Modeling and Mitigation of Interference in Multi-Antenna Receivers

Aditya Chopra

September 16, 2011
about me
Member of the Wireless Networking and Communications Group at The University of Texas at Austin since 2006.

Completed projects

<table>
<thead>
<tr>
<th>Completed projects</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADSL testbed (Oil &amp; Gas)</td>
<td>2 x 2 wired multicarrier communications testbed using PXI hardware, x86 processor, real-time operating system and LabVIEW</td>
</tr>
<tr>
<td>Spur modeling/mitigation (NI)</td>
<td>Detect and classify spurious signals; fixed and floating-point algorithms to mitigate spurs</td>
</tr>
</tbody>
</table>

Currently active projects

<table>
<thead>
<tr>
<th>Currently active projects</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference modeling and mitigation (Intel)</td>
<td>Statistical models of interference; receiver algorithms to mitigate interference; MATLAB toolbox</td>
</tr>
<tr>
<td>Impulsive noise mitigation in OFDM (NI)</td>
<td>Non-parametric interference mitigation for wireless OFDM receivers using PXI hardware, FPGAs, and LabVIEW</td>
</tr>
<tr>
<td>Powerline communications (TI, Freescale, SRC)</td>
<td>Modeling and mitigating impulsive noise; building multichannel multicarrier communications testbed using PXI hardware, x86 processor, real-time operating system, LabVIEW</td>
</tr>
</tbody>
</table>
Interference in wireless communication systems is caused by **communicating** and **non-communicating** source emissions.

- **Non-communicating devices**
  - Microwave ovens
  - Powerlines

- **Wireless systems**
  - Nearby wireless users
  - Coexisting protocols

**Computational Platform**
- Clocks, amplifiers, co-located transceivers
Interference may severely impair communication performance of wireless systems

Interference mitigation has been an **active area of research** over the past decade.

### Interference Mitigation Strategy

<table>
<thead>
<tr>
<th>Hardware design</th>
<th>LIMITATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver shielding</td>
<td>Does not mitigate interference from devices using same spectrum</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Network planning</th>
<th>LIMITATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource allocation</td>
<td>Requires user coordination</td>
</tr>
<tr>
<td>Basestation coordination</td>
<td>Slow updates</td>
</tr>
<tr>
<td>Partial frequency re-use</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Receiver algorithms</th>
<th>LIMITATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference cancellation</td>
<td>Require user coordination and channel state information</td>
</tr>
<tr>
<td>Interference alignment</td>
<td>Statistical methods require accurate interference models</td>
</tr>
<tr>
<td>Statistical interference mitigation</td>
<td></td>
</tr>
</tbody>
</table>

**Introduction** | Modeling (CoLo) | Modeling (Dist) | Outage Performance | Receiver Design
I employ a **statistical approach** to the interference modeling and mitigation problem

**Proposed solution**

1. Develop a statistical-physical model of interference generation

2. Model statistics of interference in multi-antenna receivers

3. Analyze performance of conventional multi-antenna receivers

4. Develop multi-antenna receiver algorithms using statistical models of interference
A statistical-physical model of interference generation and propagation is proposed

Key Features

- Co-located receiver antennae (▼)
- Interferers are common to all antennae (●) or exclusive to n\textsuperscript{th} antenna (▼)
- Interferers are stochastically distributed in space as a 2D Poisson point process with intensity $\lambda_0$ (●), or $\lambda_n$ (▼)
- Interferer free guard-zone (----) of radius $\delta_↑$
- Power law propagation and fast fading

System model with a 3-antenna receiver in a Poisson field of interferers
I derive **joint statistics of interference** observed by multi-antenna receivers

1. Wireless networks with guard zones

2. Wireless networks without guard zones
Using the system model, I express the sum interference at the \( n^{\text{th}} \) antenna as follows:

\[
Y_n = \sum_{i_0 \in \mathcal{S}_0} A_{i_0} e^{j\phi_{i_0}} H_{i_0,n} e^{j\theta_{i_0,n}} \|r_{i_0}\|^\frac{-\gamma}{2} + \sum_{i_n \in \mathcal{S}_n} A_{i_n} e^{j\phi_{i_n}} H_{i_n} e^{j\theta_{i_n,n}} \|r_{i_n}\|^\frac{-\gamma}{2}
\]

Next, I derive the statistics of \( Y \) for different network models.
I derive interference statistics in networks with guard zones as a mix of isotropic and i.i.d. **Class A** noise.

**Joint characteristic function**

\[
\Phi(w) = e^{A_0e^{-\frac{||w||^2\Omega_0}{2}}} \times \prod_{n=1}^{N} e^{A_ne^{-\frac{||w||^2\Omega_n}{2}}}
\]

\[A_n \propto \lambda_n \delta_{\downarrow}^2, \Omega_n \propto A_n \delta_{\downarrow}^{-\gamma}\]

**Amplitude distribution of interference**

- From common interferers: Isotropic Middleton Class A
- From exclusive interferers: Independent Middleton Class A
Interference statistics in networks without guard zones are a mix of isotropic and i.i.d. **alpha stable** noise

Joint characteristic function

\[
\Phi(w) = e^{\sigma_0 \|w\|^\alpha} \times \prod_{n=1}^{N} e^{\sigma_n |\omega_n|^\alpha}
\]

\[\alpha = \frac{4}{\gamma}, \sigma_n \propto \lambda_n\]

Amplitude distribution of interference

- From common interferers: Isotropic symmetric alpha stable
- From exclusive interferers: Independent symmetric alpha stable
Simulation results indicate a close match between proposed statistical models and simulated interference.

Tail probability of simulated interference in networks with guard zones

Tail probability of simulated interference in networks without guard zones

PARAMETER VALUES

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Model</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>4</td>
<td>‘Isotropic’</td>
<td>$\lambda_0 = 10^{-3}, \lambda_n = 0$</td>
</tr>
<tr>
<td>$\delta_\downarrow$</td>
<td>1.2 (w/ GZ), 0 (w/out GZ)</td>
<td>‘Mixture’</td>
<td>$\lambda_0 = 9.5 \times 10^{-4}, \lambda_n = 5 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
My framework for multi-antenna interference across co-located antennae results in joint statistics that are

1. Spatially isotropic (common interferers)
2. Spatially independent (exclusive interferers)
3. In a continuum between isotropic and independent (mixture)

for two impulsive distributions

1. Middleton Class A (networks with guard zones)
2. Symmetric alpha stable (networks without guard zones)
In networks without guard zones, I incorporate **antenna separation** into the system model.

**Applications**

- Cooperative MIMO
- Distributed antenna systems
- Two-hop communication
- Temporal modeling of interference in mobile receivers

Decentralized network ($\delta = 0$) with 2 receive antennae (▼) in a Poisson field of interferers (●).
Interference statistics are derived via the joint characteristic function (Φ) for three scenarios.

Co-located antennae ($d = 0$) : $\Phi(\omega_1, \omega_2) = e^{\sigma(\omega_1^2+\omega_2^2)^{\frac{\alpha}{2}}}$

Infinitely distant antennae ($d \rightarrow \infty$) : $\Phi(\omega_1, \omega_2) = e^{\sigma(\omega_1^\alpha+\omega_2^\alpha)}$

Distributed antennae ($0 < d < \infty$) :

$$\Phi(\omega_1, \omega_2) \approx e^{\nu(d)\sigma(\omega_1^2+\omega_2^2)^{\frac{\alpha}{2}}+(1-\nu(d))\sigma(\omega_1^\alpha+\omega_2^\alpha)}$$

I use curve fitting to approximate $\nu(d) \approx e^{-\alpha d^\alpha}$
I use the proposed framework to evaluate outage performance of conventional multi-antenna receivers.

1. Pre-detection diversity combiners

2. Post-detection diversity combiners
Multi-antenna receivers combine antenna outputs either before, or after the decoding block.

Pre-detection Combining

\[ y = h x + n \quad \text{wy} \]

| Equal Gain Combiner | \( w = 1_N \) |
| Selection Combiner  | \( w_n = I_{h_n = \max \{h\}} \) |
| Maximum Ratio Combiner | \( w = h^* \) |

Post-detection combining
I derive theoretical **outage probability expressions** for pre- and post-detection diversity combiners.

<table>
<thead>
<tr>
<th>RECEIVER ALGORITHM</th>
<th>OUTAGE PROBABILITY ($\mathbb{P}[\text{SIR} &lt; \theta]$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equal Gain Combining</td>
<td>$C_0 \theta^{\frac{\alpha}{2}} (\lambda_0 + \lambda_e N^{1-\frac{\alpha}{2}})$</td>
</tr>
<tr>
<td>Maximum Ratio Combining</td>
<td>$C_0 \theta^{\frac{\alpha}{2}} \mathbb{E} \left[ \frac{</td>
</tr>
<tr>
<td>Selection Combining</td>
<td>$C_0 \theta^{\frac{\alpha}{2}} \sum_{n=1}^{N} (-1)^{n+1} \frac{N C_n}{n!}$</td>
</tr>
<tr>
<td>Post Detection Combining</td>
<td>$C_0 \sum_{m=1}^{N} (-1)^{m+1} n C_m \frac{m + 1 + 2/\gamma!}{m - 1! \sin \frac{2\pi}{\gamma}} \theta^{\frac{\alpha}{2}} + (C_0 \frac{\pi^2}{\gamma \sin \frac{2\pi}{\gamma}})^N \theta^{\frac{N\alpha}{2}}$</td>
</tr>
</tbody>
</table>
Derived expressions (‘Expr’) **match** simulated outage (‘Sim’) for a variety of spatial dependence scenarios.

Next, I design robust receivers using interference statistics.
Using my knowledge of interference statistics, I design **algorithms** which outperform conventional receivers.

1. Improved pre-detection diversity combiners

2. Improved antenna selection in cooperative reception
I propose **two diversity combining algorithms** that are robust to impulsive interference.

‘Deviation’ in an antenna output $y_n$ is defined as

$$\Delta_n = | y_n - \text{median}\{|y|\}|$$

Proposed diversity combiners

1. Hard-limiting combiner
   $$w_n = 1_{\Delta_n < T} h_n^*$$

2. Soft-limiting combiner
   $$w_n = e^{-A\Delta_n} h_n^*$$
My proposed diversity combiners exhibit better outage performance compared to conventional combiners.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathloss coeff. ($\gamma$)</td>
<td>4</td>
</tr>
<tr>
<td>Guard- zone radius ($\delta_\downarrow$)</td>
<td>0</td>
</tr>
<tr>
<td>Common interferer density ($\lambda_0$)</td>
<td>0.0095</td>
</tr>
<tr>
<td>Excl. intfr. density ($\lambda_n$)</td>
<td>0.0005</td>
</tr>
<tr>
<td>HL combiner parameter ($T$)</td>
<td>1</td>
</tr>
<tr>
<td>SL combiner parameter ($A$)</td>
<td>2</td>
</tr>
</tbody>
</table>
In conclusion, the contributions of my dissertation are

1. A framework for modeling multi-antenna interference
   – Interference statistics are mix of isotropic and independent

2. Statistical modeling of multi-antenna interference
   – Co-located antennae in networks without guard zones
   – Two geographically separate antennae in networks with guard zones

3. Outage performance analysis of conventional receivers in networks without guard zones

4. Design of receiver algorithms with improved performance in impulsive interference
thank you
Interference statistics are derived via the joint characteristic function (Φ) for three scenarios of antenna separation:

\[
\log \{ \Phi(\omega_1, \omega_2) \} = \lambda \int_{\mathbb{R}^2} 1 - \frac{1}{1 + a|\omega_1|^2||r||^{-\gamma} + a|\omega_2|^2||r - d||^{-\gamma}} dr
\]

- \( d = 0 \): \( \Phi(\omega_1, \omega_2) = e^{\sigma(\omega_1^2 + \omega_2^2)^{\frac{\alpha}{2}}} \)
- \( d \to \infty \): \( \Phi(\omega_1, \omega_2) = e^{\sigma(\omega_1^\alpha + \omega_2^\alpha)} \)
- \( 0 < d < \infty \):

\[
\Phi(\omega_1, \omega_2) = e^{\nu(d)\sigma(\omega_1^2 + \omega_2^2)^{\frac{\alpha}{2}} + (1-\nu(d))\sigma(\omega_1^\alpha + \omega_2^\alpha)}
\]
Intuitively, interference statistics lie in a continuum between isotropic and independent.
A framework of common/exclusive interferers unifies interference models in co-located/distributed antennae.

Next, I use this framework to analyze communication performance of multi-antenna receivers.