \beta \Omega_0^{-1} \Gamma^{-1} \right]}{\pi \left\{ r_{\text{net}}^2 - r_{\text{ex}}^2 - [\Psi (r_{\text{net}}^\alpha) - \Psi (r_{\text{ex}}^\alpha)] \right\}}.
\]

Asymptotically for a PPP, with \( r_{\text{ex}} = 0 \) and \( p = 1 \), as \( r_{\text{net}} \to \infty \):

\[
\tau_c(\zeta) = \frac{(1 - \zeta) \left[ \log (1 - \zeta)^{-1} - \beta \Omega_0^{-1} \Gamma^{-1} \right]}{\pi \beta_0^2 \frac{2\pi}{\alpha} \csc \left( \frac{2\pi}{\alpha} \right)}
\]

Weber et al. obtained the same expression using stochastic geometry.
Transmission Capacity: Examples

Parameters:
- **BPP**
  - $r_{\text{ex}} = 0$
  - $r_{\text{net}} = 2$
  - $p = 1$
  - $\beta = -10 \text{ dB}$
  - $\alpha = 3$

Parameters:
- **PPP**
  - $r_{\text{ex}} = 0$
  - $\Gamma = 10 \text{ dB}$
  - $p = 1$
  - $\beta = -10 \text{ dB}$
  - $\alpha = 3$
Until now, we have picked the SINR threshold $\beta$ arbitrarily.

However, $\beta$ depends on the choice of modulation.

- For *ideal* (input is a complex Gaussian) signaling

  $$C(\gamma) = \log_2(1 + \gamma)$$

  $\beta$ is the value of $\gamma$ for which $C(\gamma) = R$ (the code rate),

  $$\beta = 2^R - 1$$

- For other modulations, the *modulation-constrained* capacity $C(\gamma)$ must be used, which can be found by measuring the mutual information between channel input and output.
The *area spectral efficiency* accounts for not only the number of transmissions per unit area, but also the *rate* of the transmissions.

Define as

\[ \tau' = R\eta p \lambda (1 - \epsilon) \]

where

- \( R \) is the rate of transmission, which is related to \( \beta \).
  - Units of (information) bits per channel symbol.
- \( \eta \) is the spectral efficiency of the modulation.
  - Units of channel symbols per Hz.
- \( \tau' \) has units of \( bps/Hz/m^2 \).
Outline

1. Introduction
2. Outage Analysis of Interference Networks
3. Spatial Modeling
4. Transmission Capacity
5. Optimization of Frequency-Hopping Networks
6. Analysis of Cellular Networks
7. Conclusions
The performance of a FH network depends on:
- The number of hopping channels $L = B/W$.
- The code rate $R$.
- The modulation format, and its spectral efficiency $\eta$.

For a fixed bandwidth $B$, there is a tradeoff among the above parameters.

The network can be optimized by finding the parameters that maximize the area spectral efficiency\(^4\).

Noncoherent Binary CPFSK

FH systems often use noncoherent continuous-phase frequency-shift keying, whose capacity & bandwidth depends on the modulation index $h$.

(a) channel capacity versus $E_s/N_0$

(b) bandwidth versus modulation index

Influence of Parameters: BPP

Parameters:
- $r_{ex} = 0.25$;
- $r_{net} = 2$;
- $\Gamma = 10$ dB.
- $M = 50$.
- Rayleigh fading.
Influence of Parameters: PPP

Parameters:

- $r_{ex} = 0.25$;
- $r_{net} = 2$;
- $\Gamma = 10$ dB.
- $\alpha = 3$.
- Rayleigh fading.
We assumed that all interference is co-channel interference. However, FSK modulation is not completely bandlimited. Some of the spectrum splatters into adjacent channels.

Typically, the frequency channels are matched to the 99-percent bandwidth of the modulation.

The percent of the signal power splatters into adjacent channels.

Containing 99-percent of the signal power in the channel is arbitrary.

There is a tradeoff in the choice of percent power.

Let $\psi < 1$ be the fraction of power in the band.

Then the fraction of power in each adjacent channel is $(1 - \psi)/2$.

Can determine $\psi$ that maximizes the area spectral efficiency.

Redefine $I_i$ to be the fraction of interfering power in the channel.

$I_i = \psi$ w.p. $p_i = 1/L$, and $I_i = (1 - \psi)/2$ w.p. $p_i = \frac{2(L-1)}{L^2}$.

---

ACI Optimization Example

Parameters:
- $X_0 = 1$.
- $M = 50$ interferers, with $0.25 \leq |X_i| \leq 2, \forall i > 0$.
- $\alpha = 3$ and shadow std. $\sigma = 8$ dB.
- Fading types:
  - Rayleigh: $m_i = 1, \forall i$.
  - Nakagami: $m_i = 4, \forall i$.
  - Mixed: $m_0 = 4$, $m_i = 1, \forall i > 0$.

Figure: Maximum achievable area spectral efficiency $\tau'_\text{opt}(\psi)$ as a function of the fractional in-band power $\psi$. For each value of $\psi$, the modulation-index $h$, the number of frequency channels $L$, and code rate $R$ are varied to maximize the TC.
Outline

1. Introduction
2. Outage Analysis of Interference Networks
3. Spatial Modeling
4. Transmission Capacity
5. Optimization of Frequency-Hopping Networks
6. Analysis of Cellular Networks
7. Conclusions
Current approaches form modeling cellular networks use one of two extremes:

**Classic approach (regular grid):**
- The analysis often focuses on the worst case-locations (cell edge).

**Modern approach (stochastic geometry):**
- Assumes infinite network;
- Base stations are drawn from a random point process
- No minimum separation.
The minimum spacing between base stations is $r_{bs}$.

**Figure**: Actual base-station locations from a current cellular deployment in a small city with a hilly terrain.

**Figure**: Simulated base-station locations when the minimum base-station separation is $r_{bs} = 0.25$. 
A Constrained Spatial Model

The minimum spacing between base stations is $r_{bs}$.

**Figure**: Actual base-station locations from a current cellular deployment in a small city with a hilly terrain.

**Figure**: Simulated base-station locations when the minimum base-station separation is $r_{bs} = 0.25$. Cell boundaries are indicated.
The minimum spacing between base stations is $r_{bs}$.

**Figure:** Actual base-station locations from a current cellular deployment in a small city with a hilly terrain.

**Figure:** Simulated base-station locations when the minimum base-station separation is $r_{bs} = 0.25$. Cell boundaries are indicated, and the average cell load is
A Constrained Spatial Model

Figure: Actual base-station locations from a current cellular deployment in a small city with a hilly terrain.

Figure: Simulated base-station locations when the minimum base-station separation is $r_{bs} = 0.25$. Cell and sector boundaries are indicated, and the average cell load is 16 mobiles.
Analysis of Cellular Networks

- Model can be used to analyze the downlink\(^6\) or the uplink\(^7\)
- Can be used to optimize resource allocation policies:
  - Power control.
  - Rate control.
  - Cell association.
- Fairness can be quantified by cdf of rate.
- The value of \(r_{bs}\) can be obtained through statistical analysis of actual base station placements.
- Can use the analysis to develop Cooperative Multipoint (COMP) and Intercell Interference Coordination (ICIC) strategies.

---


Downlink Performance

Figure: Complementary cdf of $R$ with either rate control or power control for a lightly loaded system ($K/M = 4$) and a moderately-loaded system ($K/M = 12$).

Example:
- $M = 50$ base stations;
- $K$ mobile users;
- $r_{net} = 2$;
- $r_{bs} = 0.25$;
- $\alpha = 3$;
- $\Gamma = 10$ dB;
- Spreading factor $G = 16$;
- Outage constraint $\hat{\epsilon} = 0.1$;
- Mixed fading:
  - $m = 3$ inside the cell.
  - $m = 1$ outside the cell.
- Shadow std. $\sigma_s = 8$ dB.
1. Introduction
2. Outage Analysis of Interference Networks
3. Spatial Modeling
4. Transmission Capacity
5. Optimization of Frequency-Hopping Networks
6. Analysis of Cellular Networks
7. Conclusions
Conclusions

- The outage probability for any particular network realization can be found in closed form.
  - Captures the effects of fading, noise, and node activity.
  - No need to simulate the fading coefficients.
- Network topology remains as a source of randomness.
  - Locations of the transmitters.
  - Realization of shadowing.
  - Node deactivation due to interference-avoidance protocols.
- Analysis should focus on effects of topology.
  - Closed-form expressions for spatially averaged outage probability only possible for certain simple scenarios.
  - For more realistic spatial models, network topology needs to be simulated.
  - The cdf of rate is more useful than the average rate.
- Analysis can be used to study many problems related to ad hoc and cellular networks, including multihop routing.
Thank you