Space-Time Signal Processing for Wireless Ad-hoc Networks

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Wireless (Ad-hoc) Networks: Challenges

- Group of nodes communicate with the base station or each other over a common wireless channel.
- Interference is one of the limiting factors in such environment.
- Fading is another limiting factor for reliable communications.
- Future wireless applications require high throughput for such networks.
Wireless (Ad-hoc) Networks: Challenges
Wireless (Ad-hoc) Networks: Solutions

- The use of multiple antennas at both transmitter and receiver.
- Foschini & Gans (98), Teletar (99): Multiple Tx/Rx antennas can increase capacity of wireless channels significantly.
- Space-time signal processing is the solution to achieve high data rates.
- Many practical communication devices can not carry multiple antennas or at least the same number of antennas as base station.
Talk summary

• Part I: Packet transmission in wireless ad-hoc networks.
• Part II: Space-time processing for uplink of wireless communications systems.
• Part III: Future research in space-time signal processing for mobile wireless networks.
Packet Transmission in Wireless Networks

- Gupta & Kumar (2000): Capacity per source-destination of fixed ad-hoc wireless networks goes to zero!
- Grossglauser & Tse (2002): Capacity per source-destination of mobile ad-hoc wireless networks goes to a constant using multiuser diversity.
- Problem: Infinite delay even with finite number of nodes in the network.

Cumulative density delay function with uniform distribution of nodes:

\[ F_T(t) = 1 - e^{-\lambda t} \]
Packet Transmission in Wireless Networks
Packet Transmission in Wireless Networks
Packet Transmission in Wireless Networks

(a) $K=2$, $\lambda=0.0052$
Packet Transmission in Wireless Networks

(b) $K=4, \lambda=0.0052$

- $(d,d_K)$ from 40 random topologies
- 7th degree poly fit
- Uniform
- 90-points average

$\text{d}_K$ (sec)

$d$ (sec)
Packet Transmission in Wireless Networks

Unit Area Disk

$R = \frac{1}{\sqrt{\pi}}$

$\gamma$

$d\gamma$

$dr$

$r'$
Packet Transmission in Wireless Networks

\[ SIR = \lim_{n \to \infty} \frac{\alpha - 2}{2} q_{r',\alpha,\theta}(n \to \infty) = \begin{cases} \frac{\alpha - 2}{2} \cdot 1 & \text{if } 0 \leq r' \leq \frac{1}{\sqrt{\pi}} - r_o \\ \frac{\alpha - 2}{2} \cdot q_{r',\alpha,\theta}(n \to \infty) & \text{if } r' = \frac{1}{\sqrt{\pi}} - r_o, \text{i.e., the cell boundary.} \end{cases} \]

\[ q_{r',\alpha,\theta}(n \to \infty) = q_{r',\alpha}(n \to \infty) = \begin{cases} 1 & \text{if } 0 \leq r' \leq \frac{1}{\sqrt{\pi}} - r_o \text{ and } \alpha > 2 \\ 1.467 & \text{if } r' = \frac{1}{\sqrt{\pi}} - r_o \text{ and } \alpha = 3 \\ 1.333 & \text{if } r' = \frac{1}{\sqrt{\pi}} - r_o \text{ and } \alpha = 4 \\ 1.270 & \text{if } r' = \frac{1}{\sqrt{\pi}} - r_o \text{ and } \alpha = 5 \\ 1.232 & \text{if } r' = \frac{1}{\sqrt{\pi}} - r_o \text{ and } \alpha = 6 \end{cases} \]
Packet Transmission in Wireless Networks

\[ SIR_r(n) = \frac{1}{r_o^2} \int_0^{\pi} \ln \left( \frac{1}{\pi} \left( \frac{1}{\frac{1 - (r' \sin \gamma)^2 - r' \cos \gamma}{r_o}} \right)^{\frac{1}{2}} \right) d\gamma \]

\[ = \frac{1}{2nr_o^2 \theta} \int_0^{\pi} \ln \left( \frac{1}{\pi} \left( \frac{1}{\frac{1 - (r' \sin \gamma)^2 - r' \cos \gamma}{r_o}} \right)^{\frac{1}{2}} \right) d\gamma \]

\[ = \frac{2}{\pi} \left\{ \int_0^{\pi} \ln \left( \sqrt{\pi \theta n} \right) \left( \frac{1}{\pi} \left( \frac{1}{\frac{1 - (r' \sin \gamma)^2 - r' \cos \gamma}{r_o}} \right)^{\frac{1}{2}} \right) d\gamma \right\}^{-1} \]
Packet Transmission in Wireless Networks

$3 \leq \alpha \leq 6$

SIR (dB)

Log$_{10}n$
Packet Transmission in Wireless Networks

\(\alpha = 4\)

\[SIR (dB) \quad \text{vs} \quad \log_{10}(n)\]

Legend:
- \(r' = 0\)
- \(r' = 0.75 / \pi^{1/2} - r_0\)
- \(r' = 0.9 / \pi^{1/2} - r\)
- \(r' = 0.99 / \pi^{1/2} - r_0\)
- \(r' = 1 / \pi^{1/2} - r_0\)
Packet Transmission in Wireless Networks

\[ \alpha = 2 \]

\[ \log_{10} n \]

![Graph showing SIR (dB) against Log_{10} n with different path loss exponents and distances.](image)
STC in Wireless Networks: Challenges

- To achieve high data rates we need multiple antennas at both ends.
- Many mobile units are not capable of carrying multiple antennas. In some cases, they only have a single transmit antenna.
- Is there any solution when there is a single transmit antenna? Cooperation diversity.
- Can we do it without the need for multiple transmit antennas or using cooperation diversity?
  Yes!!
STC in Wireless Networks

\[ r_t^j = \sum_{i=1}^{N^t} h_{i,j}(t) c_t^i \sqrt{E_s} + n_t^j \]
STC in Wireless Networks

Performance Comparison between MIMO and the PA

Space-time Convolutional codes for 4 states, Rayleigh fading channel
STC in Wireless Networks

Performance comparison between MIMO and the PA

Block Error Rate vs SNR (dB)

- MIMO
- Virtual_optimum(t)
- Virtual_Cnormal(t)
- Virtual_optimal
- Virtual_Cnormal

Space-time Convolutional codes for 16 states, Rayleigh fading channel
STC in Wireless Networks

Performance Comparison between MIMO and the PA

Block Error Rate

SNR, dB

STC for 4 states, Rician fading channel, k=0 dB
STC in Wireless Networks

Performance Comparison between MIMO and the PA

STC for 16 states, Rician fading channel, $k=0$ dB
STC in Wireless Networks

Performance Comparison between MIMO and the PA

STC for 4 states, Rician fading channel, k=6 dB
STC in Wireless Networks

Performance Comparison between MIMO and the PA

STC for 16 states, Rician fading channel, \( k=6 \) dB
STC in Wireless Networks

Performance Comparison of MIMO with the PA

Block Error Rate vs. SNR, dB

- MIMO (fading)
- Virtual (fading)
- MIMO (-10)
- Virtual (-10)
- MIMO (0)
- Virtual (0)
- MIMO (5)
- Virtual (5)
- MIMO (10)
- Virtual (10)
- MIMO (20)
- Virtual (20)
Current Activities at UCBC

- ML decoding of linear block code for application to Turbo block codes.
- Adaptive coding and modulation for OFDM systems.
- Coding and Signal processing for fiber optic channels (PMD compensation).
- Tradeoff studies between capacity and delay in various networks.