Collaborative transmission in wireless sensor networks

Randomised search approaches

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Overview and Structure

- Introduction to context aware computing
- Wireless sensor networks
- Wireless communications
- Basics of probability theory
- Randomised search approaches
- Cooperative transmission schemes
- Distributed adaptive beamforming
  - Feedback based approaches
  - Asymptotic bounds on the synchronisation time
  - Algorithmic improvements
  - Alternative Optimisation environments
  - A numeric approach for synchronisation
  - Consideration of node mobility

Overview and Structure

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Cooperative transmission schemes
Introduction

- Cooperation
  - One of the major challenges in WSNs
  - Energy consumption
  - Resource sharing
  - Finding of routing paths
  - Here:
    - Improve data transmission in WSN

Outline

Cooperative transmission schemes

1. Cooperative transmission
   - Network coding
   - Multi-hop approaches
   - Data flooding
2. Multiple antenna techniques
   - Virtual MIMO
   - Open-loop distributed carrier synchronisation
     - Master-slave open loop distributed carrier synchronisation
     - Carrier synchronisation with fixed locations of distributed nodes
     - Carrier synchronisation with unknown locations
     - Round-tip open-loop distributed carrier synchronisation
   - Closed-loop distributed adaptive carrier synchronisation
     - Full feedback closed-loop carrier synchronisation
     - 1-bit feedback closed-loop carrier synchronisation

Cooperative transmission

Introduction

- Cooperative transmission
  - Network coding
  - Multi-hop approaches
  - Data flooding

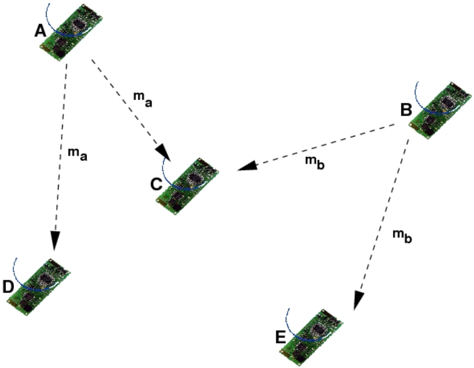
Cooperative transmission

Network coding

- Traditional approaches
  - Relay nodes forward messages unmodified
  - Reach remote receiver over multi-hop
- Network coding
  - Relay nodes modify incoming messages before forwarding
  - Combination of incoming messages
  - Reduction of transmission cost

Cooperative transmission

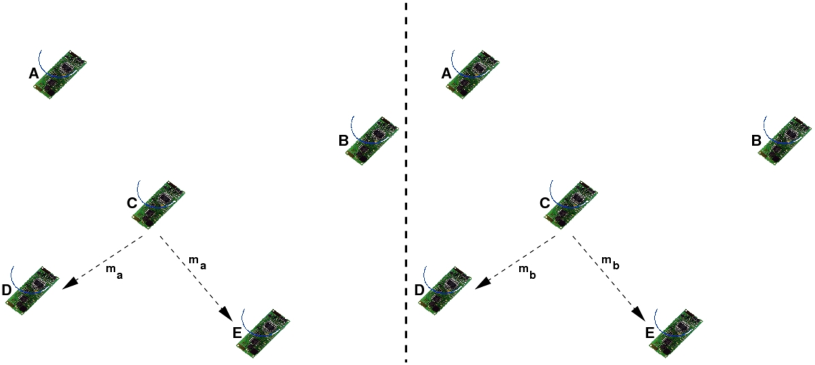
Network coding



- Nodes A and B transmit messages m_a, m_b
- Nodes D and E receive the messages directly
- Node C overhears both messages

Cooperative transmission

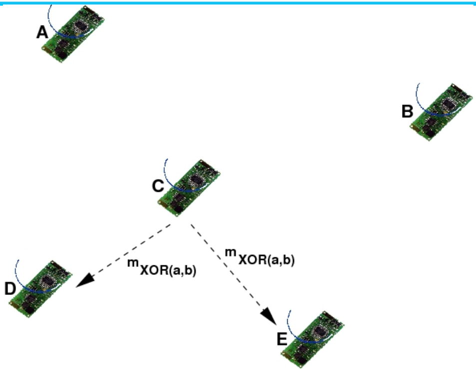
Network coding



- Traditional broadcast scheme:
  - Node C forwards both messages separately

Cooperative transmission

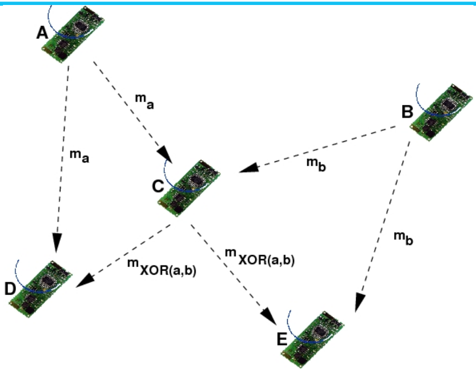
Network coding



- Network coding
  - Combination of incoming messages
  - Transmit $m_{XOR(m_a, m_b)}$
  - Nodes A and B decode the missing information by XOR combination with received message

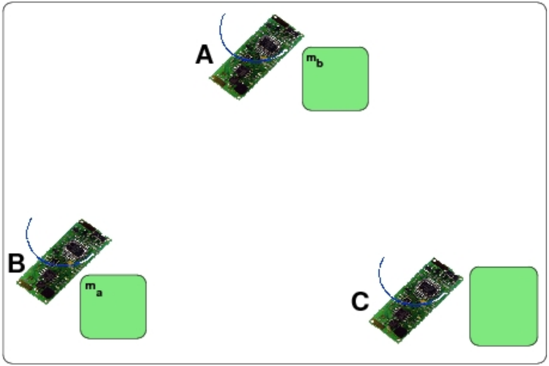
Cooperative transmission

Network coding



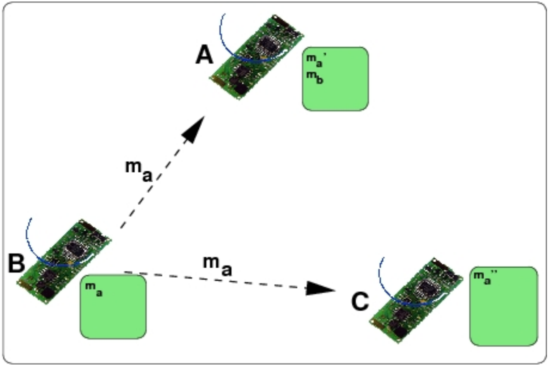
- Reduced overall transmission power
- More energy efficient transmission
- Reduced latency
- Increased in-network processing load

Cooperative transmission
Network coding



- Increase the error tolerance of transmission by network coding
  - Nodes A and B want to transmit messages m_a, m_b to node C

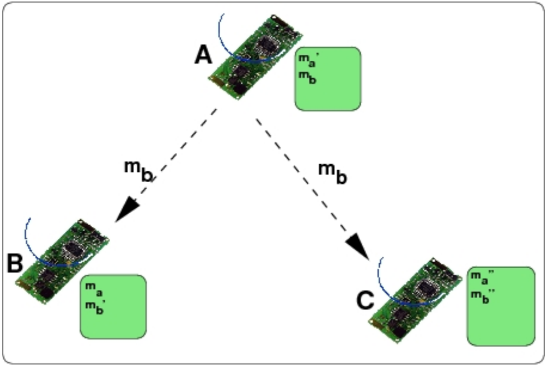
Cooperative transmission
Network coding



- Increase the error tolerance of transmission by network coding
  - Transmission of m_a by node A

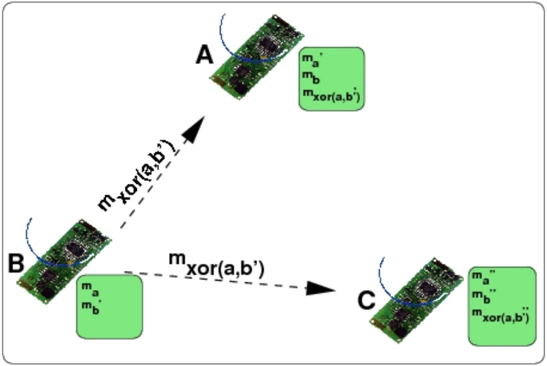
Cooperative transmission

Network coding



- Increase the error tolerance of transmission by network coding
  - Transmission of m_b by node B

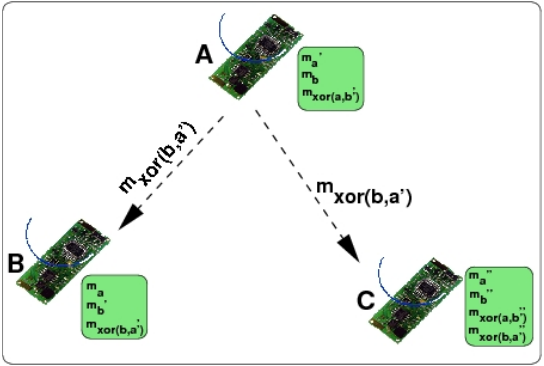
Cooperative transmission
Network coding



- Increase the error tolerance of transmission by network coding
  - Transmission of $m_{XOR(m_a, m_b')}$ by node A

Cooperative transmission

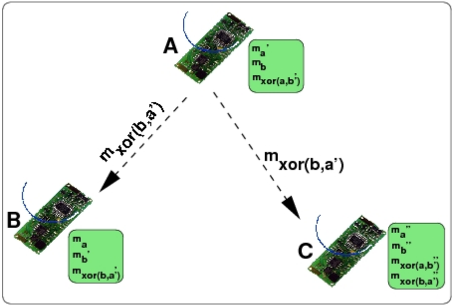
Network coding



- Increase the error tolerance of transmission by network coding
  - Transmission of $m_{XOR(m_b, m_a')}$ by node B

Cooperative transmission

Network coding



- Node C now holds the copies
  - m_a''
  - m_b''
  - $m'_{XOR(m_a, m_b')}$
  - $m'_{XOR(m_b, m_a')}$

Cooperative transmission

Network coding

- Due to redundant information from the distinct transmissions, the error probability can be reduced

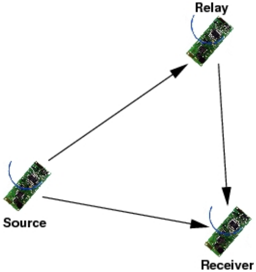
Example

- Assume: 1 bit in received message erroneous with $p_{err} = \frac{1}{m}$
- $m_a(i)''$ and $m_b(i)''$ incorrect with probability $\frac{1}{m}$
- $m_{XOR(m_a, m_b')}(i)'$ incorrect with probability $1 - \left(1 - \frac{1}{m}\right)$
- $m_{XOR(m_b, m_a')}(i)'$ incorrect with probability $1 - \left(1 - \frac{1}{m}\right)$
- Probability that more than one of these is incorrect simultaneously:

$$p_{err}^{all} \leq \frac{1}{m} \cdot \left(1 - \left(1 - \frac{1}{m}\right)^2\right) \leq \frac{1}{m}$$

Cooperative transmission

Multi-hop approaches



	Block 1	Block 2	Block 3	Block 4
Source	$c_1(1, w_1)$	$c_1(w_1, w_2)$	$c_1(w_2, w_3)$	$c_1(w_3, 1)$
Relay	$c_2(1)$	$c_2(w_1)$	$c_2(w_2)$	$c_2(w_3)$

- Multi-hop relaying for cooperative transmission
  - Retransmit received messages by relay node
  - Destination will receive redundant information from relay

Cooperative transmission

Multi-hop approaches

	Block 1	Block 2	Block 3	Block 4
Source	$c_1(1, w_1)$	$c_1(w_1, w_2)$	$c_1(w_2, w_3)$	$c_1(w_3, 1)$
Relay	$c_2(1)$	$c_2(w_1)$	$c_2(w_2)$	$c_2(w_3)$

- Message w is divided into B blocks $w_1, \ldots, w_B$
- Transmission in $B + 1$ blocks using codewords $c_1(w_i, w_j)$ and $c_2(w_i)$
- Relay node always transmits word w_i recently overheard from source node
- Source node encodes w_i and w_j

Cooperative transmission

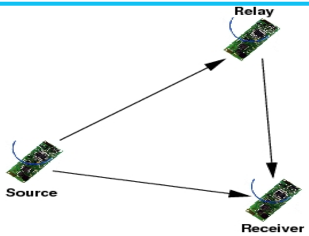
Multi-hop approaches

	Block 1	Block 2	Block 3	Block 4
Source	$c_1(1, w_1)$	$c_1(w_1, w_2)$	$c_1(w_2, w_3)$	$c_1(w_3, 1)$
Relay	$c_2(1)$	$c_2(w_1)$	$c_2(w_2)$	$c_2(w_3)$

- Both $c_1(w_i, w_j)$ and $c_2(w_i)$ depend on w_i
- Coding and decoding functions known by all nodes
- Redundant transmission, since each w_i is transmitted twice
- Strength of encoding dependent on channel characteristic

Cooperative transmission

Multi-hop approaches



- Approach optimally divides network ressources[1]
- In larger multi-hop scenarios not suited:
  - Count of successfully transmitted bits per square meter decreases quadratically with network size[2] [3]

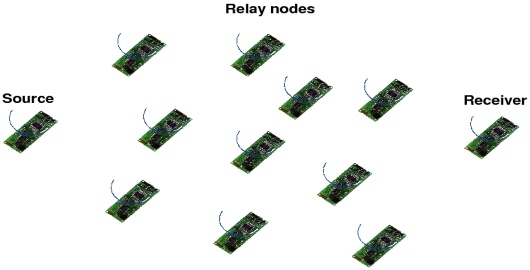
[1] A. del Coso, U. Sagnolini, C. Ibars: Cooperative distributed MIMO channels in wireless sensor networks. IEEE Journal on Selected Areas in Communications, 25(2), 2007, 402-414

[2] A. Scaglione, Y.W. Hong: Cooperative models for synchronisation, scheduling and transmission in large scale sensor networks: An overview. In: 1st IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing. (2005) 60-63

[3] P. Gupta, R.P. Kumar: The capacity of wireless networks. IEEE Transactions on Information Theory, 46(2), 2000, 388-404

Cooperative transmission

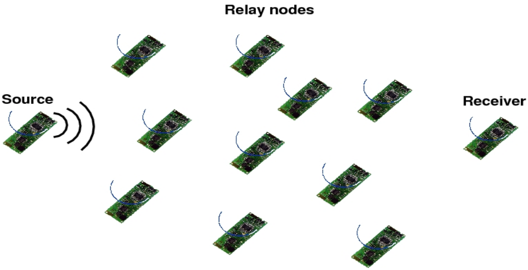
Data flooding



- Opportunistic large arrays
  - One source node
  - One receive node
  - Many relay nodes

Cooperative transmission

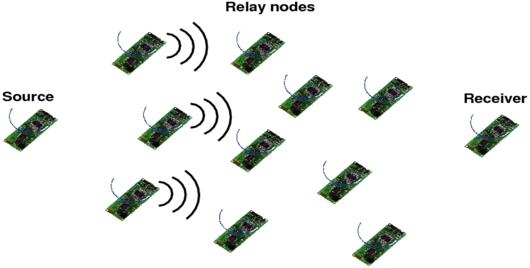
Data flooding



- Opportunistic large arrays
  - Each node retransmits message at reception

Cooperative transmission

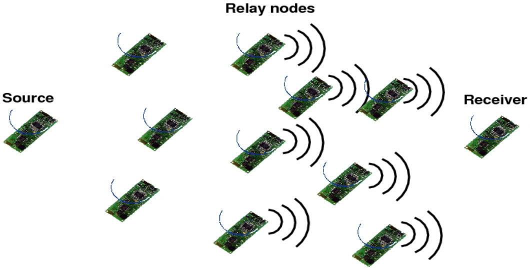
Data flooding



- Opportunistic large arrays
  - Network is flooded by nodes retransmitting a received message

Cooperative transmission

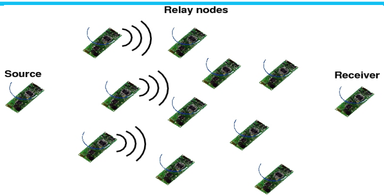
Data flooding

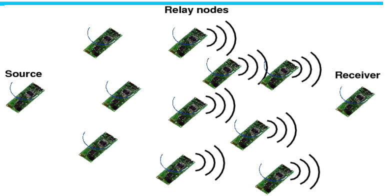


- Opportunistic large arrays
  - Avalance of signals proceeded through the network
  - When network sufficiently dense, signals superimpose
  - With special OLA modulations, it is then even possible to encode information onto the signal wave
  - Outperforms non-cooperative multi-hop schemes significantly
  - Transmission scheme robust to environmental noise

Cooperative transmission

Data flooding





- Opportunistic large arrays
  - Average energy consumption of nodes decreased[4] [5]
  - Transmission time reduced compared to traditional transmission protocols[6]
  - Not capable of coping with moving receivers due to inherent randomness of the protocol

[4] Y.W. Hong, A. Scaglione: Critical power for connectivity with cooperative transmission in wireless ad hoc sensor networks. In: IEEE Workshop on Statistical Signal Processing, 2003

[5] Y.W. Hong, A. Scaglione: Energy-efficient broadcasting with cooperative transmission in wireless sensor networks. IEEE Transactions on Wireless communications, 2005

[6] Y.W. Hong, A. Scaglione: Cooperative transmission in wireless multi-hop ad hoc networks using opportunistic large arrays. In: SPAWC, 2003

Outline

Cooperative transmission schemes

1. Cooperative transmission
   - Network coding
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2. Multiple antenna techniques
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Multiple antenna techniques

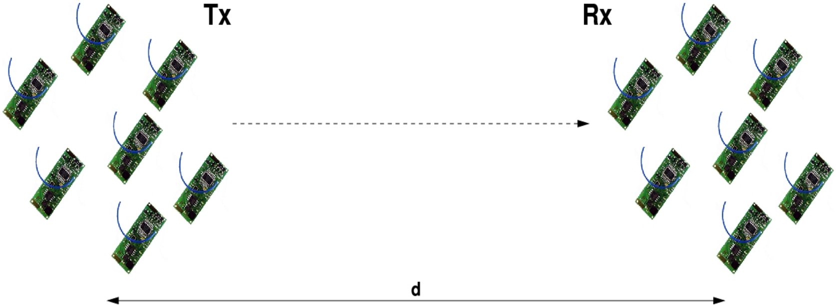
Introduction

- MIMO systems achieve higher data rates than SISO systems
- Vital requirement:
  - Independent transmission channels
  - Spatial separation of antennas: $> \frac{\lambda}{2}$
  - Not feasible on single sensor nodes
- Alternative:
  - Utilise antennas from several distributed nodes to form one transmitter

Multiple antenna techniques
Virtual MIMO

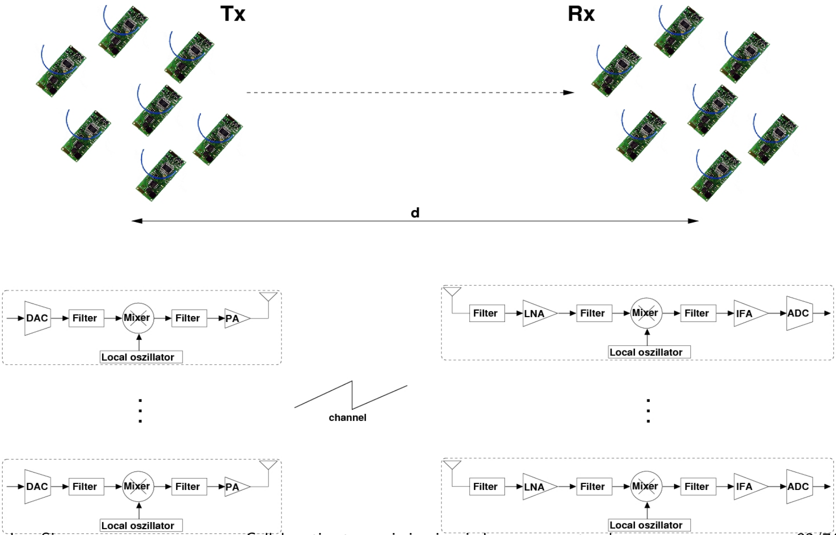
- Multiple antenna techniques
  - Virtual MIMO
  - Open-loop distributed carrier synchronisation
  - Closed-loop distributed carrier synchronisation

Multiple antenna techniques
Virtual MIMO



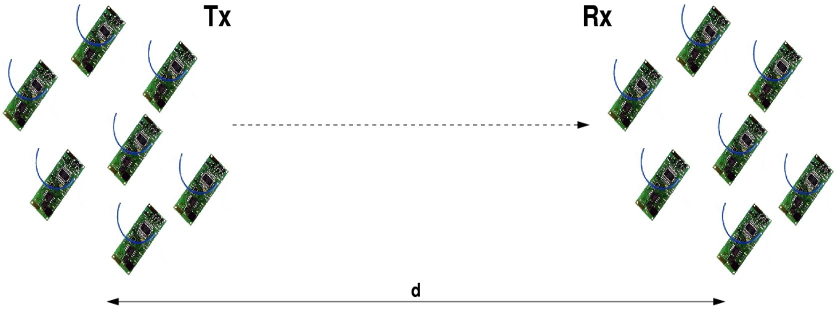
- Virtual MIMO:
  - Apply MIMO transmission scheme to a scenario of distributed transmitters and receivers
  - Utilisation of Alamouti diversity codes

Multiple antenna techniques
Virtual MIMO



Multiple antenna techniques

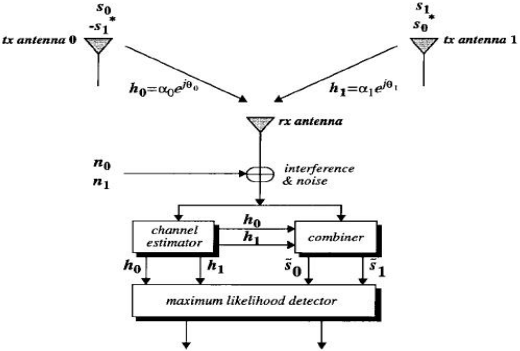
Virtual MIMO



- Problem:
  - Distributed nodes utilise non-synchronised local oscillators
  - Frequency and phase of distributed nodes differ

Multiple antenna techniques

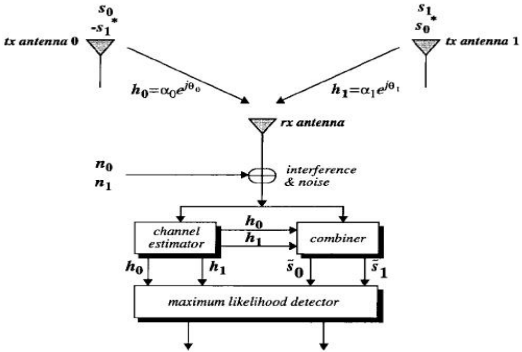
Virtual MIMO



- Alamouti diversity scheme for two receivers
  - Channel estimator
  - Combiner
  - Maximum likelihood detector

Multiple antenna techniques

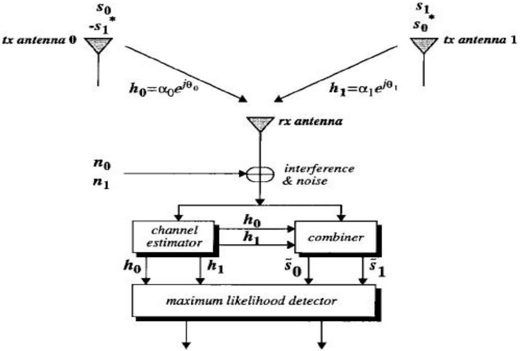
Virtual MIMO



- Both transmit nodes will simultaneously transmit signals s_0 and s_1 at time t

Multiple antenna techniques

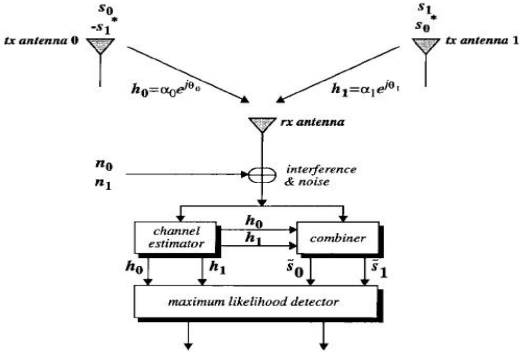
Virtual MIMO



- At time $t + T$, both transmit signals $-s_1^*$ and s_0^*
- Space-time coding
- Frequency-time coding also possible

Multiple antenna techniques

Virtual MIMO



- Channel modelled by complex multiplicative distortion $H_A(t)$ and $H_B(t)$

Multiple antenna techniques

Virtual MIMO

- Assumption: Fading constant over one symbol period:

$$
\begin{aligned}
H_A(t) &= H_A(t+T) = H_A = \alpha_A e^{j\Theta_A} \\
H_B(t) &= H_B(t+T) = H_B = \alpha_B e^{j\Theta_B}
\end{aligned}
$$

- Received signals at t and $t+T$

$$
\begin{aligned}
r_0 &= r(t) = H_A s_0 + H_B s_1 + n_0 \\
r_1 &= r(t+T) = -H_A s_1^* + H_B s_0^* + n_1
\end{aligned}
$$

- Combiner creates the signals

$$
\begin{aligned}
\overline{s_0} &= H_A^* r_0 + H_B r_1^* = (\alpha_A^2 + \alpha_B^2) s_0 + H_A^* n_0 + H_B n_1^* \\
\overline{s_1} &= H_B^* r_0 - H_A r_1^* = (\alpha_A^2 + \alpha_B^2) s_1 - H_A n_1^* + H_B^* n_0
\end{aligned}
$$

Multiple antenna techniques

Virtual MIMO

- This is forwarded to the maximum likelihood detector. Decision rules:
  - Choose s_i iff

$$\begin{aligned} & (\alpha_0^2 + \alpha_1^2 - 1)|s_i|^2 + d^2(\overline{s_0}, s_i) \\ \leq \quad & (\alpha_0^2 + \alpha_1^2 - 1|s_k|^2 + d^2(\overline{s_0}, s_k), \\ & \forall i \neq k \end{aligned}$$

  - Choose s_i iff

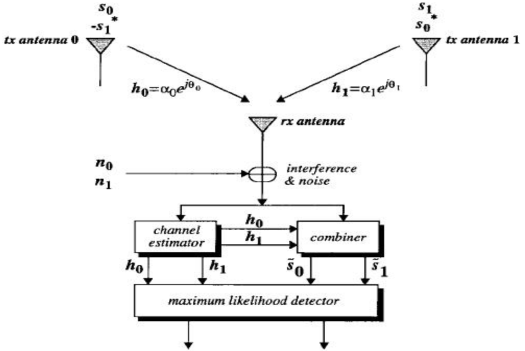
$$d^2(\overline{s_0}, s_i) \leq d^2(\overline{s_0}, s_k), \forall i \neq k$$

- $d^2(s_i, s_j)$ is the squared Euclidean distance between s_i and s_j:

$$d^2(s_i, s_j) = (s_i - s_j)(s_i^* - s_j^*)$$

Multiple antenna techniques

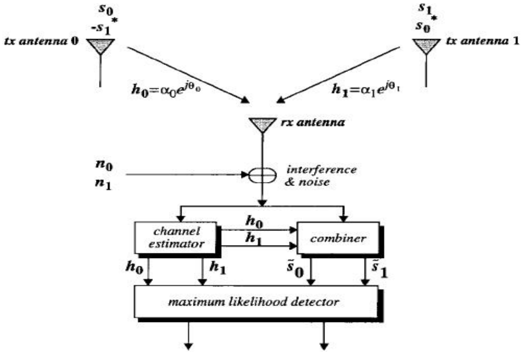
Virtual MIMO



- In virtual MIMO schemes: Each node has preassigned index i
- Node i transmits sequence of i-th Alamouti antenna
- Receiver nodes join received sum signal cooperatively

Multiple antenna techniques

Virtual MIMO



- Nodes cooperate in clusters
- Cluster seen as single multiple antenna device
- MIMO, SIMO and MISO transmission possible

Multiple antenna techniques

Virtual MIMO

- Complexity reduced by grouping of nodes
- This scheme more energy efficient than traditional SISO transmission between nodes of a network [7] [8]
- Utilisation of existing routing algorithms possible when cluster is understood as minimum entity
- However, capacity of sensor network decreased compared to other approaches for cooperative transmission [9] [10]

[7] L. Pillutla, V. Krishnamurthy: Joint rate and cluster optimisation in cooperative MIMO sensor networks. In: Proceedings of the 6th IEEE Workshop on signal Processing Advances in Wireless Communications, 2005, 265-269

[8] A. del Coso, U. Sagnolini, C. Ibars: Cooperative distributed mimo channels in wireless sensor networks. IEEE Journal on Selected Areas in Communications 25(2), 2007, 402-414

[9] P. Mitran, H. Ochiai, V. Tarokh: Space-time diversity enhancements using collaborative communications. IEEE Transactions on Information Theory 51(6), 2005, 2041-2057

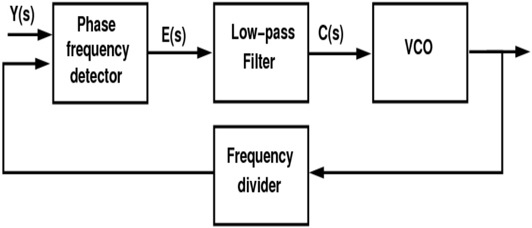
[10] M. Gastpar, M. Vetterli: On the capacity of wireless networks: the relay case. In: Proceedings of the IEEE Infocom, 2002, 1577-1586

Multiple antenna techniques

Virtual MIMO

- For virtual MIMO schemes it was presumed that local oscillators are synchronised
  - Local oscillator multiplies frequency of crystal oscillator up to fixed nominal frequency
  - Carrier frequencies generated in this manner typically vary in the order of 10-100 parts per million (ppm)
  - If uncorrelated, these frequency variations are catastrophic for transmit beamforming
  - Phases of signals drift out of phase over the duration of the transmission
- Possible solution:
  - Master-slave architecture
  - Slave source nodes use phase-locked loops (PLLs) to lock phase and frequency to a reference carrier.

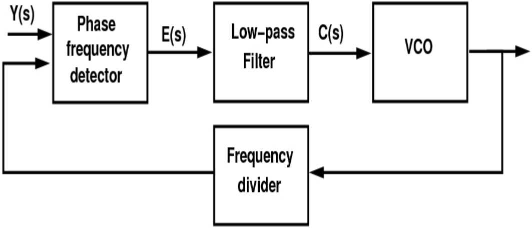
Multiple antenna techniques
Virtual MIMO



- Phase locked loop (PLL):
  - A simple PLL consists of three components:
    - Phase detector
    - Feedback path
    - Variable electronic oscillator

Multiple antenna techniques

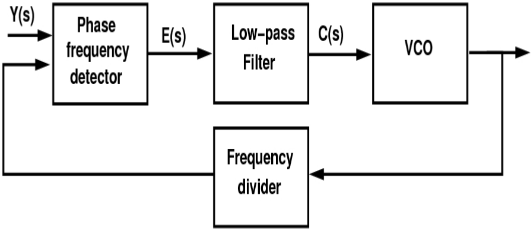
Virtual MIMO



- Phase detector
  - Compares the phase offset between the input signal $Y(s)$ and the oscillator
  - Computes an output signal $E(s)$ (Error signal) proportional to phase offset
  - When no phase offset: $E(s) = 0$

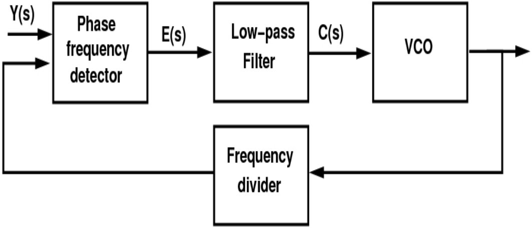
Multiple antenna techniques

Virtual MIMO



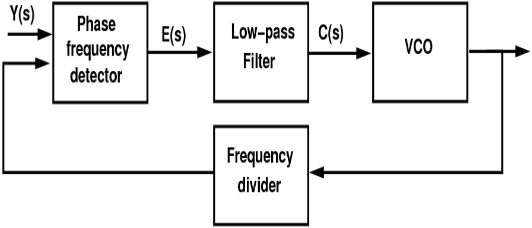
- Filter
  - Feeds the error signal $E(s)$ into the function $F(s)$
  - Creates the control signal $C(s)$ at its output

Multiple antenna techniques
Virtual MIMO



- Variable electronic oscillator
  - Often in the form of a Voltage Controlled Oscillator (VCO)
  - Frequency adapted e.g. by capacity diode
  - Digital PLLs utilise Numerically Controlled Oscillators (NCO)

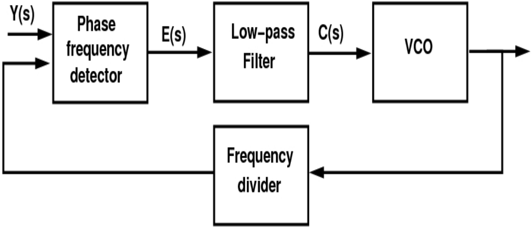
Multiple antenna techniques
Virtual MIMO



- Frequency divider
  - Takes input signal with frequency, f_{in}
  - Generates an output signal with frequency $f_{out} = \frac{f_{in}}{n}$
  - $n \in \mathbb{N}$

Multiple antenna techniques

Virtual MIMO



- With this structure, an adaptation of the oscillator frequency to a reference signal is possible

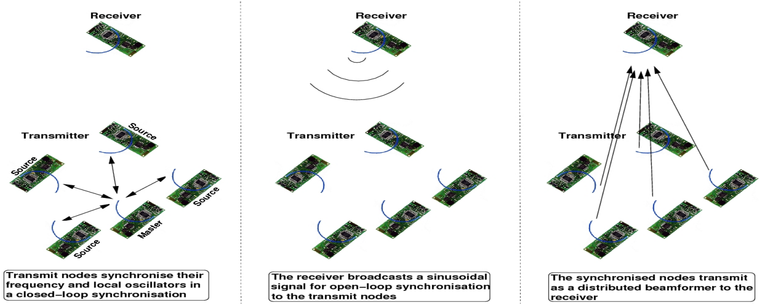
Multiple antenna techniques

Open-loop distributed carrier synchronisation

- Open-loop distributed carrier synchronisation
  - Master-slave open-loop distributed carrier synchronisation
  - Carrier synchronisation with fixed locations of distributed nodes
  - Carrier synchronisation with unknown locations
  - round-trip open-loop distributed carrier synchronisation

Multiple antenna techniques

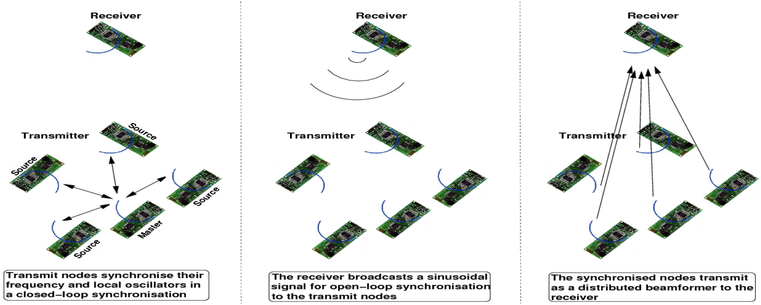
Open-loop distributed carrier synchronisation



- Master-slave open-loop distributed carrier synchronisation
  1. Initially, one transmitter is identified as master node
  2. Other transmitters are slaves
  3. Master and slave nodes synchronise their frequency and local oscillators

Multiple antenna techniques

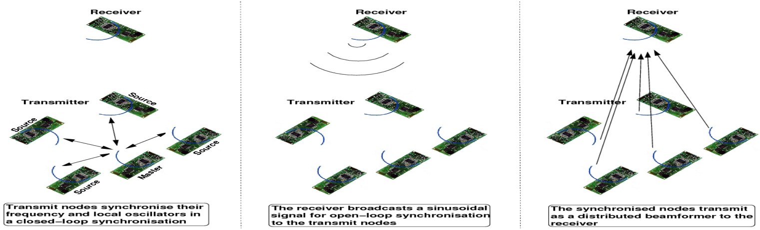
Open-loop distributed carrier synchronisation



- Master-slave open-loop distributed carrier synchronisation
  - Frequency synchronisation:
    - Master node broadcasts sinusoidal signal to slave nodes
    - Slave nodes estimate and correct relative frequency offset of the signal
    - Phase synchronisation over PLL

Multiple antenna techniques

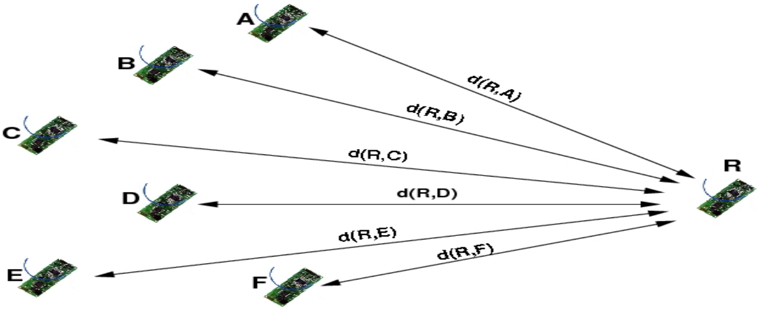
Open-loop distributed carrier synchronisation



- Master-slave open-loop distributed carrier synchronisation
  - Achieve beamforming:
    - Transmitters estimate their channel response to the destination (E.g. by destination broadcasts sinusoidal signal)
    - Transmitters are already synchronised and estimate their individual complex channel gain to destination
    - Transmission as distributed beamformer by applying the complex conjugate of the gains to their transmitted signals

Multiple antenna techniques

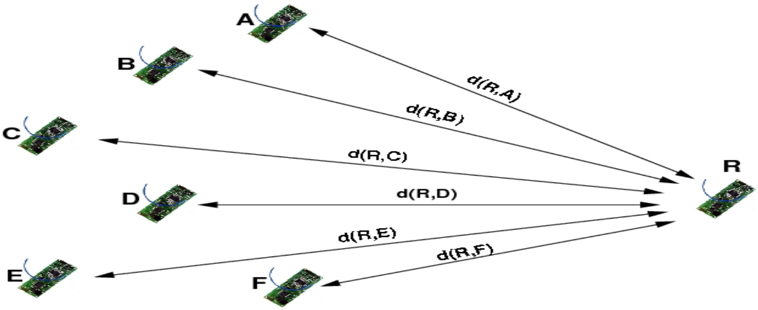
Open-loop distributed carrier synchronisation



- Carrier localisation with fixed locations of distributed nodes
    - Distance between receiver node and transmit nodes known
    - Line-of-sight (LOS) connections

Multiple antenna techniques

Open-loop distributed carrier synchronisation



- Receiver node serves as a master
- Master broadcasts carrier and timing signals
- Slave node i at distance $d(i) = d_0(i) + d_e(i)$ to the master

Multiple antenna techniques

Open-loop distributed carrier synchronisation

- Master node broadcasts signal

$$\Re\left(m(t)e^{j(2\pi f_0 t)}\right)$$

- Slave node i receives noisy signal

$$\Re\left(n_i(t)m(t)e^{j(2\pi f_0 t+\gamma_0(i)+\gamma_e(i))}\right)$$

- Phase offset from transmitted carrier

$$\gamma_0(i) = \frac{2\pi f_0 d_0}{c} = \frac{2\pi d_0}{\lambda_0}$$

- Phase error resulting from placement error $d_e(i)$

$$\gamma_e(i) = \frac{2\pi f_0 d_i(i)}{c} = \frac{2\pi d_i(i)}{\lambda_0}$$

Multiple antenna techniques

Open-loop distributed carrier synchronisation

- Each transmit node applies a PLL to lock on to the carrier with the result

$$\Re\left(n_i(t)m(t)e^{j(2\pi f_0 t+\gamma_\Delta(i))}\right)$$

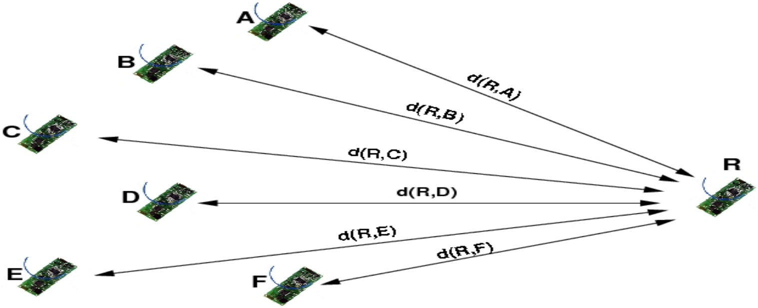
- With:

$$\gamma_\Delta(i)=\gamma_0(i)+\gamma_e(i)-\gamma_{pll}(i)$$

- Phase variations among slaves originate from placement errors and PLL errors.
- When locations are sufficiently well known and fixed, phase synchronisation possible

Multiple antenna techniques

Open-loop distributed carrier synchronisation



- Sufficiently accurate location information required
- No movement of nodes

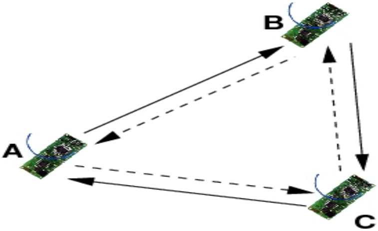
Multiple antenna techniques

Open-loop distributed carrier synchronisation

- Carrier localisation with unknown locations
    - When distance estimation among nodes is sufficiently accurate, the previous approach is feasible
    - In advance of synchronising carrier phase offsets, clock offsets of nodes are estimated by a standard relative positioning approach
    - Shortcomings
        - Relative positioning typically not very accurate
        - Only low velocity allowed
        - Energy consuming

Multiple antenna techniques

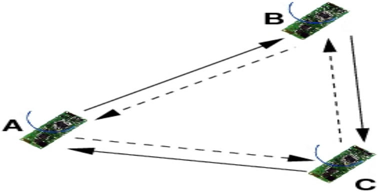
Open-loop distributed carrier synchronisation



- Round-tip open-loop distributed carrier synchronisation
  - Phase synchronisation between two sources nodes and one receiver node
  - High mobility of nodes supported

Multiple antenna techniques

Open-loop distributed carrier synchronisation



- Destination node C broadcasts a sinusoidal beacon signal

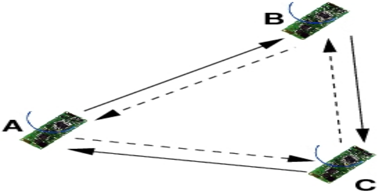
$$\Re\left(m(t)e^{j(2\pi f_0 t+\gamma_0)}\right)$$

- Received signals at the nodes

$$\Re\left(m(t)e^{j(2\pi f_0 t+\gamma_0^A)}\right) \text{ and } \Re\left(m(t)e^{j(2\pi f_0 t+\gamma_0^B)}\right)$$

Multiple antenna techniques

Open-loop distributed carrier synchronisation

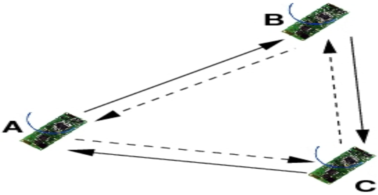


- Nodes A and B employ PLL tuned onto beacon frequency f_0
- Nodes A and B generate low-power secondary sinusoidal beacon signal that is phase locked to received beacon signal with frequencies

$$f_1^A = \frac{N_1^A}{M_1^A} f_0^A \text{ and } f_1^B = \frac{N_1^B}{M_1^B} f_0^B$$

Multiple antenna techniques

Open-loop distributed carrier synchronisation



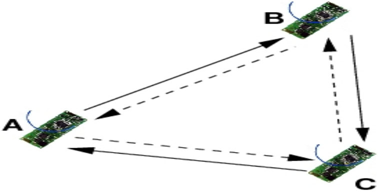
- At receiving a secondary beacon signal, Nodes A and B generate a new carrier signal at frequency

$$f_c^A = \frac{N_1^A}{M_1^A} \cdot f_1^B = f_c^B = \frac{N_1^B}{M_1^B} \cdot f_1^A$$

that is phase locked to the beacon signal

Multiple antenna techniques

Open-loop distributed carrier synchronisation

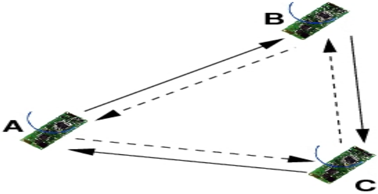


- These carrier signals are utilised to transmit to destination node
- Received signal at the destination:

$$\Re\left(m(t)e^{j(2\pi f_c^A t+\gamma_2^A)} + m(t)e^{j(2\pi f_c^B t+\gamma_2^B)}\right)$$

Multiple antenna techniques

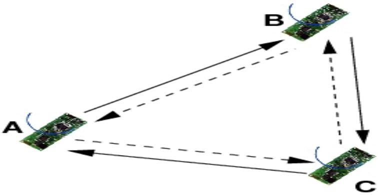
Open-loop distributed carrier synchronisation



- Frequencies from both source nodes are identical
- When round trip times are similar, phase offset $\gamma_{\Delta} = \gamma_2^A - \gamma_2^B$ small

Multiple antenna techniques

Open-loop distributed carrier synchronisation



- Since low delay of round-trip signal propagation: Applicable at high node velocities
- However, only feasible for exactly two source nodes
- Expected maximum gain limited

Multiple antenna techniques

Closed-loop distributed carrier synchronisation

- Full feedback closed-loop carrier synchronisation
  - Carrier frequency synchronisation achieved using a master-slave approach
  - Destination node acts as master
  - Phase offset between destination and i-th source node corrected via closed-loop protocol

Multiple antenna techniques

Closed-loop distributed carrier synchronisation

- Closed-loop carrier synchronisation protocol
  1. Destination broadcasts a beacon to all source nodes
  2. Each source node bounces beacon back to destination on different frequency.
     - Source nodes utilise distinct codes in a DS-CDMA scheme to allow the destination to distinguish received signals
  3. Destination estimates received phase of each source relative to originally transmitted master beacon
     - Destination divides estimates by two
     - quantise them
     - Transmits estimates via DS-CDMA to source nodes as phase compensation message
  4. Source nodes adjust carrier phases accordingly

Multiple antenna techniques

Closed-loop distributed carrier synchronisation

- 1-bit feedback closed-loop carrier synchronisation
  - Iterative process to synchronise phases of transmit signals
  - No inter-node communication
  - Receiver node acts as master node

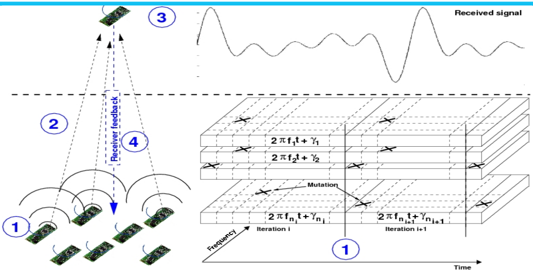
Multiple antenna techniques

Closed-loop distributed carrier synchronisation

- For a network of size n, carrier phase offsets γ_i of transmit signals $e^{j(2\pi(f+f_i)t+\gamma_i)}$; $i \in \{1..n\}$ arbitrarily distributed
- When receiver requests transmission, carrier phases are iteratively synchronised
  - Carrier phase adjustment of source nodes
  - Superimposed transmission
  - Receiver estimates phase synchronisation
  - Receiver broadcasts feedback signal

Multiple antenna techniques

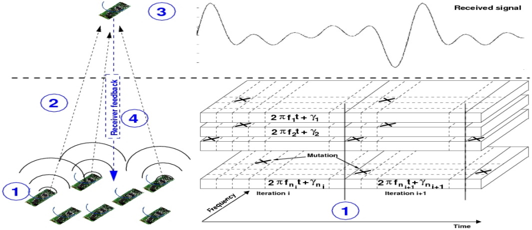
Closed-loop distributed carrier synchronisation



1. Source nodes: Randomly adjust γ_i and f_i
2. Source nodes: Simultaneously transmit to destination
3. Receiver node: Estimate phase synchronisation (e.g. SNR)
4. Feedback and Phase adjustment
    1. Receiver node: Broadcast synchronisation level
    2. Source nodes: Sustain or discard recent phase adjustments

Multiple antenna techniques

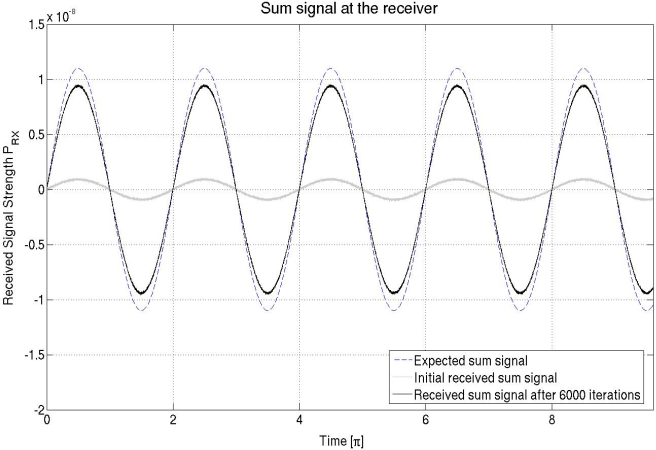
Closed-loop distributed carrier synchronisation



- These four steps iterated repeatedly
- Until stop criteria is reached (e.g.)
  - maximum iteration count
  - sufficient synchronisation
- Adaptation of phase and frequency possible by this approach
- Low computational complexity for source nodes
  - Only phase and frequency adjustments

Multiple antenna techniques

Closed-loop distributed carrier synchronisation



Multiple antenna techniques

Closed-loop distributed carrier synchronisation