Collaborative transmission in wireless sensor networks

Introduction to wireless communications

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Overview and Structure

- Wireless sensor networks
- Wireless communications
- Basics on probability theory
- Randomised search approaches
- Cooperative transmission schemes
- Distributed adaptive beamforming
  - Feedback based approaches
  - Asymptotic bounds on the synchronisation time
  - Alternative algorithmic approaches
  - Alternative Optimisation environments
- An adaptive communication protocol

Overview and Structure

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- **Wireless communications**
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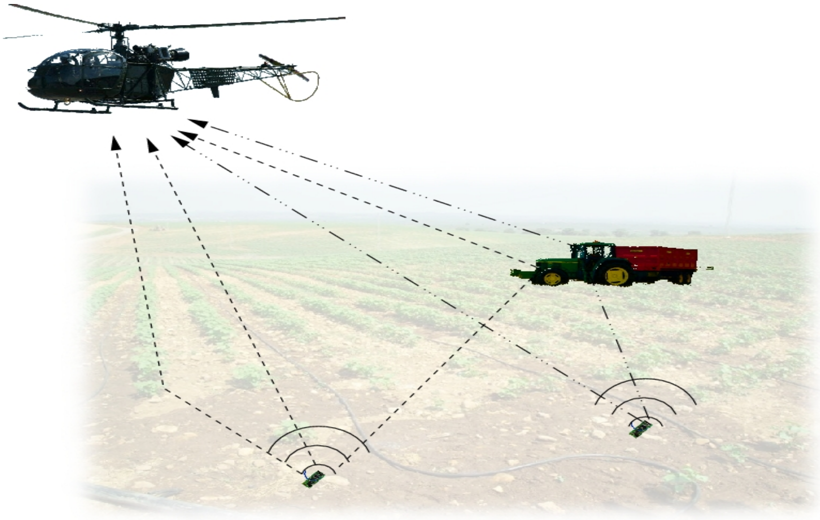
Outline
Wireless communications

Introduction
Wireless communications

- Wireless communication
  - Utilisation of shared medium
  - Electromagnetic waveform transmitted between communication partners
  - Information modulated on top of a signal wave

Introduction

Wireless communications



Outline

Wireless communications

1. Introduction
2. Aspects of the mobile radio channel
3. MIMO
4. Centralised beamforming

Aspects of the mobile radio channel

Wireless communications

RF transmission

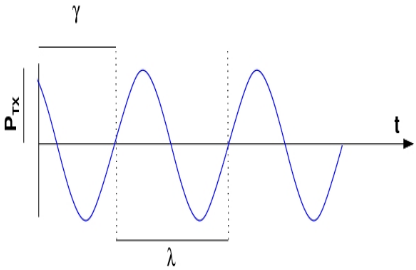
- Electromagnetic signals
- Transmitted in wave-Form
- Omnidirectional transmission
- Speed of light
  - $c = 3 \cdot 10^8 \frac{m}{s}$

Aspects of the mobile radio channel

Wireless communications

RF signal

- Transmission power:
  - $P_{TX}[W]$
- Frequency:
  - $f[\frac{1}{sec}]$
- Phase offset:
  - $\gamma[\pi]$
- Wavelength:
  - $\lambda = \frac{c}{f}[m]$

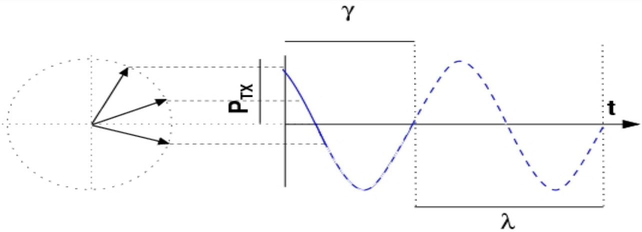


Aspects of the mobile radio channel

Wireless communications

RF signal

- Real part of rotating vector
  - $\zeta = \Re\left(e^{j(ft+\gamma)}\right)$
- Instantaneous signal stength:
  - $\cos(\zeta)$
- Rotation Speed: Frequency f



Aspects of the mobile radio channel

Wireless communications

Noise

- In every realistic setting, noise can be observed on the wireless channel
- Tpyical noise power:[a]

$$P_N = -103 dBm$$

- Value observed by measurements

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[a] 3GPP: 3rd generation partnership project; technical specification group radio access networks; 3g home nodeb study item technical report (release 8). Technical Report 3GPP TR 25.820 V8.0.0 (2008-03) (March)

Aspects of the mobile radio channel

Wireless communications

Noise

- Thermal noise can also be estimated analytically as

$$P_N = \kappa \cdot T \cdot B$$

- $\kappa = 1.3807 \cdot 10^{-23} \frac{J}{K}$: Boltzmann constant
- T: Temperature in Kalvin
- B: Bandwidth of the signal.

Aspects of the mobile radio channel

Wireless communications

Example

- GSM system with $200kHz$ bands
- Average temperature: $300K$
- Estimated noise power:

$$
\begin{aligned}
P_N &= \kappa \cdot T \cdot B \\
&= 1.3807 \cdot 10^{-23} \frac{J}{K} \cdot 300K \cdot 200kHz \\
P_N &= -120.82dBm
\end{aligned}
$$

Aspects of the mobile radio channel

Wireless communications

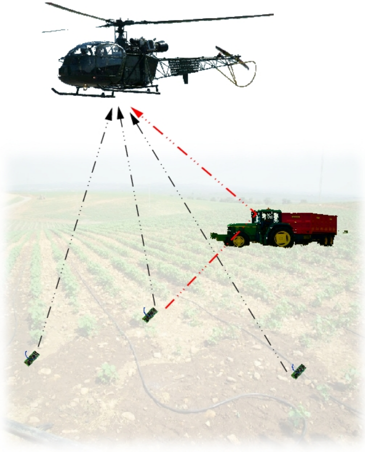
Path-loss

- Signal strength decreases while propagating over a wireless channel
- Order of decay varies in different environments
- Impact higher for higher frequencies
- Can be reduced by antenna gain (e.g. directed)

Location	Mean Path loss exponent	Shadowing variance σ^2 (dB)
Apartment Hallway	2.0	8.0
Parking structure	3.0	7.9
One-sided corridor	1.9	8.0
One-sided patio	3.2	3.7
Concrete Canyon	2.7	10.2
Plant fence	4.9	9.4
Small boulders	3.5	12.8
Sandy flat beach	4.2	4.0
Dense bamboo	5.0	11.6
Dry tall underbrush	3.6	8.4

Aspects of the mobile radio channel

Wireless communications



Path-loss

- For analytic consideration: Path-loss approximated
- Friis free-space equation:

$$P_{TX} \cdot \left(\frac{\lambda}{2\pi d}\right)^2 \cdot G_{TX} \cdot G_{RX}$$

Aspects of the mobile radio channel

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Path-loss

$$P_{RX} = P_{TX} \cdot \left(\frac{\lambda}{2\pi d}\right)^2 \cdot G_{TX} \cdot G_{RX}$$

- Utilised in outdoor scenarios
  - Direct line of sight
  - No multipath propagation
- d impacts the RSS quadratically
- Other values for the path-loss exponent α possible.
- Path-loss:

$$PL^{FS}(\zeta_i) = \frac{P_{TX}(\zeta_i)}{P_{RX}(\zeta_i)}$$

Aspects of the mobile radio channel

Wireless communications

Path-loss (Log-distance model)

- Path-loss model suited in buildings or densely populated areas:

$$PL^{LD}(\zeta_i) = \frac{P_{TX}(\zeta_i)}{P_{RX}(\zeta_i)} = 10^{\frac{L_0}{10}} \cdot d^{\alpha} \cdot 10^{\frac{x_g}{10}}$$

  - in dB:

$$\begin{aligned} PL^{LD}(\zeta_i) &= P_{TX}(\zeta_i) - P_{RX}(\zeta_i) \\ &= L_0 + 10 \cdot \alpha \cdot \log_{10}\left(\frac{d}{d_0}\right) + X_g [dB] \end{aligned}$$

- L_0: Path-loss at reference distance d_0
- X_g: Attenuation due to fading (random with zero mean)

Aspects of the mobile radio channel

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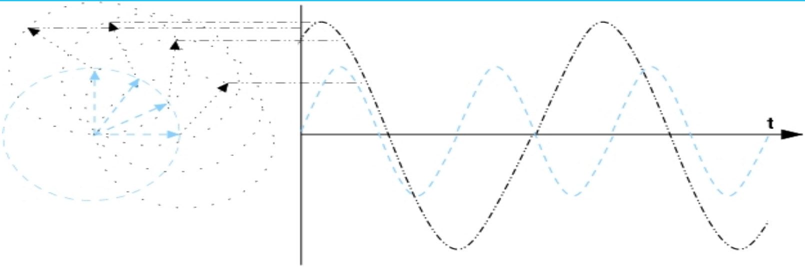
Superimposition of RF signals

- Broadcast channel
- Multipath transmission
  - Reflection
  - Diffraction
  - Different path lengths
  - Signal components arrive at different times
- Interference

Aspects of the mobile radio channel

Wireless communications

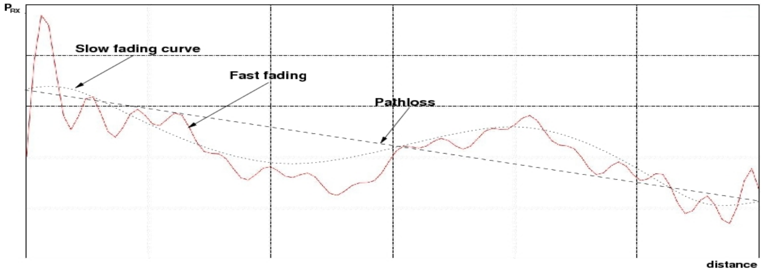


Superimposition of RF signals

- At a receiver, all incoming signals add up to one superimposed sum signal
- Constructive and destructive interference
- Normally: Heavily distorted sum singal

Aspects of the mobile radio channel

Wireless communications



Fading

- Signal quality fluctuating with location and time
- Slow fading
- Fast fading

Aspects of the mobile radio channel

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Slow fading

- Result of environmental changes
- Temporary blocking of signal paths
- Changing reflection angles
- Movement in the environment
  - Trees
  - Cars
  - Opening/closing doors
- Amplitude changes can be modelled by log-normal distribution

Aspects of the mobile radio channel

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Fast fading

- Signal components of multiple paths
- Cancelation of signal components
- Fading incursions expected in the distance of $\frac{\lambda}{2}$
- Channel quality changes drastically over short distances
- Example: Low radio reception of a car standing in front of a headlight is corrected by small movement
- Stochastic models are utilised to model the probability of fading incursions
  - Rice
  - Rayleigh

Aspects of the mobile radio channel

Wireless communications

Fast fading

- Fast fading weakened when direct signal component observed

- Modelled by Rice distribution:

$$f(A) = \frac{A}{\sigma^2} e^{-\frac{A^2+s^2}{2\sigma^2}} I_0\left(\frac{As}{\sigma^2}\right)$$

- s: Dominant component of received signal
- σ: Standard deviation
- Modified Bessel function with order 0:

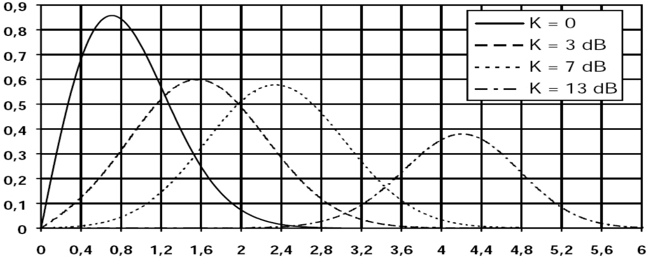
$$I_0(x) = \frac{1}{2\pi} \int_0^{2\pi} e^{x\cos(\Psi)} d\Psi$$

Aspects of the mobile radio channel
Wireless communications

- Ricean factor:

$$K = \frac{s^2}{2\sigma^2}$$

  - Impacts probability density function of Rice distribution
  - Most probable outcome impacted



Aspects of the mobile radio channel

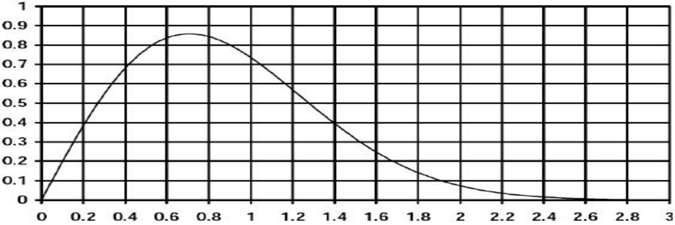
Wireless communications

- For $K = 0$, Rice distribution migrates to Rayleigh distribution:

$$\begin{aligned}
\lim_{K\to 0} f(A) &= \lim_{K\to 0} \frac{A}{\sigma^2} e^{-\frac{A^2}{2\sigma^2}-K} I_0\left(\frac{A\sqrt{2K}}{\sigma}\right) \\
&= \lim_{K\to 0} \frac{A}{\sigma^2} e^{-\frac{A^2}{2\sigma^2}-K} \frac{1}{2\pi}\int_0^{2\pi} e^{\frac{A\sqrt{2K}}{\sigma}\cos(\Psi)} d\Psi \\
&= \frac{A}{\sigma^2} e^{-\frac{A^2}{2\sigma^2}-0} \frac{1}{2\pi}\int_0^{2\pi} e^{\frac{A\sqrt{2\cdot 0}}{\sigma}\cos(\Psi)} d\Psi \\
&= \frac{A}{\sigma^2} e^{-\frac{A^2}{2\sigma^2}}
\end{aligned}$$

Aspects of the mobile radio channel

Wireless communications



Rayleigh distribution

- Probability density function of received sum singal for $n \gg 1$
- Assumption:
  - No direct signal component exists
  - Received signal components of approximately equal strength
- Example: Urban scenarios with dense house blocks

Aspects of the mobile radio channel

Wireless communications

- With large K, Rice distribution evolves to Gauss distr.:

$$I_0(x) \quad \rightarrow_{x \gg 1} \rightarrow \quad \frac{e^x}{\sqrt{2\pi x}}$$

$$\Rightarrow f(A) \quad \rightarrow_{K \gg 1} \rightarrow \quad \frac{A}{\sigma^2} e^{-\frac{A^2}{2\sigma^2} - K} \frac{e^{\frac{A\sqrt{2K}}{\sigma}}}{\sqrt{2\pi \frac{A\sqrt{2K}}{\sigma}}}$$

$$f(A) = \frac{A}{\sigma^2 \sqrt{\frac{2\pi}{\sigma}} \sqrt{A\sqrt{2K}}} e^{-\frac{A^2}{2\sigma^2} - \frac{s^2}{2\sigma^2}} e^{\frac{A\sqrt{2K}}{\sigma}}$$

$$= \frac{A}{\sigma^2 \sqrt{\frac{2\pi}{\sigma}} \sqrt{A\sqrt{2K}}} e^{-\frac{A^2+s^2-2As}{2\sigma^2}}$$

$$= \sqrt{\frac{A}{s}} \frac{1}{\sigma 2\pi} e^{-\frac{1}{2}\left(\frac{A-s}{\sigma}\right)^2}$$

Aspects of the mobile radio channel

Wireless communications

- The term

$$\sqrt{\frac{A}{s}}\frac{1}{\sigma 2\pi}e^{-\frac{1}{2}\left(\frac{A-s}{\sigma}\right)^2}$$

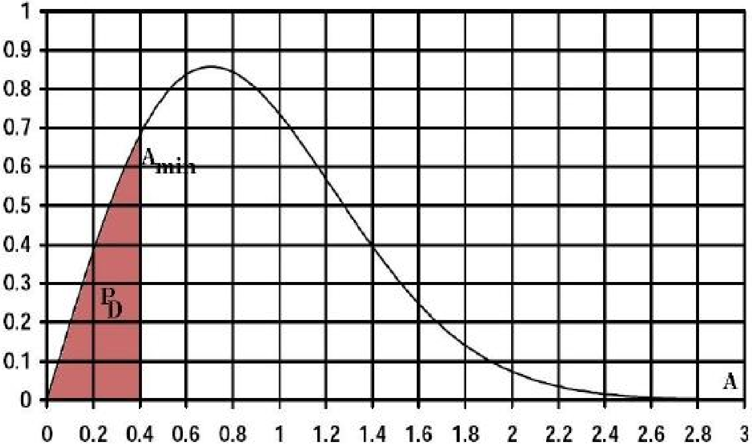
- differs from the Gauss distribution in $\sqrt{\frac{A}{s}}$:

$$f_{Gauss}(x) = \frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{A-s}{\sigma}\right)^2}$$

- With $\sqrt{\frac{A}{s}} \approx 1$, Rice distribution can be approximated by Gauss distribution

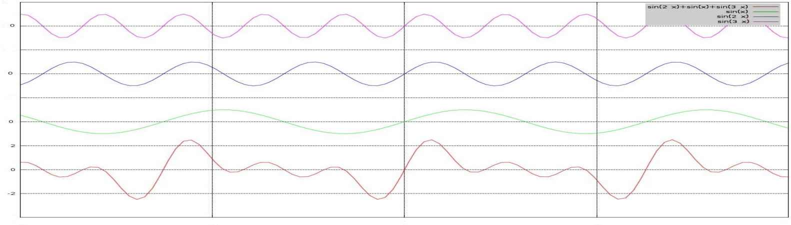
Aspects of the mobile radio channel

Wireless communications



Aspects of the mobile radio channel

Wireless communications



Interference

- Signal components arrive from more than one transmitter
- Neighbouring nodes generate interference:

$$\zeta_{\text{sum}} = \sum_{i=1}^{\iota} \Re\left(e^{j(f_i t + \gamma_i)}\right)$$

Aspects of the mobile radio channel
Wireless communications

Interference

- A radio system typically requires a specific minimum signal power over interference and noise level:

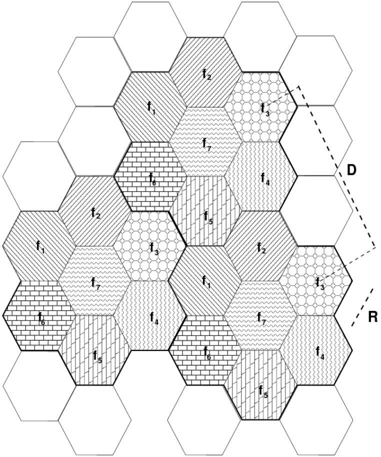
$$SINR = \frac{P_{\text{signal}}}{P_{\text{noise}} + P_{\text{interference}}}$$

- Concepts to reduce interference:
  - Clustering (cellular networks)
  - Spread spectrum techniques (Code divisioning)

Aspects of the mobile radio channel

Wireless communications

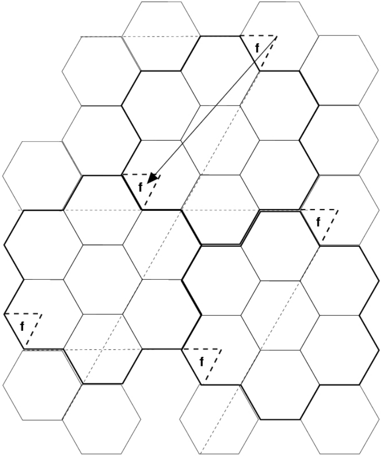
- Clustering
  - Cells with identical frequencies separated
  - Interference in one frequency band reduced



Aspects of the mobile radio channel

Wireless communications

- Clustering
  - Further reduction of interference by sectioning antennas
  - Typically not implemented in WSNs
    - Relative locations of sensors unknown
    - Organisation of cluster structure problematic



Aspects of the mobile radio channel

Wireless communications

Spread spectrum system

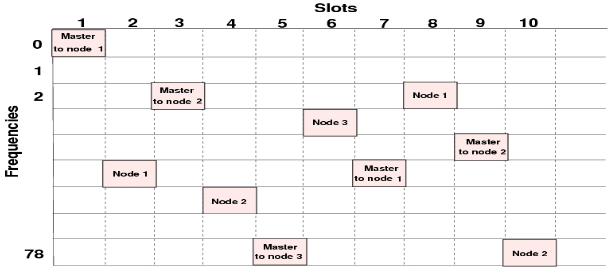
- Utilise a very wide bandwidth for transmission
- Interference in a small frequency band has reduced impact on the overall transmission

Aspects of the mobile radio channel

Wireless communications

Spread spectrum system – Frequency hopping

- E.g. Bluetooth
  - 79 sub-frequency bands
  - Hop 1600 times per second
  - Pseudo random hop sequence
  - Master node controls hopping sequence



Aspects of the mobile radio channel

Wireless communications

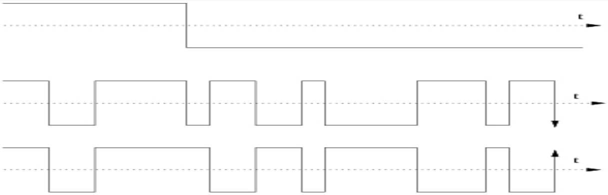
- Spread spectrum system – Frequency hopping
  - Not well suited for WSNs
  - Processing required for frequency hopping would surcharge processing capabilities of sensor nodes

Aspects of the mobile radio channel

Wireless communications

Spread spectrum system – Code divisioning

- Spread transmit signal over whole frequency band
- Add redundancy to the signal
- Combination of the transmit symbols with pseudo-random code sequence
- Interference in limited frequency band with low effect
- Transmitters simultaneously utilise identical frequency



Aspects of the mobile radio channel

Wireless communications

Spread spectrum system – Code divisioning

- Transmitters share the same frequency
- Unique, orthogonal pseudo noise sequences
- Decoding possible: Pseudo noise sequence linked to transmitter
- Transmission below noise level possible
- Creation of pseudo noise sequences: E.g. OVSF

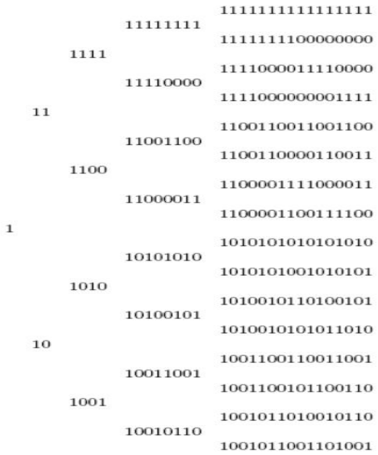
Orthogonal Variable Spreading Factor (OVSF)

- Root spreading code:

$$c_{i,j} \in \{0,1\}^i;\ i,j \in \mathbb{N}$$

- Create

$$\begin{aligned} c_{2i,2j-1} &= (c_{i,j} c_{i,j}) \\ c_{2i,2j} &= (c_{i,j} \overline{c_{i,j}}) \end{aligned}$$



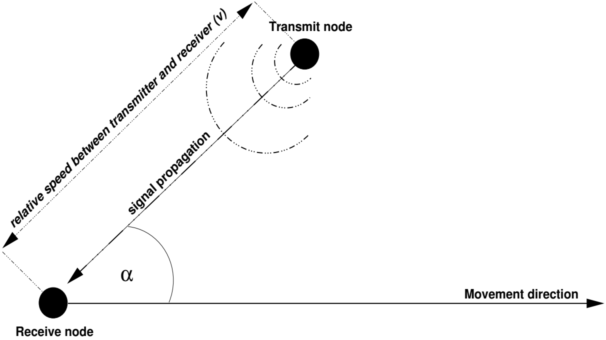
Aspects of the mobile radio channel

Wireless communications

- Spread spectrum system – Code divisioning
  - Utilised also in WSNs
  - E.g. CDMA
  - Number of code seqeunces of a given length restricted

Aspects of the mobile radio channel

Wireless communications



- Doppler Shift
  - Frequency of a received signal may differ to the frequency of the transmitted signal
  - Dependent on relative speed between transmitter and receiver
  - $f_d = \frac{v}{\lambda} \cdot \cos(\alpha)$

Outline

Wireless communications

MIMO
Wireless communications

- Wireless communication
  - Typically one transmitter and one receiver
    - SISO
  - Capacity increased by diversity schemes as
    - Time diversity
    - Frequency diversity
    - Code divisioning

MIMO
Wireless communications

- Spatial diversity
  - Clustering
  - Multiple transmit or receive antennas for a single communication link
    - SIMO
    - MISO
    - MIMO
  - Spatially separated antennas
    - Independent communication channels
    - Fading characteristics for these channels different
    - Probability of inferior reception on all channels simultaneously low

MIMO
Wireless communications

Vector-Matrix of a MIMO-System:

$$\overrightarrow{\zeta^{RX}} = \begin{bmatrix} \zeta_1^{RX} \\ \zeta_2^{RX} \\ \vdots \\ \zeta_M^{RX} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1L} \\ h_{21} & \ddots & & h_{2L} \\ \vdots & & \ddots & \vdots \\ h_{M1} & h_{M2} & \cdots & h_{ML} \end{bmatrix} \begin{bmatrix} \zeta_1^{TX} \\ \zeta_2^{TX} \\ \vdots \\ \zeta_L^{TX} \end{bmatrix} + \begin{bmatrix} \zeta_1^{\text{noise}} \\ \zeta_2^{\text{noise}} \\ \vdots \\ \zeta_M^{\text{noise}} \end{bmatrix}$$

MIMO

Wireless communications

$$\overrightarrow{\zeta^{RX}} = \begin{bmatrix} \zeta_1^{RX} \\ \zeta_2^{RX} \\ \vdots \\ \zeta_M^{RX} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1L} \\ h_{21} & \ddots & & h_{2L} \\ \vdots & & \ddots & \vdots \\ h_{M1} & h_{M2} & \cdots & h_{ML} \end{bmatrix} \begin{bmatrix} \zeta_1^{TX} \\ \zeta_2^{TX} \\ \vdots \\ \zeta_L^{TX} \end{bmatrix} + \begin{bmatrix} \zeta_1^{\text{noise}} \\ \zeta_2^{\text{noise}} \\ \vdots \\ \zeta_M^{\text{noise}} \end{bmatrix}$$

Vector of received signal components:

$$\overrightarrow{\zeta^{RX}} = (\zeta_1^{RX}, \zeta_2^{RX}, \dots, \zeta_M^{RX})^T$$

Vector of noise signals:

$$\overrightarrow{\zeta^{\text{noise}}} = (\zeta_1^{\text{noise}}, \zeta_2^{\text{noise}}, \dots, \zeta_M^{\text{noise}})^T$$

Channel Matrix H describes connection of inputs and outputs.

MIMO
Wireless communications

- Potential gain of a MIMO system
  - Improve communication speed
    - Parallel transmission over all channels
  - Improve robustness of communication
    - Transmit redundant information over all channels

MIMO

Wireless communications

- MIMO for WSNs?
  - Not probable since antennas have to be sufficiently separated
    - Typical estimation: $\frac{\lambda}{2}$
    - With 2.4GHz:

$$\frac{3 \cdot 10^8 \frac{m}{sec}}{2.4 * 10^9 \frac{1}{sec}} = 12.5cm$$

    - Typical sensor nodes smaller in size

Outline

Wireless communications

Centralised beamforming

Wireless communications

Centralised beamforming

- Create an antenna beam of synchronised transmissions that is focused on a restricted area
- Signal components form transmit antennas coherently overlaid
- Constructive interference at the receiver
- Outside the restricted area, signal components vanish in the noise signal
  - Reduced interference to neighbouring receivers

Centralised beamforming

Wireless communications

Centralised beamforming

- Fixed antenna Array
  - Exact relative location of all antennas known
  - All antenna elements tightly synchronised
  - Signals from each antenna element suitably weighted
- Focus and control transmission beam
- Received sum signal:

$$\sum_{i=1}^{n} \Re\left(e^{j(2\pi f_i t + \gamma_i)}\right)$$

- When all signal components are in phase,
  - signal strength increases linear to count of signal components

Questions?

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