Collaborative transmission in wireless sensor networks

Alternative algorithmic 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
  - Alternative algorithmic approaches
  - Alternative Optimisation environments

Overview and Structure

- Introduction to context aware computing
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- **Feedback based distributed adaptive beamforming**
  - Feedback based approaches
  - Asymptotic bounds on the synchronisation time
  - **Alternative algorithmic approaches**
  - Alternative Optimisation environments

Outline

Alternative beamforming approaches

1. Hierarchical clustering
2. Local random search
3. An asymptotically optimal algorithm
4. Environmental changes
    - Velocity of nodes
    - Multiple receiver nodes
    - Increased population size
    - Receive beamforming

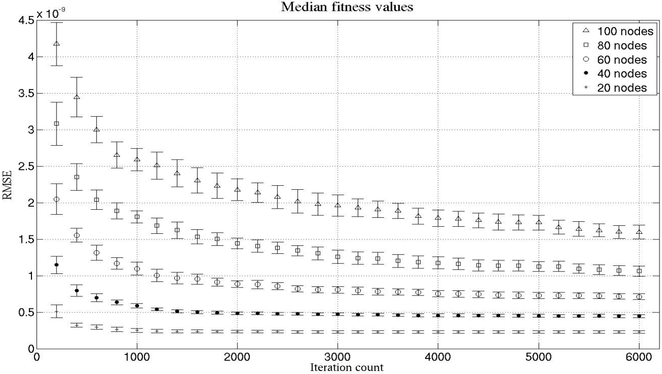
Alternative algorithmic approaches

Hierarchical clustering

- For feedback based distributed adaptive transmit beamforming:
  - RSS_{sum} changes linear with the network size n.
  - Bound on the synchronisation time is more than linear in n

Alternative algorithmic approaches

Hierarchical clustering



$$E[T_{\mathcal{P}}] = \Theta\left(n \cdot k \cdot \log(n)\right)$$

Alternative algorithmic approaches

Hierarchical clustering

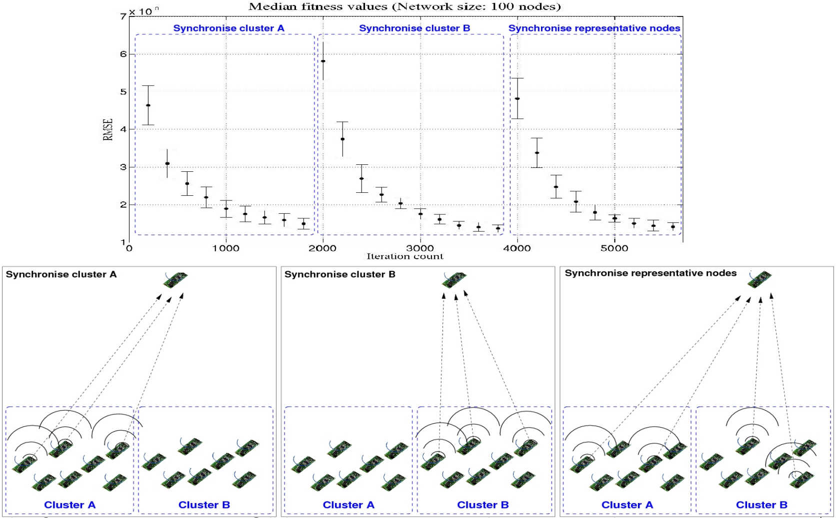
- Hierarchical clustering
  1. Determine clusters
  2. Synchronise clusters successively (with possibly increased transmit power for nodes)
  3. Build and synchronise overlay-cluster of representative nodes from all clusters.
  4. Nodes alter carrier phase by phase offset experienced by representative node:
     - $\zeta_i = \Re\left(m(t)\mathrm{RSS}_i e^{j2\pi f_c t(\gamma_i+\phi_i+\psi_i)}\right)$ (before)
     - $\zeta_i' = \Re\left(m(t)\mathrm{RSS}_i e^{j2\pi f_c t(\gamma_i'+\phi_i+\psi_i)}\right)$ (after)

     Node h from same cluster alters carrier signal
     - $\zeta_h = \Re\left(m(t)\mathrm{RSS}_h e^{j2\pi f_c t(\gamma_h+\phi_h+\psi_h)}\right)$ to
     - $\zeta_h' = \Re\left(m(t)\mathrm{RSS}_h e^{j2\pi f_c t(\gamma_h+\phi_h+\psi_h+\gamma_i-\gamma_i')}\right)$

     Ideal conditions: All nodes should now in phase
  5. Final synchronisation among all nodes

Alternative algorithmic approaches

Hierarchical clustering



Alternative algorithmic approaches

Hierarchical clustering

Potential problem : Phase noise

- Only one cluster synchronised at a time
- Due to practical properties of oscillators, phases of nodes in the inactive clusters experience phase noise and start drifting out of phase
- Sufficient synchronisation possible in the order of milliseconds

Positive :

- No inter-node communication required

Open Issue :

- More than one hierarchy stage might be optimal
- for optimisation time
- for energy consumption
- Optimum hierarchy depth and cluster size derived by integer programming in time $\mathcal{O}(n^2)$

Alternative algorithmic approaches

Hierarchical clustering

Determine optimum cluster size and hierarchy depth :

- Expected optimisation time:
  $E[T_{\mathcal{P}n}] = c \cdot k \cdot n \cdot \log(n)$
- Expected energy consumption:
  $E[\mathcal{E}_{\mathcal{P}n}] = c \cdot k \cdot n \cdot \log(n) \cdot \overline{\mathcal{E}_{\mathcal{P}n}}$

Hierarchy and cluster structure that minimises these formulae optimal

Alternative algorithmic approaches

Hierarchical clustering

Opt. cluster size and hierarchy depth (integer programming) :

- For a cluster size of m:

$$E[T_{\mathcal{P}n}] = E[T_{\mathcal{P}\frac{n}{m}}] \cdot \frac{n}{m} \cdot E[T_{\mathcal{P}m}]$$
$$E[\mathcal{E}_{\mathcal{P}n}] = E[\mathcal{E}_{\mathcal{P}\frac{n}{m}}] \cdot \frac{n}{m} \cdot E[\mathcal{E}_{\mathcal{P}m}].$$

- Define recursion by

$$E_{\text{opt}}[T_{\mathcal{P}n}] = min_m \left[E_{\text{opt}}[T_{\mathcal{P}\frac{n}{m}}] \cdot \frac{n}{m} \cdot E_{\text{opt}}[T_{\mathcal{P}m}]\right]$$
$$E_{\text{opt}}[\mathcal{E}_{\mathcal{P}n}] = min_m \left[E_{\text{opt}}[\mathcal{E}_{\mathcal{P}\frac{n}{m}}] \cdot \frac{n}{m} \cdot E_{\text{opt}}[\mathcal{E}_{\mathcal{P}m}]\right]$$

- Start of recursion (η min feasible cluster size):
  - $E_{\text{opt}}[T_{\mathcal{P}\eta}]$
  - $E_{\text{opt}}[\mathcal{E}_{\mathcal{P}\eta}]$

Alternative algorithmic approaches

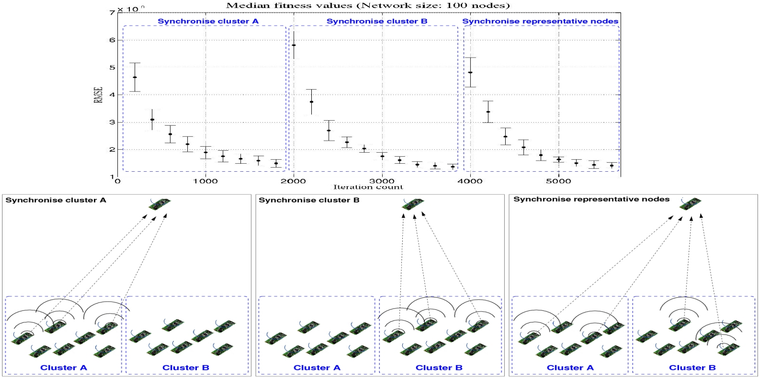
Hierarchical clustering

Opt. cluster size and hierarchy depth (integer programming) :

- Time required for calculation is quadratic.
  - With a network of n nodes, at most n^2 distinct terms
    - $E_{\text{opt}}[T_{\mathcal{P}i}]$
    - $E_{\text{opt}}[\mathcal{E}_{\mathcal{P}i}]$
- Start calculation at
  - $E_{\text{opt}}[\mathcal{E}_{\mathcal{P}\eta}]$
  - $E_{\text{opt}}[T_{\mathcal{P}\eta}]$
- All other values by table loop-up in time $\mathcal{O}(n^2)$ according to
  - $E_{\text{opt}}[T_{\mathcal{P}n}]$
  - $E_{\text{opt}}[\mathcal{E}_{\mathcal{P}n}]$ in time $\mathcal{O}(n^2)$

Alternative algorithmic approaches

Hierarchical clustering



- Reduction of synchronisation time and transmission power
- Calculation of optimum cluster size and depth in $\mathcal{O}(n^2)$

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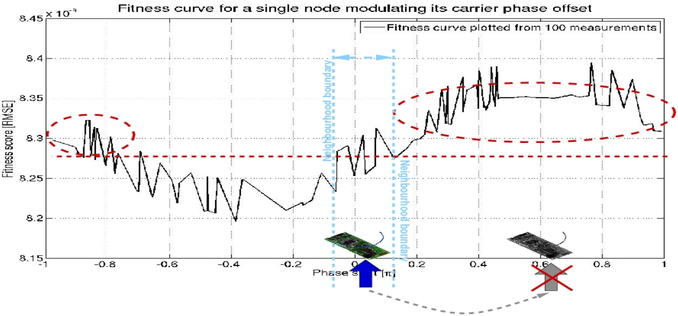
Scenario analysis and algorithmic improvement
Local random search



- Global random search:
    - Synchronisation performance might deteriorate when the optimum is near
- With small local search space:
    - Majority of worse points excluded

Local random search

An upper bound on the synchronisation performance

Assumptions :

Mutation probability: n^{-1}

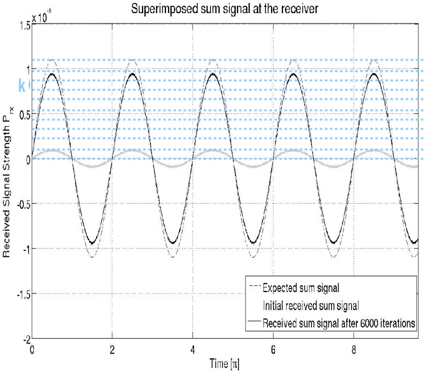
Uniform phase alteration

Initial distance to the optimum :

$\geq \frac{n \cdot \log(k)}{2}$ (Chernoff)

Technical assumption :

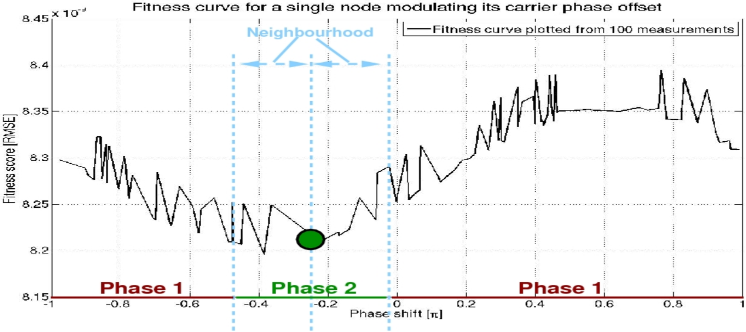
Fitness space divided in k slices of identical width



Local random search

An upper bound on the synchronisation performance

Analysis in two phases for the synchronisation process



Phase 1: Optimum outside search neighbourhood for at least one node

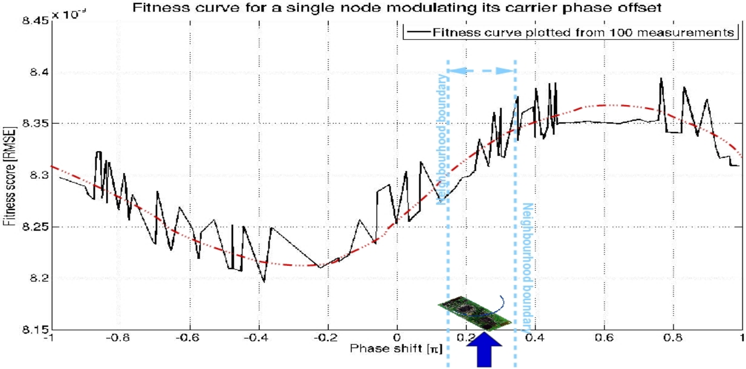
Phase 2: Optimum within search neighbourhood for all nodes

Local random search

An upper bound on the synchronisation performance

Phase 1: Optimum is outside the neighbourhood

- Reach search point with improved fitness: $\geq \frac{1}{2}$



Local random search

An upper bound on the synchronisation performance

When i signals synchronised:

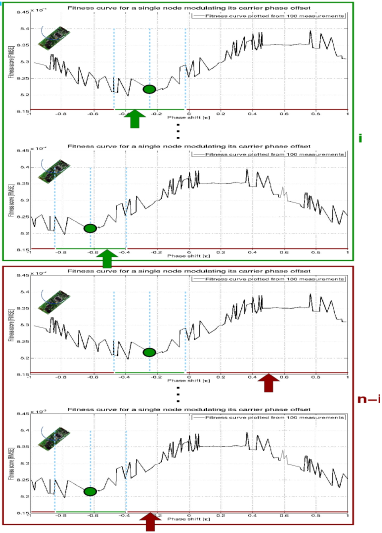
- Improve $n-i$ non-optimal signals
- i already optimal ones unchanged:

$$
\begin{aligned}
& (n-i) \cdot \frac{1}{n} \cdot \frac{1}{2} \cdot \left(1 - \frac{1}{n}\right)^{i} \\
= \quad & \frac{n-i}{2n} \cdot \left(1 - \frac{1}{n}\right)^{i}
\end{aligned}
$$

- since $\left(1 - \frac{1}{n}\right)^{n} < e < \left(1 - \frac{1}{n}\right)^{n-1}$

$$
s_i \geq \frac{n-i}{2en}
$$

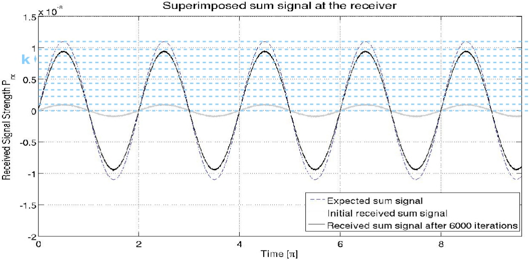
- Expected number of mutations to increase fitness bounded by s_i^{-1}.



Local random search

An upper bound on the synchronisation performance

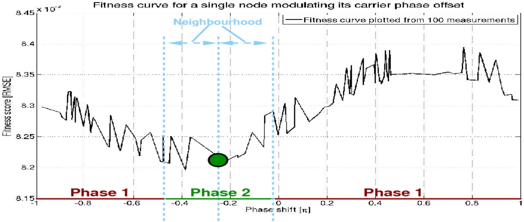
- Time until optimum is within the neighbourhood?
  - Constant time to leave slice
  - k distinct slices



$$
\begin{aligned}
E[T_{\mathcal{P}}] \leq \quad & c \cdot \textstyle\sum_{i=0}^{k} \frac{2en}{n-i} && = 2cen \cdot \sum_{i=1}^{k+1} i^{-1} \\
< \quad & 2cen \cdot \ln(k+1) && = \mathcal{O}\left(n \cdot \log(k)\right)
\end{aligned}
$$

Local random search

An upper bound on the synchronisation performance



Phase 2: Optimum within search neighbourhood

- Worst case: Increase fitness with probability $\frac{1}{N}$
- Similar to consideration above:

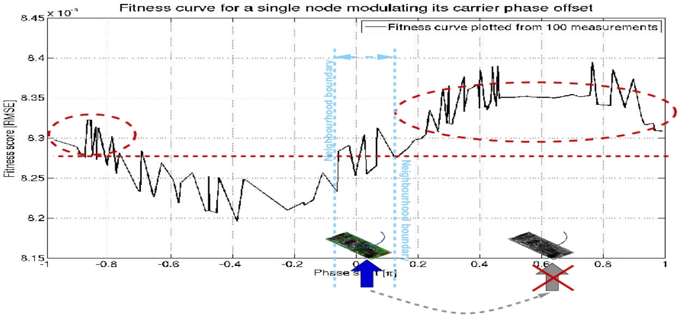
$$\mathcal{O}(N \cdot n \cdot \log(k))$$

Overall synchronisation time :

$$\mathcal{O}(N \cdot n \cdot \log(k)).$$

Scenario analysis and algorithmic improvement

Local random search



A lower bound on the synchronisation time :

- Method of the expected progress
- Similar to estimation for global random search
- Basically: Substitute network size n by neighbourhood size N

Scenario analysis and algorithmic improvement

Local random search

A lower bound on the synchronisation time :

- Method of the expected progress
- Similar to estimation for global random search
- Basically: Substitute network size n by neighbourhood size N
    - Probability to alter individual bit

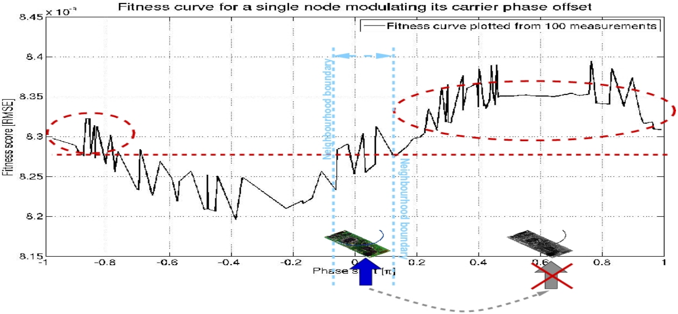
$$\frac{1}{N \cdot \log(k)}$$

    - Instead of

$$\frac{1}{n \cdot \log(k)}$$

Scenario analysis and algorithmic improvement

Local random search



A lower bound on the synchronisation time :

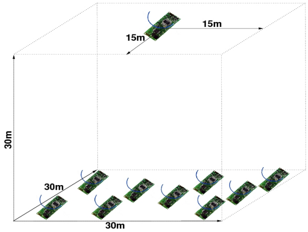
- With similar arguments as for global random search, lower bound

$$\Omega(N \cdot \log(k) \cdot \Delta)$$

Mathematical simulation environment

Impact of the node choice

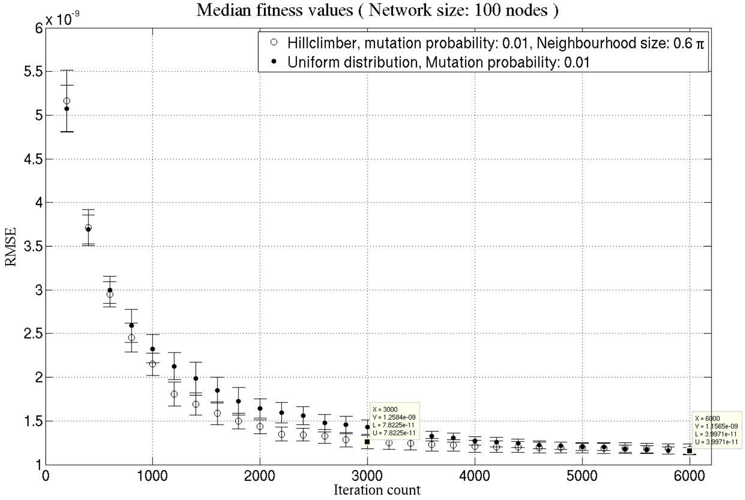
Property	Value
Node distribution area	$30m \times 30m$
Location of the receiver	$(15m, 15m, 30m)$
Mobility	stationary nodes
Base band frequency	f_{base} = 2.4 GHz
Transmission power of nodes	P_{tx} = 1 mW
Gain of the transmit antenna	G_{tx} = 0 dB
Gain of the receive antenna	G_{rx} = 0 dB
Iterations per simulations	6000
Identical simulation runs	10
Random noise power [46]	−103 dBm
Pathloss calculation (P_{rx})	$P_{tx}\left(\frac{\lambda}{2\pi d}\right)^2 G_{tx}G_{rx}$



- Fitness measure:

$$RMSE = \sqrt{\sum_{t=0}^{\tau} \frac{\left(\sum_{i=1}^{n} s_i + s_{noise}(i) - s^*\right)^2}{n}}.$$

Scenario analysis and algorithmic improvement
Local random search



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Multivariable equations

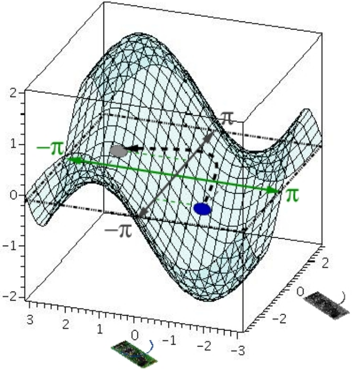
Received sum signal

- Reduce the amount of randomness in the optimisation
- Improve the synchronisation performance
- Improve the synchronisation quality

Scenario analysis and algorithmic improvements

Search space

- Search space:
  - Spanned by all Configurations of carrier phase offsets γ_i
- Search point / Configuration:
  - One possible configuration of carrier phase offsets

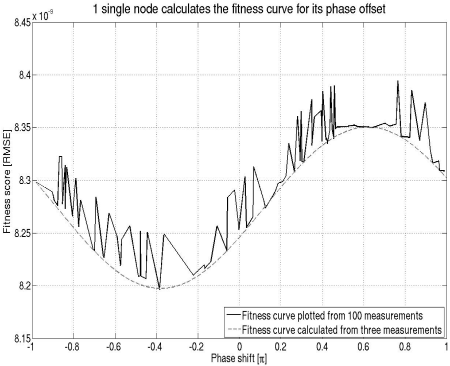


Multivariable equations

Received sum signal

- Fitness function observed by single node
- Constant carrier phase offset for $n-1$ nodes
- Fitness function:

$$\mathcal{F}(\Phi_i) = A\sin(\Phi_i + \phi) + c$$

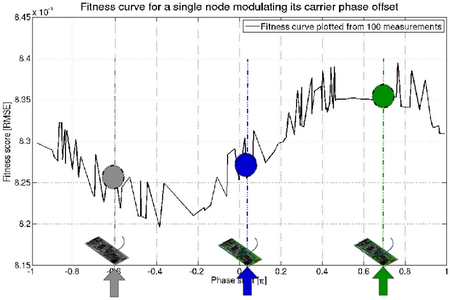


Multivariable equations

Received sum signal

Approach:

- Measure feedback at 3 points
- Solve multivariable equations
- Apply optimum phase offset calculated

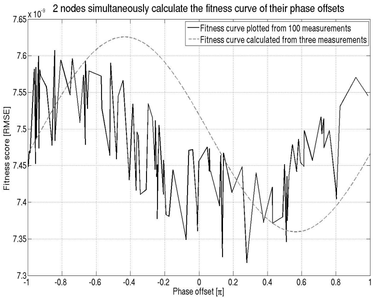


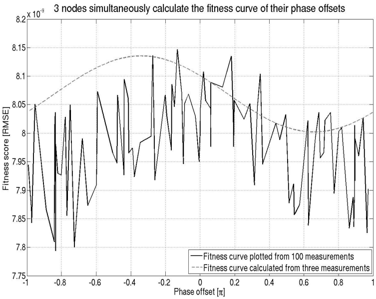
$$\mathcal{F}(\Phi_i) = A\sin(\Phi_i + \phi) + c$$

Multivariable equations

Received sum signal

- Problem:
    - Calculation not accurate when two or more nodes alter the phase of their transmit signals





Multivariable equations

Solution

An active node will :

1. Transmit with three distinct phase offsets $\gamma_1 \neq \gamma_2 \neq \gamma_3$ and measure feedback.
2. From these three feedback values and phase offsets, estimate feedback function and optimum phase offset γ_i^*.
3. Transmit a fourth time with $\gamma_4 = \gamma_i^*$.
4. If the deviation is less than 1% save γ_i^* as optimal phase offset, otherwise discard it.

A passive node will :

1. Transmit 4 times with identical phase offset γ_i.

Multivariable equations

Solution

- Node estimates the quality of the function estimation itself
- Transmit with optimum phase offset and measure channel again
- When Expected fitness deviates significantly from measured fitness, discard altered phase offset
- Deviation:

  1 node: $\approx 0.6\%$
  2 nodes: $\approx 1.5\%$
  3 nodes: $> 3\%$

Multivariable equations

Synchronisation process

1. Transmit with phase offsets $\gamma_1 \neq \gamma_2 \neq \gamma_3$; measure feedback
2. Estimate feedback function and calculate γ_i^*
3. Transmit with $\gamma_4 = \gamma_i^*$
4. If deviation smaller 1% finished, otherwise discard γ_i^*

Multivariable equations

Received sum signal

- Asymptotic synchronisation time:

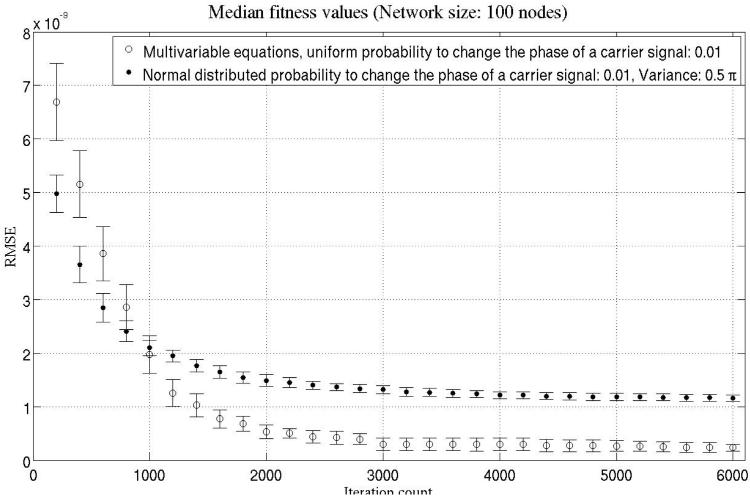
$$\mathcal{O}(n)$$

- Classic approach:[1]

$$\Theta(n \cdot k \cdot \log(n))$$

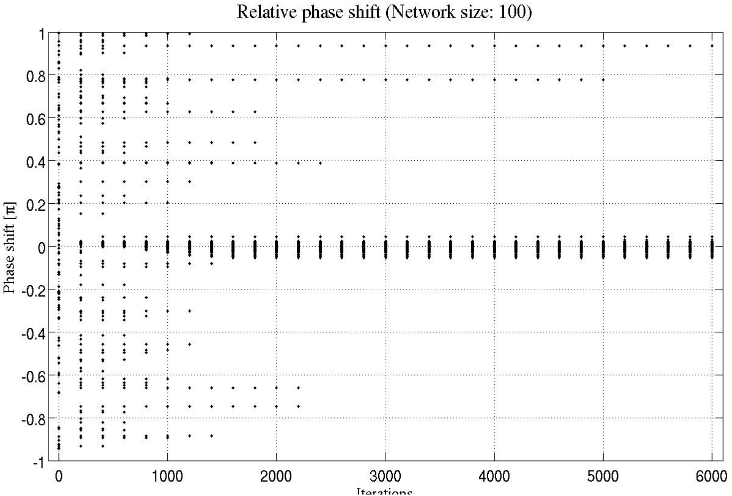
[1] Sigg, El Masri and Beigl, A sharp asymptotic bound for feedback based closed-loop distributed adaptive beamforming in wireless sensor networks (submitted to Transactions on Mobile Computing)

Multivariable equations
Performance estimation

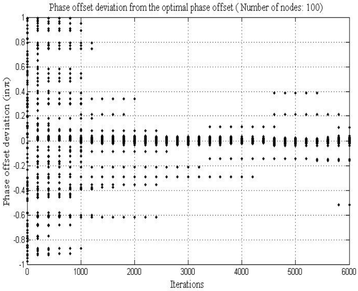


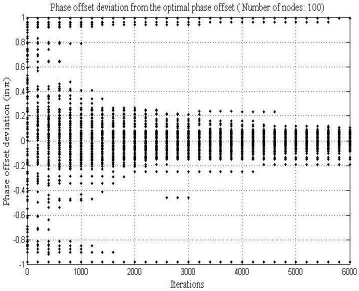
Multivariable equations

Performance estimation



Multivariable equations
Performance estimation

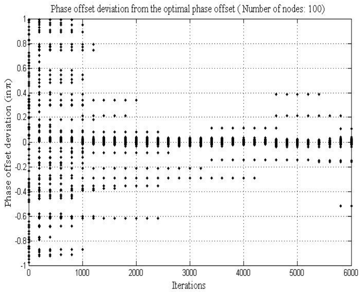


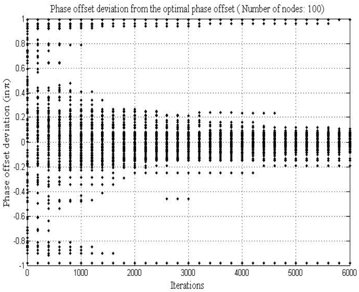


- Phase offset of distinct nodes is within $+/-0.05\pi$ for up to 99% of all nodes.

Multivariable equations

Performance estimation





- Asymptotically optimal synchronisation time
- Simulations: $\approx 12n$
- Further improvement:
  - 3 iterations per turn
  - Utilise last transmission from previous iteration

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Environmental changes

Introduction

- Velocity of nodes
- Multiple receiver nodes
- Increased population size
- Receive beamforming

Environmental changes

Velocity of nodes

Moving receiver :

- Straight line
- Random walk

Moving transmitter :

Straight line

Random walk

Environmental changes

Velocity of nodes

Moving receiver :

- Straight line
- Random walk

Aspects :

Only one moving node

Simple case

Also applicable when all transmitters move identically

Environmental changes

Velocity of nodes

Moving transmit nodes :

- Straight line
- Random walk

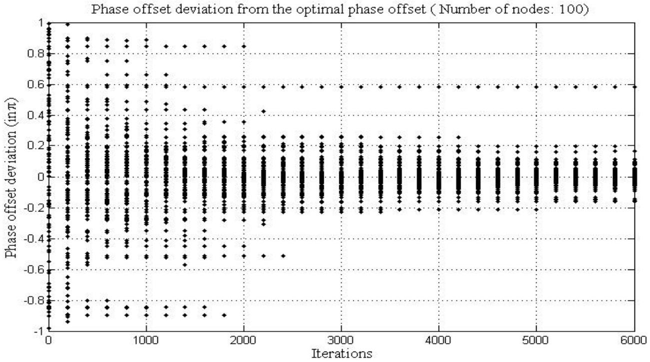
Aspects :

Multiple nodes moving

Hard case

Environmental changes

Velocity of nodes

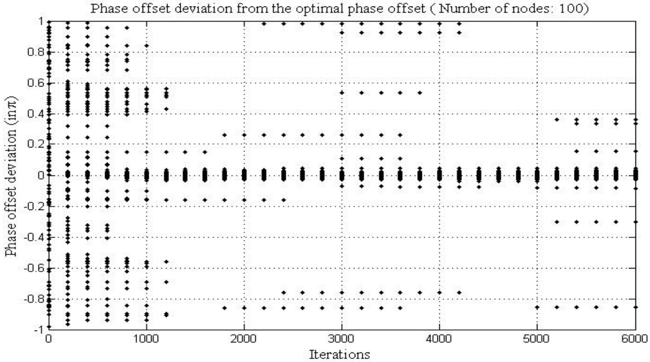


Random walk – receiver :

- Maximum velocity for classic algorithm: 5m/sec

Environmental changes

Velocity of nodes

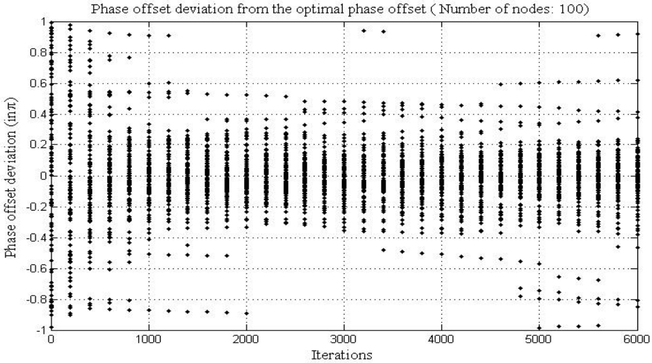


Random walk – receiver :

- Max. velocity for Multivariable equations: 5m/sec easily supported

Environmental changes

Velocity of nodes

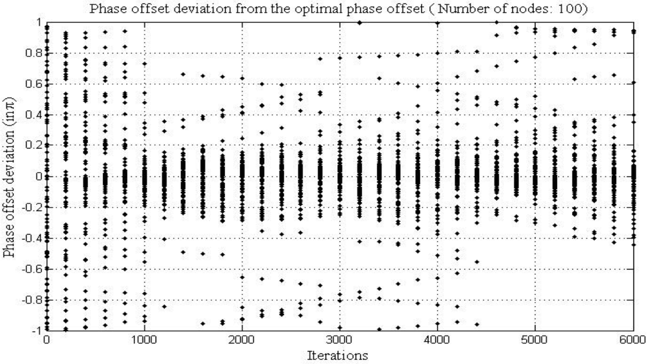


Random walk – transmitter :

- Maximum velocity for classic algorithm: 2m/sec

Environmental changes

Velocity of nodes

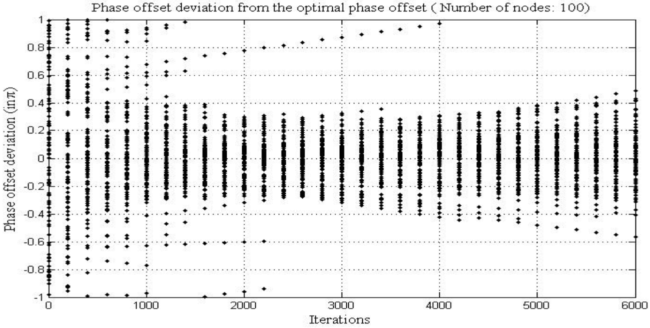


Random walk – transmitter :

- Max. velocity for Multivariable equations: 5m/sec supported

Environmental changes

Velocity of nodes

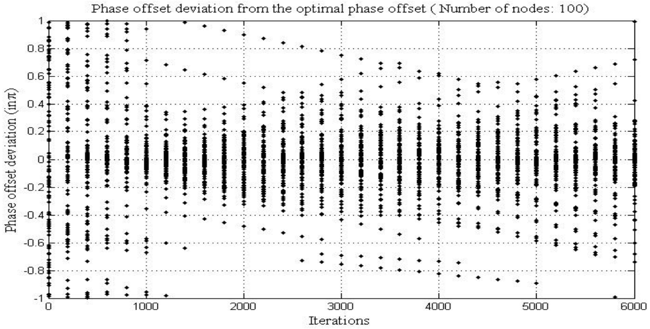


straight line – maximum relative speed :

- Maximum velocity for classic algorithm: 30m/sec
- Regardless if transmitter or receiver move

Environmental changes

Velocity of nodes



straight line – maximum relative speed :

- Maximum velocity for Multivariable equations algorithm: 60m/sec
- Regardless if transmitter or receiver move

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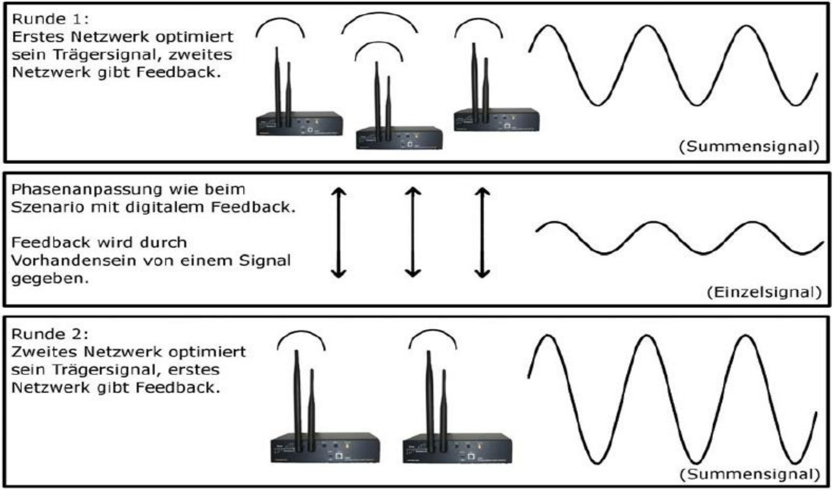
Environmental changes

Multiple receiver nodes



Environmental changes

Multiple receiver nodes

3m

Knoten	$n0$	$n1$	$n2$	$m0$	$m1$
Gain zur Anfangsamplitude (Median) [dB]	0,96	2,39	1,40	1,46	1,10
Gain zu einem Knoten (Median) [dB]	2,33	2,32	2,37	3,50	4,05
Anzahl letztes Feedback	5/11	3/11	3/11	8/11	7/11
Amplitude nach Synchronisation [%]	92,4	51,4	65,3	91,0	90,7

12m

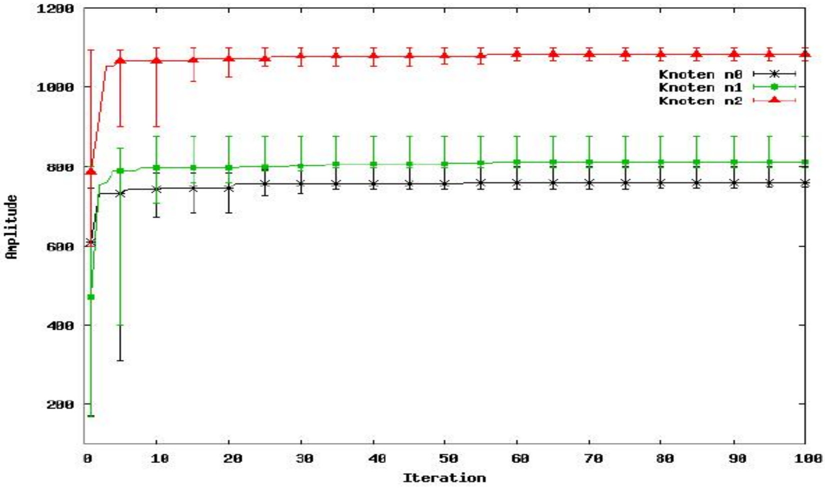
Knoten	$n0$	$n1$	$n2$	$m0$	$m1$
Gain zur Anfangsamplitude (Median) [dB]	1,24	0,63	1,39	2,06	1,47
Gain zu einem Knoten (Median) [dB]	2,53	1,09	2,00	2,74	4,18
Anzahl letztes Feedback	2/10	4/10	4/10	5/10	5/10
Amplitude nach Synchronisation [%]	57,1	92,0	86,5	86,4	86,6

24m

Knoten	$n0$	$n1$	$n2$	$m0$	$m1$
Gain zur Anfangsamplitude (Median) [dB]	1,12	2,33	2,76	3,61	1,67
Gain zu einem Knoten (Median) [dB]	1,2	2,54	2,03	5,15	3,76
Anzahl letztes Feedback	4/5	0/5	1/5	4/5	3/5
Amplitude nach Synchronisation [%]	94,2	80,0	61,4	95,8	97,9

Environmental changes
Multiple receiver nodes

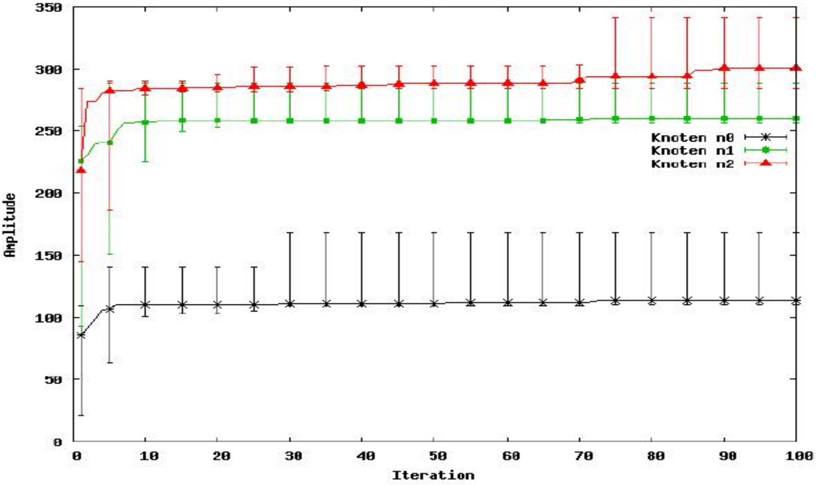
3m



Environmental changes

Multiple receiver nodes

12m



Environmental changes

Multiple receiver nodes

Multiple receiver nodes – issues :

- Only binary feedback value
  - Therefore only classic optimisation approach
- Distance between transmit and receive nodes relative to spatial diversity of nodes in one network
  - Better synchronisation when nodes in one network in spatial proximity
  - When nodes in one network communicate: No issue

Outline

Environmental changes

1. Hierarchical clustering
2. Local random search
3. An asymptotically optimal algorithm
4. Environmental changes
   - Velocity of nodes
   - Multiple receiver nodes
   - Increased population size
   - Receive beamforming

Environmental changes

Increased population size

Increased population size – Discussion :

How to achieve population size greater than one?

- Separate transmit times
- WCDMA
- Distinct frequencies simultaneously

Only separate transmit times feasible for WSN

More time for each iteration

- Initial solution: Random search
- Not clear if performance improvement possible by crossover

Outline

Environmental changes

1. Hierarchical clustering
2. Local random search
3. An asymptotically optimal algorithm
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   - Velocity of nodes
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Environmental changes

Receive beamforming

Receive beamforming – Discussion :

- Transmit node transmits only once
- Receiver nodes combine received signal fragments in the network
- Tradeoff:
  - Transmission power for in-network communication
  - Transmission over several iterations with receiver node
- More complex computation of transmit nodes

Questions?

- 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