Intelligent Antenna Sharing in Cooperative Diversity Wireless Networks

Ph.D. Thesis Defense
June 2005

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Motivation and Inspirations

You are (probably) here because you have all:

- experience *bad reception* while using your cell phone...
- left without *battery* because you forgot to recharge your cell phone the previous night...
- been unable to use your cell phone in large gatherings (such as 4th of July celebration, alongside Charles river!)

Could we fix all the above problems?
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- Gupta and Kumar IT 2000 result: local communication through other users could be beneficial...
- Multiple Antennas at each radio, in combination with the richness of the wireless channel, could be beneficial...
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- Multiple Antennas at each radio, in combination with the richness of the wireless channel, could be beneficial...
- Could we merge the two above? More users $\Rightarrow$ *better* wireless communication?
In general, multi-antenna systems could increase:
- reliability (diversity gain).
- spectral efficiency bps/Hz (multiplexing gain)

Objective: we would like to explore use of multiple antennas in the Relay channel, via cooperative relays.
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IMPLEMENTATION TODAY, with existing RF-front ends.
Main Difficulties

- Information is not a priori known at the relays.
- Number of participating antennas is unknown.
- Number of useful participating antennas is unknown.
- Coordination and Group formation ought to be distributed, not "genie-aided".
- MIMO ST-coding = coding for the Relay channel.
- Radio transceiver complexity.
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Outline

- Assumptions and Background
- Approach
- Performance
- Implementation Example
- Relevant Technologies
- Conclusion
- Acknowledgements
Assumptions and System Model

Inline with prior art in the field:

- Half-duplex radios.
- Simple RF-front ends:
  - Half-duplex radios.
  - No phased arrays (No *beamforming*).
  - No rate adaptation (no CSI at the source).
- Discrete, baseband, flat fading signal model: \( y_d = a_{sd} x_s + n_d \).
- Neighboring *interfering* streams will be treated as noise.
- (Mostly) Rayleigh fading, \( \mathcal{E}[|a_{sd}|^2] \propto \frac{1}{d_{sd}} \).
- Slow Fading (most difficult communication problem).
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Approaches

- Non-cooperative communication.

- Cooperative Repetition.

- Simultaneous transmissions (Space-Time Coding).

- Our Approach.
  - Proactive single relay selection (before any message is transmitted from source).
  - Selection based on instantaneous channel conditions (instead of average).
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Approach

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Receiver cares about signal strength (not distance).

Selection based on distance or average SNR... is suboptimal.

Relays as wireless channel sensors in a fast and distributed way: instantaneous channel conditions matter!
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**Our Approach: Opportunistic Relaying**

Policy I: \( h_i = \min\{|a_{si}|^2, |a_{id}|^2\} \)

Policy II: \( h_i = \frac{2}{|a_{si}|^2 + |a_{id}|^2} = \frac{2 |a_{si}|^2 |a_{id}|^2}{|a_{si}|^2 + |a_{id}|^2} \)

\[
T_i = \frac{\lambda}{h_i}
\]

Here \( \lambda \) has the units of time. For the discussion in this work, \( \lambda \) has simply values of \( \mu\text{secs} \).

\[
h_b = \max\{h_i\}, \quad \iff \quad T_b = \min\{T_i\}, \quad i \in [1..M].
\]
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Discussion: a note on CSI and time synchronization

RTS/CTS exchange is only needed at the relays to estimate uplink/downlink channel.

CTS reception is not exploited at the source.

No beamforming or rate adaptation at the relays.

No need for an explicit time sync protocol.

It is a multi-hop scheme.

We do know that the term "Opportunistic" has been used before...

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Outage Performance (1)

- Outage event between source $s$ and destination $d$:

\[
\log(1 + |a_{sd}|^2 \cdot SNR) \leq \rho \iff |a_{sd}|^2 \leq (2^\rho - 1) / SNR \iff \gamma_{sd} \leq \Theta
\]

- "Best" opportunistic relay is chosen, according to \textit{instantaneous}, end-to-end channel conditions:

\[
b = \arg \max_i \min \{\gamma_{si}, \gamma_{id}\}, \quad i \in [1..M]
\]  \hspace{1cm} (13)

- Probability of outage via "best" relay:

\[
P_r(\gamma_{sb} < \Theta_2 \cup \gamma_{bd} < \Theta_2), \quad \Theta_2 = 2 (2^{2\rho} - 1) / SNR
\]  \hspace{1cm} (14)

Notice the factor of 2 loss in spectral efficiency. Total tx power is fixed.
The above outage probability of opportunistic relaying is calculated for the case of Rayleigh Fading:

\[
P_r(\gamma_{sb} < \Theta_2 \cup \gamma_{bd} < \Theta_2) = \prod_{i=1}^{M} (1 - \exp(-\Theta_2 \left( \frac{1}{\gamma_{si}} + \frac{1}{\gamma_{id}} \right)))
\]  

(15)

Taking into account the direct path between source and destination, the overall outage probability becomes:
The above outage probability of opportunistic relaying is calculated for the case of Rayleigh Fading:

\[ P_r(\gamma_{sb} < \Theta_2 \cup \gamma_{bd} < \Theta_2) = \prod_{i=1}^{M} (1 - exp(-\Theta_2 (\frac{1}{\overline{\gamma}_{si}} + \frac{1}{\overline{\gamma}_{id}}))) \]  

(16)

Taking into account the direct path between source and destination, the overall outage probability becomes:

\[ P_{out}^{r} = (1 - exp(-\Theta_2/\overline{\gamma}_{sd})) \left[ \prod_{i=1}^{M} (1 - exp(-\Theta_2 (\frac{1}{\overline{\gamma}_{si}} + \frac{1}{\overline{\gamma}_{id}}))) \right] \]

(17)
A single relay doesn’t help... [has been shown before...]

Opportunistic relays do help, even under a total tx power constraint!
Outage Performance (3)

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Outage Performance (4)

Capacity for outage probability=0.01, $d_{sd} = d_{sr} = d_{rd}$

$$P_{out} = \delta.$$  

$$\rho_{opportunity} = \frac{1}{2} \log_2 \left( 1 - \ln(1 - \delta^{1/M}) \right) \frac{SNR}{\bar{\gamma}_{sid}}$$  \hspace{2cm} (18)  

$$\rho_{direct} = \log_2 \left( 1 - \ln(1 - \delta) \right) \frac{SNR}{\bar{\gamma}_{sid}}$$  \hspace{2cm} (19)
Diversity-Multiplexing Tradeoff (1)

\[
d(\rho) \triangleq - \lim_{\text{SNR} \to \infty} \frac{\log P_e(\rho)}{\log \text{SNR}}
\]

\[
r(\rho) \triangleq \lim_{\text{SNR} \to \infty} \frac{\rho(\text{SNR})}{\log \text{SNR}}
\]

- Diversity-Multiplexing Gain tradeoff tool averages out geometry.
- Cooperative diversity \(\neq\) multihop communication. This tool can reveal associated gains/losses.

**Theorem 0**: The achievable diversity multiplexing tradeoff for the decode and forward strategy with \(M\) intermediate relay nodes is given by 
\[
d(r) = (M + 1)(1 - 2r)
\]
for \(r \in (0, 0.5)\).
Diversity-Multiplexing Tradeoff (1)

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d \triangleq - \lim_{SNR \to \infty} \frac{\log P_e(\rho)}{\log SNR} \quad \quad \quad \quad \quad \quad r \triangleq \lim_{SNR \to \infty} \frac{\rho(SNR)}{\log SNR}
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**Theorem 1**: Under opportunistic relaying, the decode and forward protocol with \( M \) intermediate relays achieves the same diversity multiplexing tradeoff, as in Theorem 0.
Diversity-Multiplexing Tradeoff (1)

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**Theorem 1***: Under opportunistic relaying, the decode and forward protocol with \(M\) intermediate relays achieves the same diversity multiplexing tradeoff, as in Theorem 0.

**Theorem 2***: Opportunistic amplify and forward achieves the same diversity multiplexing tradeoff stated in Theorem 0.

*: In cooperation with Ashish Khisti.
Opportunistic, single relay selection is as good as space-time coding simultaneous transmissions!

This result holds for decode/forward as well as amplify/forward!
Diversity-Multiplexing Tradeoff (2)

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**Diversity-Multiplexing Tradeoff (2)**

![Graph](image)

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This result holds for decode/forward as well as amplify/forward!
Energy gains could counterbalance the decrease of rate by a factor of 2.

For the example above, 50% throughput increase is possible (8-PSK uncoded cooperative vs 2-PSK uncoded direct).
Results: Reception Energy Gains

- Existing cooperative techniques ignore RECEPTION energy for communication.
- Cooperative reception of $M$ relays scales reception energy cost... by a factor of $M$.
- This is not small: Reception energy can become comparable to transmission energy in modern transceivers [R. Min 2003].
- Opportunistic relaying does not have this disadvantage: reception energy is fixed.
- This is because best relay is chosen proactively, before message transmission. All other relays could go to sleep.
What if TOTAL power allocated to the relays was fixed?

For amplify and forward networks, the equivalent system equation can be shown to be:

It can be shown that opportunistic relaying is superior to other approaches in the field.
Results: Power Allocation Optimality (1)

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For amplify and forward networks, the equivalent system equation can be shown to be:

\[
\begin{bmatrix}
  y_{D,1} \\
  \frac{y_{D,2}}{\omega}
\end{bmatrix} = \begin{bmatrix}
  \sqrt{P_{SD}} a_{SD} & 0 \\
  \frac{1}{\omega} \sum_{i=1}^{M} \sqrt{\frac{P_{SRi} P_{RiD}}{P_{SRi} + N_0}} a_{SRi} a_{RiD} & \frac{1}{\omega} \sqrt{P_{SD}} a_{SD}
\end{bmatrix} \begin{bmatrix}
  x_1 \\
  x_2
\end{bmatrix} + \begin{bmatrix}
  n_{D,1} \\
  \frac{n_{D,2}}{\omega}
\end{bmatrix}
\]

\[
\mathcal{E}[\bar{r}_{D,2} \bar{r}_{D,2} | H_{R \rightarrow D}] = N_0 (1 + \sum_{i=1}^{M} \frac{P_{RiD} |a_{Ri}|^2}{P_{SRi} + N_0}) = \omega^2 N_0
\]

\[\text{(20)}\]
Results: Power Allocation Optimality (1)

What if TOTAL power allocated to the relays was fixed?

For amplify and forward networks, the equivalent system equation can be shown to be:

\[ y = \begin{bmatrix} \sqrt{P_{SD}} h_{SD} \\ H_{21} \\ \frac{1}{\omega} \sqrt{P_{SD}} h_{SD} \end{bmatrix} x + n \]  

(21)

\[ y = H x + n \]  

(22)

\[ I_{AF} = \frac{1}{2} \log_2 \left( 1 + \frac{P_{SD}}{N_0} |h_{SD}|^2 + \frac{|H_{21}|^2}{N_0} \right) \]  

(23)
Three cases considered, with all relays equivalent (same AVERAGE received SNR):

- Power to one relay (selection based on Average SNR).
- Power distributed to all relays (space-time coding).
- Power to opportunistic relay (Our Approach).
Results: Power Allocation Optimality (2)

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![Graph of CDF of Mutual Information with 6 relays showing Selection one random relay, Selecting all relays, and Opportunistic Relaying.]
Under a sum power constraint (and no beamforming capabilities) using all relays is suboptimal compared to opportunistic relaying.

Similar results for decode and forward.
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Similar results for decode and forward.
Overhead: Collision Probability (1)

Policy I:  \( h_i = \min\{|a_{si}|^2, |a_{id}|^2\} \)

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\[ T_i = \frac{\lambda}{h_i} \]  

\( T_b = \min\{T_i\}, \quad i \in [1..M]. \)

\( h_b = \max\{h_i\}, \quad \leftrightarrow \)

Here \( \lambda \) has the units of time. For the discussion in this work, \( \lambda \) has simply values of \( \mu\text{secs} \).

\[ (24) \]

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Worst case scenario: the probability of having two or more relays expire within the same interval $c$, out of a collection of $M$ relays is:

$$Pr(Collision) \leq Pr(\text{any } T_j < T_b + c \mid j \neq b)$$

where $T_b = \min\{T_j\}$, $j \in [1, M]$ and $c > 0$.

(a) No Hidden Relays: $c = r_{max} + |n_b - n_j|_{max} + d_s$

(b) Hidden Relays: $c = r_{max} + |n_b - n_j|_{max} + 2d_s + dur + 2n_{max}$
Worst case scenario: the probability of having two or more relays expire within the same interval \( c \), out of a collection of \( M \) relays is:

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where \( T_b = \min\{T_j\}, j \in [1, M] \) and \( c > 0 \).

\[
(a) \text{ No Hidden Relays : } c = r_{max} + |n_b - n_j|_{max} + d_s
\]

\[
(b) \text{ Hidden Relays : } c = r_{max} + |n_b - n_j|_{max} + 2d_s + dur + 2n_{max}
\]

- \( n_j \): propagation delay between relay \( j \) and destination. \( n_{max} \) is the maximum.
- \( r \): propagation delay between two relays. \( r_{max} \) is the maximum.
- \( d_s \): receive-to-transmit switch time of each radio.
- \( dur \): duration of flag packet, transmitted by the "best" relay.
If $T_b = \min \{ T_j \}, j \in [1, M]$ and $Y_1 < Y_2 < \ldots < Y_M$ the ordered random variables $\{ T_j \}$ with $T_b = Y_1$, and $Y_2$ the second minimum timer, then:
If $T_b = \min\{T_j\}, j \in [1, M]$ and $Y_1 < Y_2 < \ldots < Y_M$ the ordered random variables $\{T_j\}$ with $T_b \equiv Y_1$, and $Y_2$ the second minimum timer, then:

\[
Pr(\text{any } T_j < T_b + c \mid j \neq b) \equiv Pr(Y_2 < Y_1 + c)
\]  

(30)
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second minimum timer, then:

$$Pr(\text{any } T_j < T_b + c \mid j \neq b) \equiv Pr(Y_2 < Y_1 + c)$$ (33)

Given that $Y_j = \lambda/h(j)$, $Y_1 < Y_2 < \ldots < Y_M$ is equivalent to
$1/h(1) < 1/h(2) < \ldots < 1/h(M)$

$$Pr(Y_2 < Y_1 + c) = Pr\left(\frac{1}{h(2)} < \frac{1}{h(1)} + \frac{c}{\lambda}\right)$$ (34)

Ratio $\frac{\lambda}{c}$ needs to be as high as possible. $\lambda$ and $c$ are user controlled.
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\]

Ratio $\frac{\lambda}{c}$ needs to be as high as possible. $\lambda$ and $c$ are user controlled.

However $\lambda$ needs to be kept small:

\[
E[T_j] = E[\lambda / h_j] \geq \lambda / E[h_j]
\]
Lemma: Given $M \geq 2$ i.i.d. positive random variables $T_1, T_2, \ldots, T_M$, each with probability density function $f(x)$ and cumulative distribution function $F(x)$, and $Y_1 < Y_2 < Y_3 \ldots < Y_M$ are the $M$ ordered random variables $T_1, T_2, \ldots, T_M$, then $Pr(Y_2 < Y_1 + c)$, where $c > 0$, is given by the following equations:

$$Pr(Y_2 < Y_1 + c) = 1 - I_c$$

(39)

$$I_c = M (M - 1) \int_c^{+\infty} f(y) [1 - F(y)]^{M-2} F(y - c) \, dy$$

(40)

Wireless channel statistics of $h \Rightarrow \text{pdf } f$ and $\text{cdf } F$ of $T = \lambda/h \Rightarrow Pr(\text{collision})$. 
Lemma: Given $M \geq 2$ i.i.d. positive random variables $T_1, T_2, \ldots, T_M$, each with probability density function $f(x)$ and cumulative distribution function $F(x)$, and $Y_1 < Y_2 < Y_3 \ldots < Y_M$ are the $M$ ordered random variables $T_1, T_2, \ldots, T_M$, then $Pr(Y_2 < Y_1 + c)$, where $c > 0$, is given by the following equations:

$$Pr(Y_2 < Y_1 + c) = 1 - I_c$$  \hspace{1cm} (41)

$$I_c = M (M - 1) \int_c^{+\infty} f(y) [1 - F(y)]^{M-2} F(y - c) \, dy$$  \hspace{1cm} (42)

Wireless channel statistics of $h \Rightarrow$ pdf $f$ and cdf $F$ of $T = \lambda/h \Rightarrow Pr(collision)$.

Example: for a mobility of $0 - 3$ km/h $\Rightarrow$ maximum Doppler shift is $f_m = 2.5$ Hz $\Rightarrow$ minimum coherence time on the order of $T_c \approx 200$ milliseconds.

For $c/\lambda \approx 1/200 \Rightarrow Pr(Collision) \leq 0.6\%$ for policy I.

For $c \approx 5\mu s \Rightarrow \lambda \approx 1ms \approx \frac{1}{100} T_c$.

For $c \approx 1\mu s \Rightarrow \lambda \approx 200\mu s \approx \frac{1}{1000} T_c$.
Rigorous analysis earns you trips around the world...
Overhead: Collision Probability (5)

Rayleigh and Ricean Fading vs $\lambda/c$, for M=6

- Policy II (harmonic), Rayleigh, Simulation
- Policy II (harmonic), Rayleigh, Analysis
- Policy I (min), Ricean, Simulation
- Policy I (min), Rayleigh, Simulation
- Policy I (min), Rayleigh, Analysis

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Overhead: Collision Probability (6)

Assymetry and collision probability

Case 1
Case 2
Case 3
Case 4

v=3, Policy II (harmonic)
v=4, Policy II (harmonic)
v=3, Policy I (min)
v=4, Policy I (min)

4 different topologies for M=6

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...and a Remark...

\[ b = \arg \max_i \min \{ SNR_{si}, SNR_{id} \} = \max_i \{ SNR_{sid} \}, \quad i \in [1..M] \] (43)
...and a Remark...

\[ b = \arg \max \min \{ \text{SNR}_{si}, \text{SNR}_{id} \} \]  
\[ = \max \{ \text{SNR}_{sid} \}, \quad i \in [1..M] \] \hspace{1cm} (45)

\[ b = \arg \max \min \{ \text{SINR}_{si}, \text{SINR}_{id} \} \]  
\[ = \max \{ \text{SINR}_{sid} \}, \quad i \in [1..M] \] \hspace{1cm} (46)
Outline

- Assumptions and Background
- Approach
- Performance
- Implementation Example
- Relevant Technologies
- Conclusion
- Acknowledgements
Rethinking wireless: approach needs access to physical (layer 1), link (layer 2), routing (layer 3).

COTS radios usually give limited access to all layers ⇒

We built our own radios. Simple, low cost, embedded Software Defined Radios (SDRs).

We built a room size demo.
Implementation: Demo Setup
Implementation: Demo Setup

right view

left view

aggelos@mit.edu, Ph.D. Thesis Defense, MIT June 2005. – p. 35/51
Implementation: Signal Structure

Direct transmission of 16 frames

CTS

Flag

Packet 16/32 data frames

Direct and best relay transmission (16 + 16 = 32 frames)

Signal structure of each frame

Preamble 32 bits (on-off keying)
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Coordination, Cooperation and Time Keeping

- Relays (or receiver) might be busy!
- Relays (or receiver) might be in sleep mode.
- Therefore, relays need to be awake *on time*!

Time keeping could simplify required *scheduling*.

Other researchers believe that time keeping is the basis of scalable communication.

We briefly present two approaches on network time keeping:

- centralized
- decentralized
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Centralized Time Keeping

- No control over the network: noisy environment.
- No control over the time server: would like to use existing infrastructure.

Three End-to-End algorithms were compared:
- Averaging (NIST).
- Linear Programming (proposed before).
- Kalman Filtering (our proposal).

Objective: estimate $\phi$ and $\theta$, with minimum communication BW and computation requirements.

Could we do better than simple averaging?
Proposed technique can improve *accuracy* (error) and *precision* (variance of error), compared to existing approaches.

Computation efficient (since it is recursive) -

Implemented and tested using existed NTP infrastructure.
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- Computation efficient (since it is recursive) -

- Implemented and tested using existed NTP infrastructure.
Decentralized Time Keeping

The network is the time server.

- Only local communication.
- Exchange timestamps and keep the highest (Lamport’s idea).
- Redefine time as a periodic function!
- The network *re-calibrates* periodically and autonomously.
Decentralized Time Keeping Results

Error could decrease with increasing network diameter!

\[
\epsilon(t_c) = C_i(t_c) - C_j(t_c) = \\
= \epsilon(t_0 + x) + (\phi_i - \phi_j) \Delta t \\
\Delta t = t_c - (t_0 + x)
\]

Error depends on communication BW.

\[x = \text{propagation delay} + \text{transmission delay} + \text{operating system delay}.\]
Objective: play music in synchrony, display *heartbeat* at the edges...
This algorithm is based on oscillator’s coupling (no averaging).

Coupling among terminals with semi-periodic signal ≡ Entrainment.

It is relevant to natural phenomena of synchronization (fireflies, cardiac neurons etc.)
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**Conclusions (1)**

*Intelligent* single antenna selection:

- performs as good as ST-coding simultaneous transmissions, in terms of diversity-multiplexing tradeoff.
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- outperforms simultaneous transmissions, in terms of power allocation at the relays.
- provides for significant RECEPTION energy savings (proactive character).
- simplifies processing at the relays and the receiver (reduced complexity).
- is (really) fast and (really) distributed - other proposals might follow.
This thesis suggests:

- Instead of searching for ST coding for the relay channel at the physical layer, we could alternatively research *smart* relay selection techniques, at the routing layer. Emphasis on instantaneous channel conditions (vs average).
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Conclusions (2)

This thesis suggests:

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- Coordination and group formation are not trivial and require special attention.
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- Concrete centralized or decentralized network time keeping algorithms could be of help. Specific examples were analyzed in theory and implemented in practice.
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- Concrete centralized or decentralized network time keeping algorithms could be of help. Specific examples were analyzed in theory and implemented in practice.

- Formation of virtual antenna arrays can be simplified to practice, using existing RF-front ends. Proposed method is applicable today and a demonstration example was built.
Papers

Conferences


Journals

A. Bletsas, "Evaluation of Kalman Filtering for Network Time Keeping", accepted for publication, IEEE Transactions in Ultrasonics, Ferromagnetics and Frequency Control (TUFFC).
"Tolerating ambiguity is a sign of maturity..."
Acknowledgements

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In memory of Stephen A. Benton (1941-2003)
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