Modeling Mutual Coupling and OFDM System with Computational Electromagnetics

Nicholas J. Kirsch
Drexel University Wireless Systems Laboratory

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Introduction

- MIMO Communications
- Mutual Coupling and Local Scattering
- MIMO-OFDM
- Mobile Ad-hoc Networking
- Conclusions
MIMO Communications

- Multiple transmitting antennas to multiple receiving antennas
Modeling MIMO Channels

- Effects of scatterers in the near field
- Incorporate effects of OFDM
- Extend simulations to experimental test bed
Mutual Coupling and Local Scattering

- **Motivation**
  - Determine the degree of importance of including mutual coupling (MC)
  - Accurately model vehicular mobile ad hoc networks (MANETs) which include local scattering (LS)

- **Hybrid Computational Electromagnetic Simulation**
  - Near field
    - Method of Moments (NEC, FEKO)
  - Far field
    - Ray tracing (FASANT)
Inclusion of mutual coupling and local scattering

- Run simulation with isotropic radiation patterns to determine the electric fields and geometric solutions for multipath rays: $E_\theta(\theta)$ and $E_\phi(\phi)$
Inclusion cont’d
Inclusion cont’d

- Create antenna e-field weight signal components with appropriate radiation pattern value (which includes MC and LS)
- Sum \( \sum \) the appropriate multipath \( E_z \) rays for every pairwise combination of transmit and receive antennas to create the channel matrix \( \mathbf{H} \)
Inclusion cont’d

\[ E^{(n,m)}_\text{weight} (\theta) = T_m (\theta) E_\theta (\theta) R_n (\theta) \]
\[ E^{(n,m)}_\text{weight} (\varphi) = T_m (\varphi) E_\varphi (\varphi) R_n (\varphi) \]
\[ h_{n,m} = \sum_{l=0}^{L-1} E^{(n,m)}_{z,l} \]
\[ H = [h_{n,m}]_{N \times M} \]
Method of Analysis

- Spatial Multiplexing (SM) Capacity - to evaluate spectral efficiency due to multipath richness (without path loss)
- Beamforming (BF) Capacity – used to compare the effectiveness of antennas in vehicular MANET
- SM and BF capacities are used to evaluate which signaling technique is best in a MANET

\[
C(H) = \log_2 \left( I_N + \frac{\rho \mathbf{H} \mathbf{H}^H}{M \alpha(H)} \right)
\]

\[
B(H) = \log_2 \left( 1 + \frac{\rho \lambda_{\max}^2(H)}{\alpha(H)} \right)
\]

\[
\alpha(H) = \frac{1}{M} \| \mathbf{H} \|_F^2
\]
Angular spread

Angular Spread – used to understand the multipath richness

\[ \Lambda = \sqrt{1 - \frac{|F_1|^2}{F_0^2}} \]

\[ F_k = \int_0^{2\pi} p(\theta)e^{-jk\theta} \, d\theta \]
Simulations

- Inclusion of MC at both ends of the link
  - 4 x 4 MIMO System, ULA
- Performance analysis of a vehicular MANET
  - 4x4 MIMO, antennas arranged on each side of vehicle
Radiation patterns

- 2.4 GHz dipole antenna in a λ/2 ULA
- 2.4 GHz patch antenna on the front of a bumper of a vehicle
- Radiation patterns due to near field effects are shown
Results: Inclusion of MC at both ends of the link

- Inclusion of MC at both ends of the link results in greater capacity in both the LOS and NLOS cases.
Results: Performance evaluation of a vehicular MANET

- Due to the array geometry, some transmitting antennas may not communicate with certain receiving antennas even in a multipath rich environment.
- A rank deficient channel will have lower spatial multiplexing capacity, but higher beamforming capacity.
MIMO-OFDM

- Current research on MIMO-OFDM based on statistical channel models
- Statistical channel model: either insufficiently wideband or not suited for the physical environment of interest
- Ray-tracing simulation: site-specific information
Electromagnetic Ray Tracing

- Computational electromagnetic-based simulation technique;
- ERT is computationally complex and demanding;
- ERT has been applied to narrowband system so far.
Channel Response Extrapolation

- Assumptions
  - Subcarrier frequencies are not so far apart that the geometric ray solutions remain the same across all subcarriers
  - The number and type of multipath signal components remain the same from one subcarrier to another
FASANT computes the electric field of each ray

\[ E_{z,m} = E_z e^{-j k_m d} = E_z e^{-j \frac{2 \pi d}{c} f_m} \]

The response \( E_{z,n} \) at carrier \( f_n \) can be computed by extrapolation

\[ E_{z,n} = E_z e^{-j \frac{2 \pi d}{c} f_n} = E_{z,m} e^{-j \frac{2 \pi d}{c} \Delta f} \]

where \( \Delta f = f_n - f_m \)
SISO Channel Model

- Time-varying channel

\[
\alpha(t,\tau) = \sum_{i=0}^{N-1} E_{z,m}^{(i)} e^{j2\pi f_d^{(i)} t} \delta(\tau - \tau_i)
\]

- For a finite bandwidth receiver, some of the rays cannot be distinguished in time. Group them to be a cluster \( \beta_l(t) = \sum_{i=1}^{p_l} E_{z,m}^{(i)}(t) \)

- The time-clustered channel is

\[
\alpha(t,\tau) = \sum_{l=0}^{L-1} \beta_l(t) \delta(\tau - \tau_l)
\]
MIMO Channel Model and Capacity

- Input Output relation
  \[ y(n) = \sum_{l=0}^{L-1} H_l x(n-l) \]

- Frequency response of wideband channel matrix at \( k \)th subcarrier
  \[ H(e^{j2\pi k/N}) = \sum_{l=0}^{L-1} H_l e^{-j2\pi kl/N} \]

- If CSI is not available at the transmitter
  \[ I = \frac{1}{N} \sum_{k=0}^{N-1} I_k = \frac{1}{N} \sum_{k=0}^{N-1} \log_2 \left[ \det \left( I_{M_r} + \frac{P}{NM_t \sigma_n^2} H(e^{j2\pi k/N})H^H(e^{j2\pi k/N}) \right) \right] \]

- If CSI is known at the transmitter: use water-filling to maximize mutual information.
Simulated Capacity in Ad Hoc network

- Center frequency = 2.4GHz
- Number of carriers = 64
- Channel spacing = 312.5KHz
Capacities fluctuate at different subcarriers.
Eigenvalues vs Subcarriers

- The larger the eigenvalue an eigenmode has, the more power flows to that mode.
- Frequency diversity achieved.
Mobile Ad hoc Network

- Ad-hoc network
- MIMO Communications
- Software Defined Radio
- Modular Networking Layer
- Wide bandwidth (10MHz Baseband)
Node infrastructure overview

Upper Level Application Software  Routing Algorithm  Cross Layer Resource Allocation Algorithm  MAC Algorithm  Gigabit Ethernet  Gigabit Ethernet  Chassis RAM/RAID  PXI Controller (NI PXI-8186)  Analog-to-Digital Conversion (NI PXI-5122)  Digital-to-Analog Conversion (NI PXI-5421)  Dual Band 802.11 a/b/g (RC2432-RC2431/6) RF Transceiver Texas Instruments

Multi-Processor Linux PC making use of the Click Modular Router

(PXI Chassis (National Instruments PXI-1045 making use of LabView))
Summary

- Demonstrated importance of including MC and LS for design of ad hoc network nodes making use of antenna arrays
- Developed simulation methodology for including these practical electromagnetic effects
Summary cont’d

- Fast way to generate channel responses in OFDM system with CEM.
- This technique is used for simulating MIMO-OFDM Ad Hoc network, which shows both spatial and frequency diversity are achieved.
- Combine ray tracing channel model with correlation (stochastic) channel model to provide site-specific information as well as numerous channel realizations – Semi-stochastic spatial-temporal channel model.