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# Collaborative transmission in wireless sensor networks

## Cooperative transmission schemes

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# Overview and Structure

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- 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
  - Alternative algorithmic approaches
  - Alternative Optimisation environments

# Overview and Structure

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- 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
  - Alternative algorithmic approaches
  - Alternative Optimisation environments

# Cooperative transmission schemes

## Introduction

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- 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

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- 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

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

# Cooperative transmission

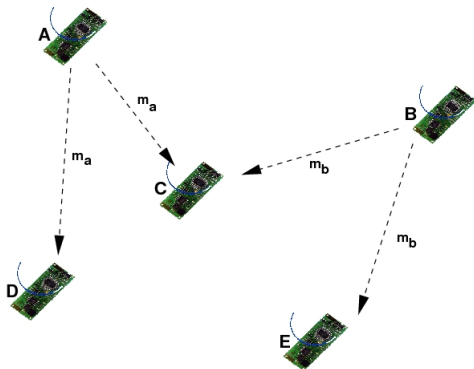
## Network coding

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- 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

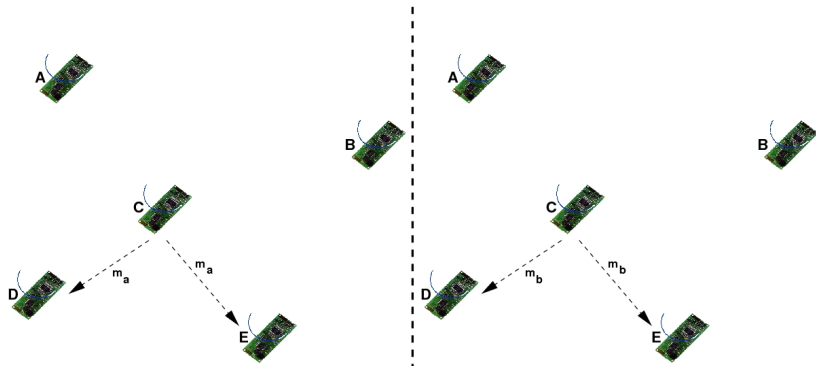


- Nodes A and B transmit messages  $m_a$ ,  $m_b$
- Nodes D and E receive the messages directly
- Node C overhears both messages



# Cooperative transmission

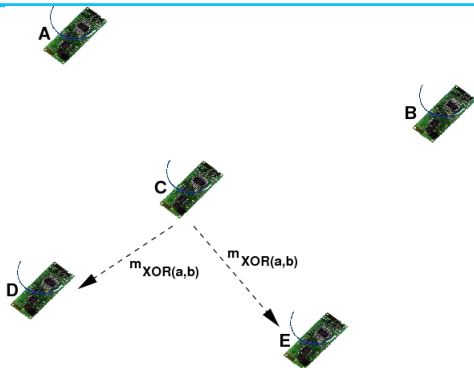
## Network coding



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

# Cooperative transmission

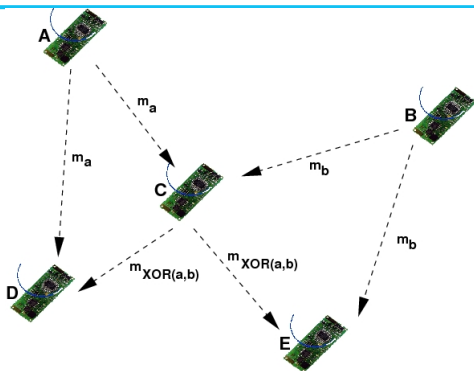
## Network coding



- 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

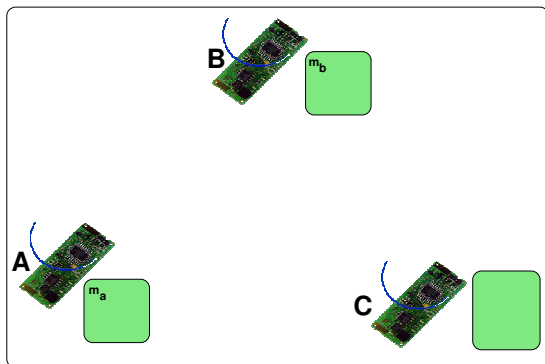
## Network coding



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

# Cooperative transmission

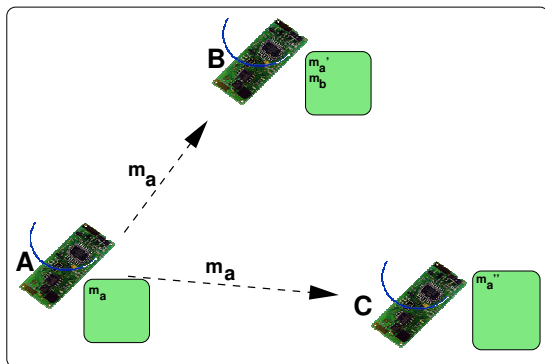
## Network coding



- 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

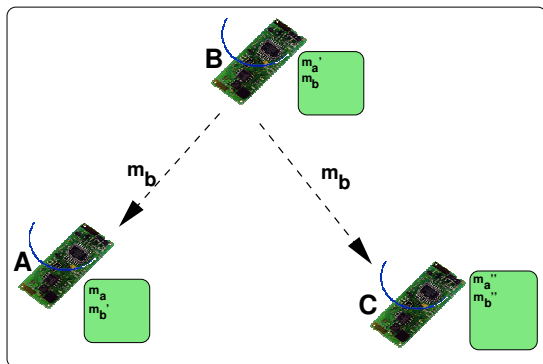
## Network coding



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

# Cooperative transmission

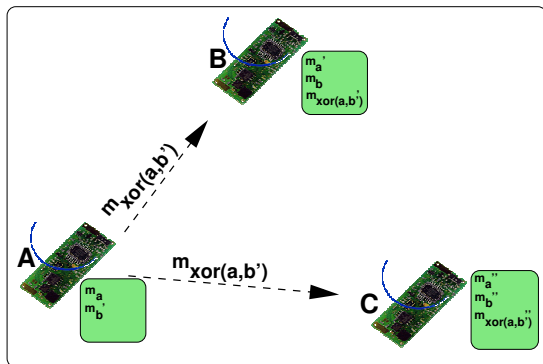
## Network coding



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

# Cooperative transmission

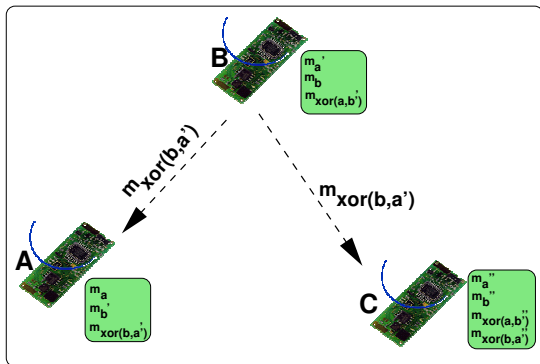
## Network coding



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

# Cooperative transmission

## Network coding

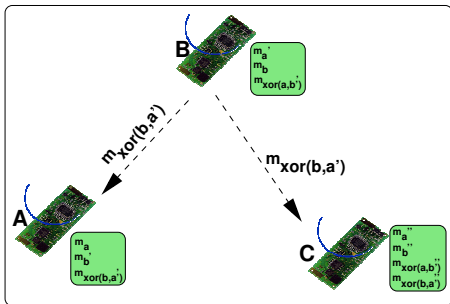


- Increase the error tolerance of transmission by network coding
  - Transmission of  $m_{XOR(m_b, m'_a)}$  by node B



# 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

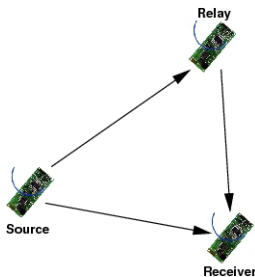
### Example

- 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  $1 - \left(1 - \frac{1}{m}\right)^2$
- $m_{XOR(m_b, m'_a)}(i)'$  incorrect with probability  $1 - \left(1 - \frac{1}{m}\right)^2$
- Probability that more than one of these is incorrect simultaneously:

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

# 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

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	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  $w_1, \dots, w_B$
- 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

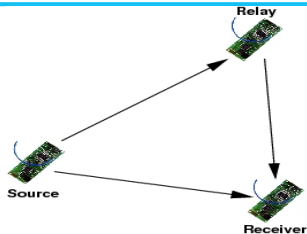
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	Block 1	Block 2	Block 3	Block 4
Source	$c_1(1, w_1)$	$c_1(w_1, w_2)$	$c_1(w_2, w_3)$	$c_1(w_3, 1)$
Relay	$c_2(1)$	$c_2(w_1)$	$c_2(w_2)$	$c_2(w_3)$

- 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 resources<sup>1</sup>
- In larger multi-hop scenarios not suited:
  - Count of successfully transmitted bits per square meter decreases quadratically with network size<sup>2 3</sup>

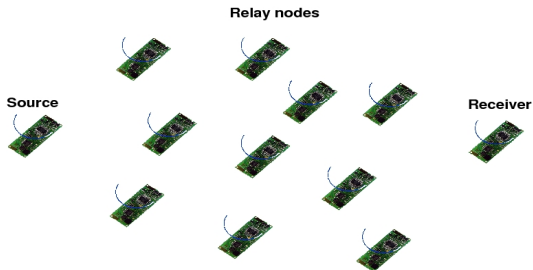
<sup>1</sup> A. del Coso, U. Sagnolini, C. Ibars: Cooperative distributed MIMO channels in wireless sensor networks. IEEE Journal on Selected Areas in Communications, 25(2), 2007, 402-414

<sup>2</sup> 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

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

# Cooperative transmission

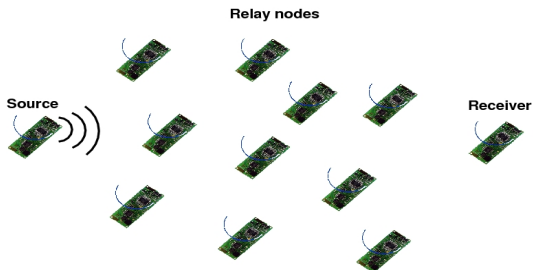
## Data flooding



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

# Cooperative transmission

## Data flooding

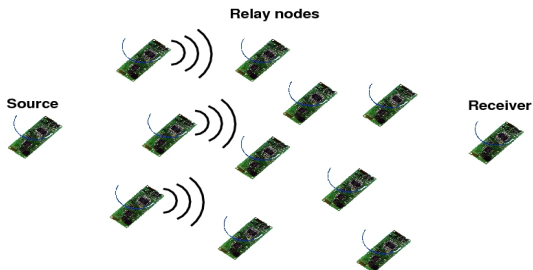


- Opportunistic large arrays
  - Each node retransmits message at reception



# Cooperative transmission

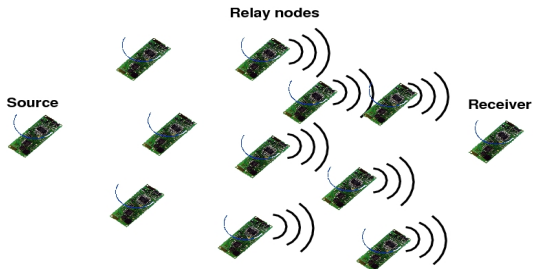
## Data flooding



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

# Cooperative transmission

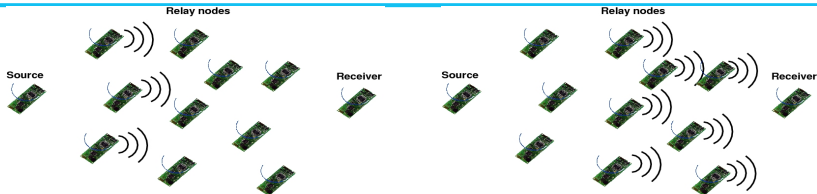
## Data flooding



- Opportunistic large arrays
  - A valance 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<sup>4 5</sup>
  - Transmission time reduced compared to traditional transmission protocols<sup>6</sup>
  - Not capable of coping with moving receivers due to inherent randomness of the protocol

<sup>4</sup>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

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

<sup>6</sup>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

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  - Network coding
  - Multi-hop approaches
  - Data flooding
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  - Virtual MIMO
  - Open-loop distributed carrier synchronisation
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# Multiple antenna techniques

## Introduction

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- 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

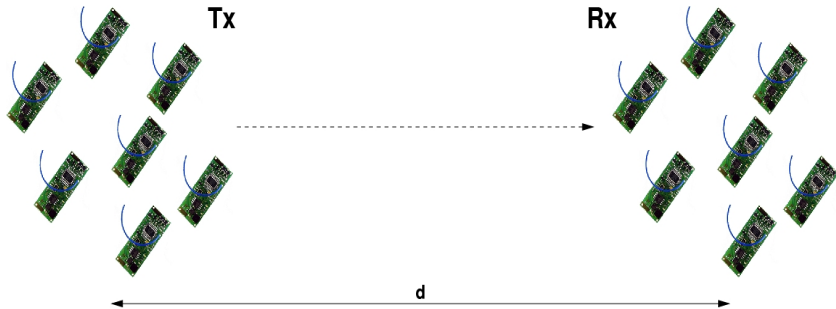
## Virtual MIMO

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

# Multiple antenna techniques

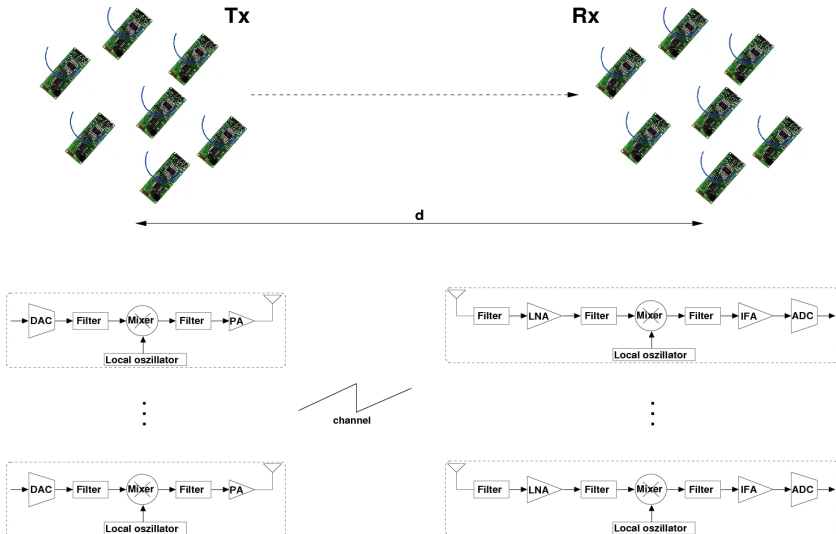
## Virtual MIMO



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

# Multiple antenna techniques

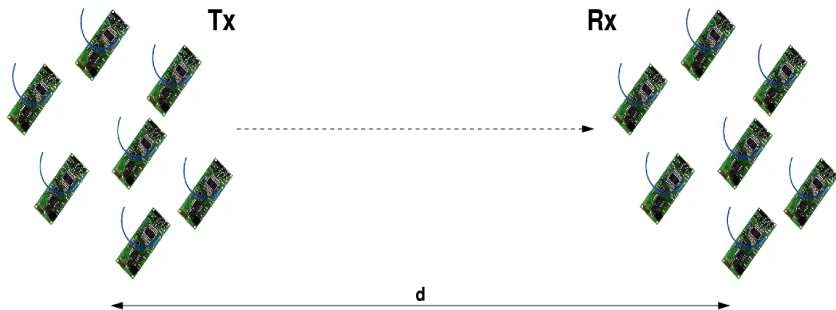
## Virtual MIMO





# Multiple antenna techniques

## Virtual MIMO

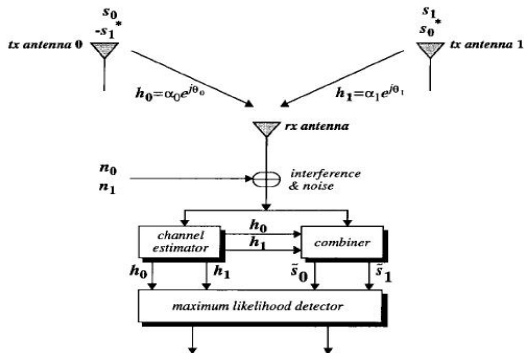


- Problem:

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

# Multiple antenna techniques

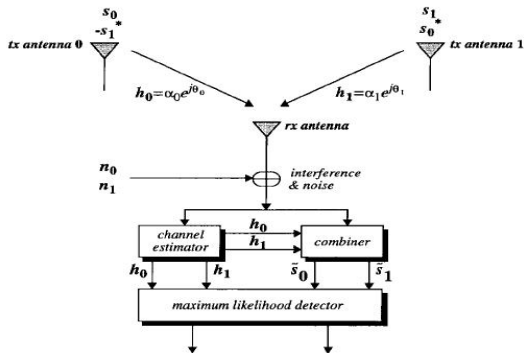
## Virtual MIMO



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

# Multiple antenna techniques

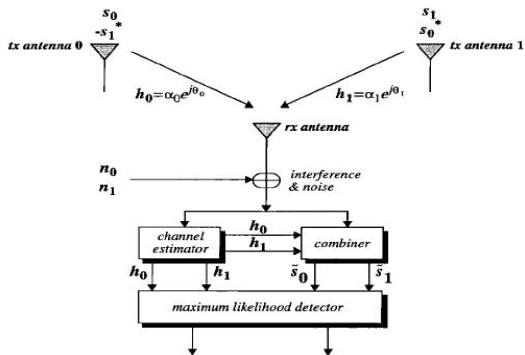
## Virtual MIMO



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

# Multiple antenna techniques

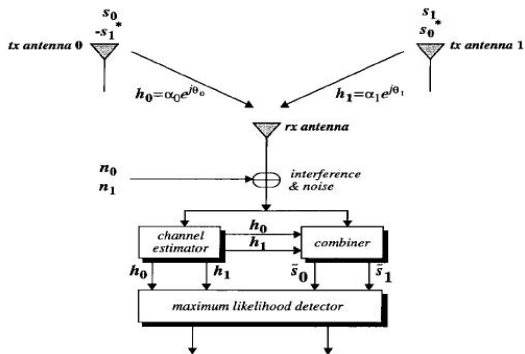
## Virtual MIMO



- 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

$$\begin{aligned}\bar{s}_0 &= H_A^* r_0 + H_B r_1^* = (\alpha_A^2 + \alpha_B^2) s_0 + H_A^* n_0 + H_B n_1^* \\ \bar{s}_1 &= H_B^* r_0 - H_A r_1^* = (\alpha_A^2 + \alpha_B^2) s_1 - H_A n_1^* + H_B^* n_0\end{aligned}$$

# Multiple antenna techniques

## Virtual MIMO

- This is forwarded to the maximum likelihood detector.

Decision rules:

- Choose  $s_i$  iff

$$\begin{aligned} & (\alpha_0^2 + \alpha_1^2 - 1)|s_i|^2 + d^2(\bar{s}_0, s_i) \\ \leq & (\alpha_0^2 + \alpha_1^2 - 1)|s_k|^2 + d^2(\bar{s}_0, s_k), \\ & \forall i \neq k \end{aligned}$$

- Choose  $s_i$  iff

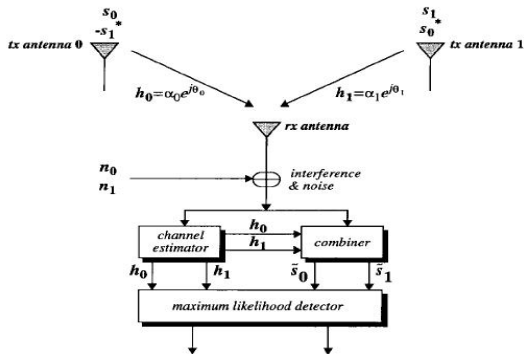
$$d^2(\bar{s}_0, s_i) \leq d^2(\bar{s}_0, s_k), \forall i \neq k$$

- $d^2(s_i, s_j)$  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

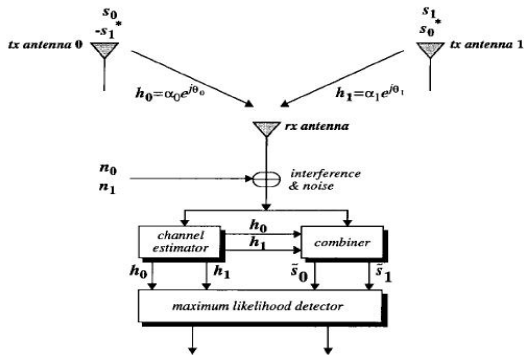


- In virtual MIMO schemes: Each node has preassigned index  $i$
- Node  $i$  transmits sequence of  $i$ -th Alamouti antenna
- Receiver nodes join received sum signal cooperatively



# 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 <sup>7 8</sup>
- 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 <sup>9 10</sup>

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<sup>7</sup> 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

<sup>8</sup> 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

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

<sup>10</sup> 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

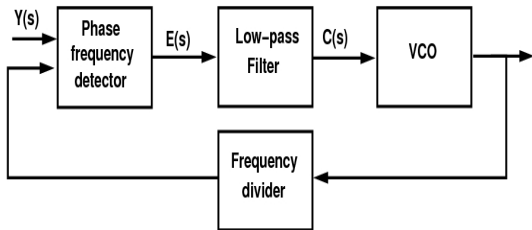
## Virtual MIMO

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- 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

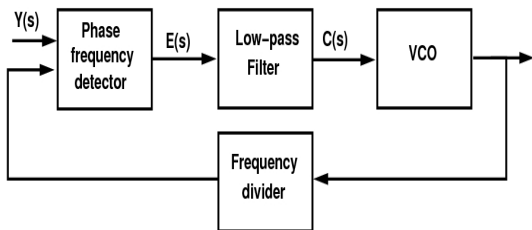
## Virtual MIMO



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

# Multiple antenna techniques

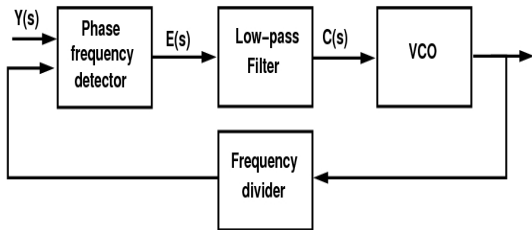
## Virtual MIMO



- 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

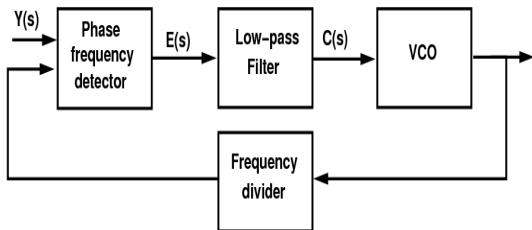
## Virtual MIMO



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

# Multiple antenna techniques

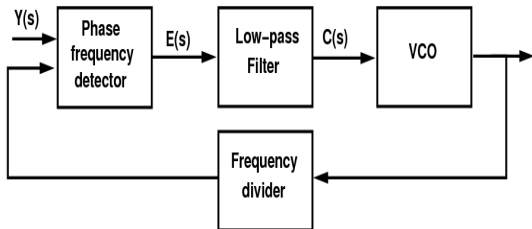
## Virtual MIMO



- 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

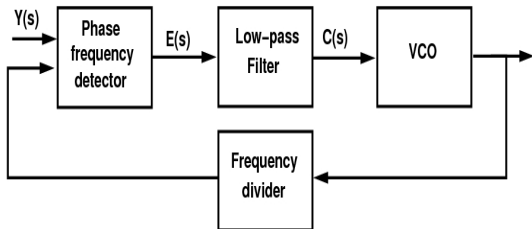


- Frequency divider
  - Takes input signal with frequency,  $f_{in}$
  - Generates an output signal with frequency  $f_{out} = \frac{f_{in}}{n}$
  - $n \in \mathbb{N}$



# Multiple antenna techniques

## Virtual MIMO



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

# Multiple antenna techniques

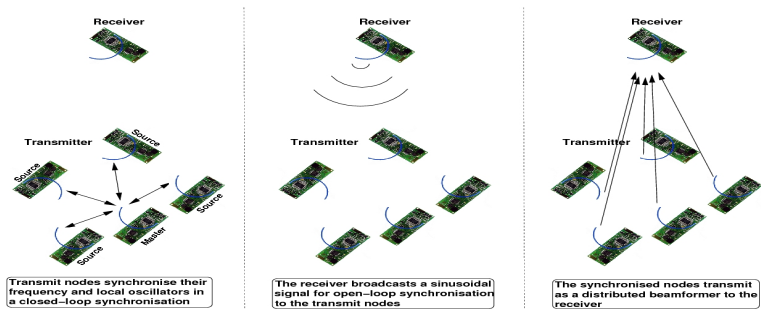
## Open-loop distributed carrier synchronisation

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- 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

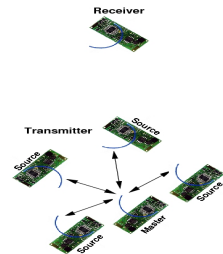
## Open-loop distributed carrier synchronisation



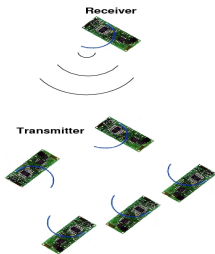
- Master-slave open-loop distributed carrier synchronisation
  - 1 Initially, one transmitter is identified as master node
  - 2 Other transmitters are slaves
  - 3 Master and slave nodes synchronise their frequency and local oscillators

# Multiple antenna techniques

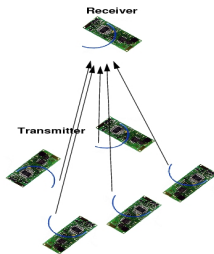
## Open-loop distributed carrier synchronisation



Transmit nodes synchronise their frequency and local oscillators in a closed-loop synchronisation



The receiver broadcasts a sinusoidal signal for open-loop synchronisation to the transmit nodes

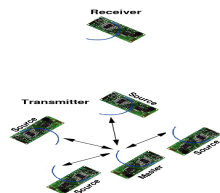


The synchronised nodes transmit as a distributed beamformer to the receiver

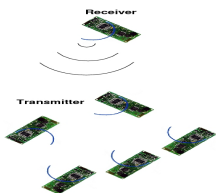
- Master-slave open-loop distributed carrier synchronisation
  - Frequency synchronisation:
    - Master node broadcasts sinusoidal signal to slave nodes
    - Slave nodes estimate and correct relative frequency offset of the signal
    - Phase synchronisation over PLL

# Multiple antenna techniques

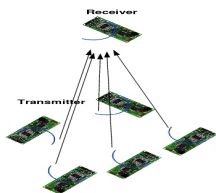
## Open-loop distributed carrier synchronisation



Transmit nodes synchronise their frequency and local oscillators in a closed-loop synchronisation



The receiver broadcasts a sinusoidal signal for open-loop synchronisation to the transmit nodes

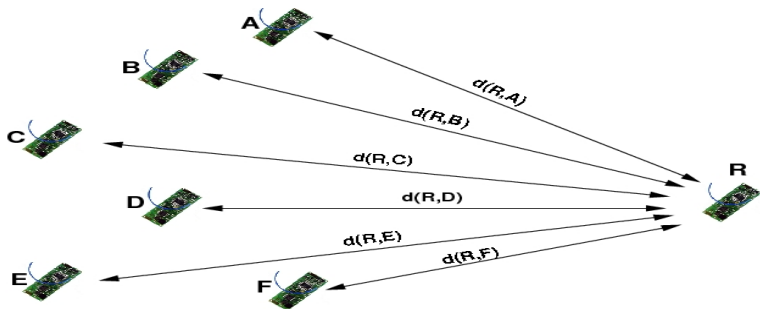


The synchronised nodes transmit as a distributed beamformer to the receiver

- 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

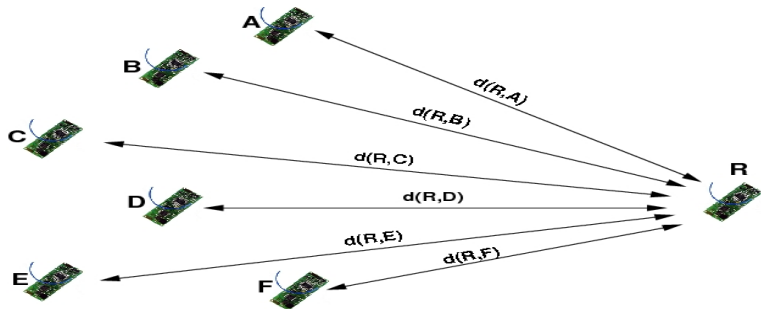
## Open-loop distributed carrier synchronisation



- 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

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- 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

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

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

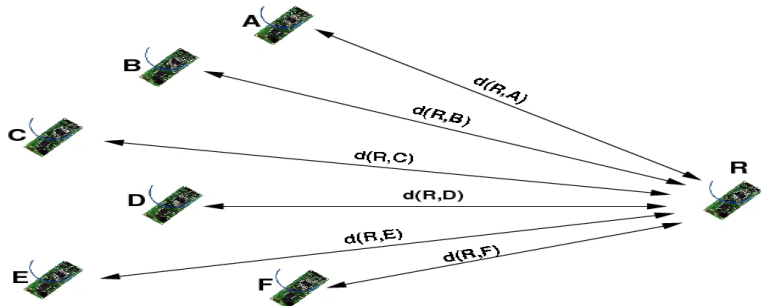
- With:

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

- 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

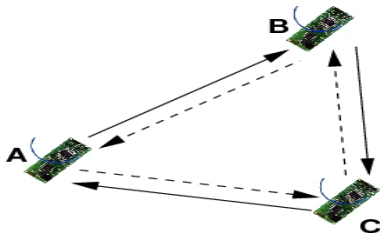
## Open-loop distributed carrier synchronisation

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- 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

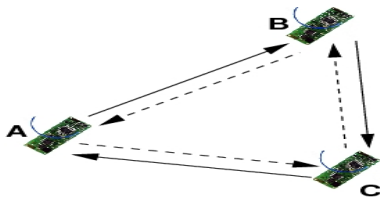
## Open-loop distributed carrier synchronisation



- Round-tip open-loop distributed carrier synchronisation
  - Phase synchronisation between two source 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

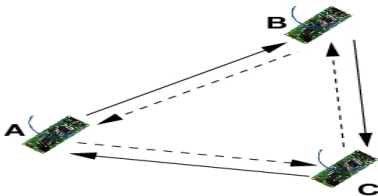
$$\Re \left( m(t) e^{j(2\pi f_0 t + \gamma_0)} \right)$$

- 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

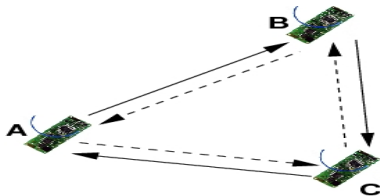


- Nodes A and B employ PLL tuned onto beacon frequency  $f_0$
- Nodes A and B generate low-power secondary sinusoidal beacon signal that is phase locked to received beacon signal with frequencies

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

# Multiple antenna techniques

## Open-loop distributed carrier synchronisation



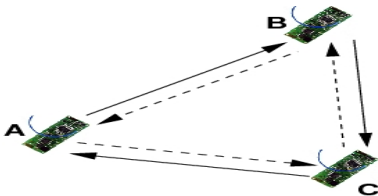
- At receiving a secondary beacon signal, Nodes A and B generate a new carrier signal at frequency

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

that is phase locked to the beacon signal

# Multiple antenna techniques

## Open-loop distributed carrier synchronisation



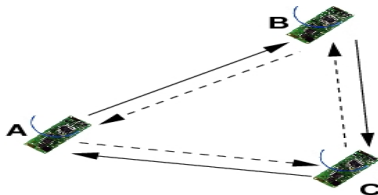
- These carrier signals are utilised to transmit to destination node
- Received signal at the destination:

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



# Multiple antenna techniques

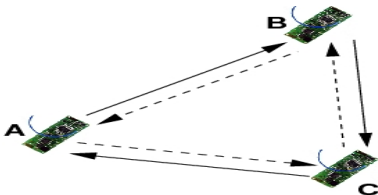
## Open-loop distributed carrier synchronisation



- 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

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- 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

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- 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
    - quantises 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

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- 1-bit feedback based 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

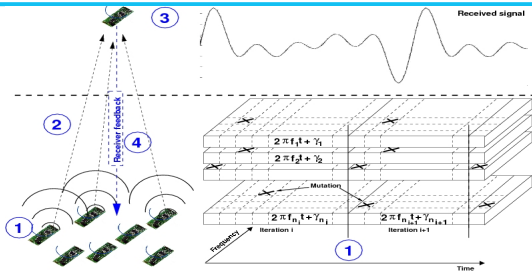
## Closed-loop distributed carrier synchronisation

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- For a network of size  $n$ , carrier phase offsets  $\gamma_i$  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

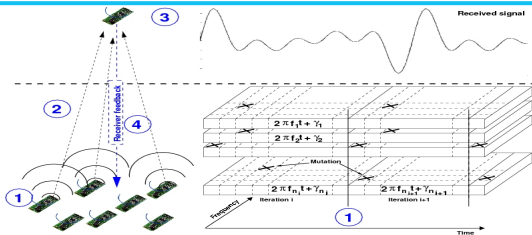
## Closed-loop distributed carrier synchronisation



- 1 Source nodes: Randomly adjust  $\gamma_i$  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

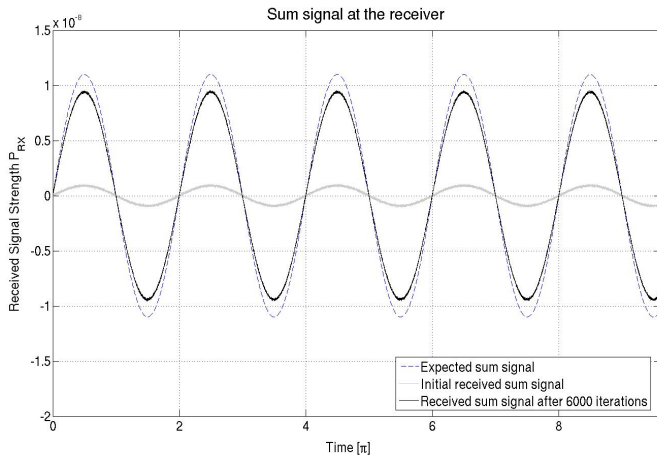


- These four steps iterated repeatedly
- Until stop criteria is reached (e.g.)
  - maximum iteration count
  - sufficient synchronisation
- Adaptation of phase and frequency possible by this approach
- Low computational complexity for source nodes
  - Only phase and frequency adjustments



# Multiple antenna techniques

## Closed-loop distributed carrier synchronisation



# Multiple antenna techniques

## Closed-loop distributed carrier synchronisation

