Intelligent Antenna Sharing in Cooperative Diversity Wireless Networks

Ph.D. Thesis Defense
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Motivation and Inspirations

You are (probably) here because you have all experienced:

- bad reception...
- battery problems...
- no connectivity during large gatherings (4th of July problem!)

Could we fix all the above problems?
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- Gupta and Kumar IT 2000 result: local communication helps...
- Multiple Antennas at each radio help...
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Could we fix all the above problems?

Inspirations:

- Gupta and Kumar IT 2000 result: local communication helps...
- Multiple Antennas at each radio help...
- Could we merge the two above? More users $\Rightarrow$ *better* wireless communication?
In general, multi-antenna systems increase:

- reliability (diversity gain).
- spectral efficiency bps/Hz (multiplexing gain)

Explore multiple antennas in the **Relay** channel, via *cooperative* relays.
Additional Problem Constraint: Low Complexity and Implementation

In general, multi-antenna systems increase:
- reliability (diversity gain).
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- Explore multiple antennas in the Relay channel, via cooperative relays.
- IMPLEMENTATION TODAY, with existing RF-front ends.

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Main Difficulties

Information is not a priori known at the relays.
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- MIMO ST-coding ≠ coding for the Relay channel.
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MIMO ST-coding ≠ coding for the Relay channel.

Radio transceiver complexity.
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 rate adaptation (no CSI at the source).
  - No phased arrays (No beamforming).
- \( y_d = a_{sd} x_s + n_d \).
- Neighboring interfering streams: noise.
- (Mostly) Rayleigh fading. \( \mathcal{E}[|a_{sd}|^2] = 1/d^\nu \)
- Slow Fading (most difficult communication problem).
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- Slow Fading (most difficult communication problem).
Approaches

Non-cooperative communication.

Cooperative Repetition.
Simultaneous transmissions (Space-Time Coding).
Our Approach.
Proactive single relay selection.
Instantaneous channel conditions (instead of average).

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- Implementation Example
- Relevant Technologies
- Conclusion
- Acknowledgements
Wireless Channel Observations

Receiver cares about signal strength (not distance).

Selection based on distance or \textit{average} SNR... is suboptimal.

\textit{Instantaneous} channel conditions matter!
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Wireless Channel Observations

Receiver cares about signal strength (not distance).

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*Instantaneous* channel conditions matter!
Our Approach: *Opportunistic Relaying*

\[ Policy \, I: \quad h_i = \min\{|a_{si}|^2, |a_{id}|^2\} \]

\[ Policy \, II: \quad h_i = \frac{2}{\frac{1}{|a_{si}|^2} + \frac{1}{|a_{id}|^2}} = \frac{2|a_{si}|^2|a_{id}|^2}{|a_{si}|^2 + |a_{id}|^2} \]

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

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

\[ h_b = \max\{h_i\}, \quad \iff \]

\[ T_b = \min\{T_i\}, \quad i \in [1..M]. \]
Our Approach: *Opportunistic Relaying*

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

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h_b = \max\{h_i\}, \quad \iff \quad T_b = \min\{T_i\}, \quad i \in [1..M].
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**Policy I**:
\[ h_i = \min\{|a_{si}|^2, |a_{id}|^2\} \]

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\[ T_i = \frac{\lambda}{h_i} \] (10)

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

\[ h_b = \max\{h_i\}, \quad \iff \]
\[ T_b = \min\{T_i\}, \quad i \in [1..M]. \] (11) (12)

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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 \( d \):

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

"Best" opportunistic relay is chosen, according to instantaneous, end-to-end channel conditions:

\[
b = \arg \max \left\{ \min \{\gamma_{si}, \gamma_{id}\}, \quad i \in [1..M] \right\}
\]

(13)

Probability of outage via "best" relay:

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

(14)
The above outage probability of opportunistic relaying is calculated for the case of Rayleigh Fading:

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

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

(16)

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

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

(17)
Outage Performance (3)

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

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

Capacity for outage prob. = 0.01 and FIXED total transmission power (SNR=10)

- A single relay doesn’t help... [has been shown before...]
- Opportunistic relays do help, even under a total tx power constraint!

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Outage Performance (4)

```
\[ P_{\text{out}} = \delta. \]

\[ \rho_{\text{opportunity}} = \frac{1}{2} \log_2 \left( 1 - \ln(1 - \delta^{1/M}) \right) \frac{SNR}{2} \frac{\gamma_{\text{sid}}}{M} \]  \hspace{1cm} (18)

\[ \rho_{\text{direct}} = \log_2 \left( 1 - \ln(1 - \delta) \right) SNR \frac{\gamma_{\text{sid}}}{M} \]  \hspace{1cm} (19)
```
Diversity-Multiplexing Tradeoff (1)

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

\[ r \Delta = \lim_{SNR \to \infty} \frac{\rho(SNR)}{\log SNR} \]

- Diversity-Multiplexing Gain tradeoff tool averages out geometry.
- Cooperative diversity ≠ 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 \( r \in (0, 0.5) \).
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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)

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

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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.

**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!
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Diversity-Multiplexing Tradeoff (2)

- *Opportunistic*, single relay selection is as good as space-time coding simultaneous transmissions!

- This result holds for decode/forward as well as amplify/forward!
● **Opportunistic**, single relay selection is as good as space-time coding simultaneous transmissions!

● This result holds for decode/forward as well as amplify/forward!
Energy gains 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

- Cooperative reception of $M$ relays $\Rightarrow$ reception energy cost increases by a factor of $M$.

- Rx energy is comparable to Tx energy in modern radios [R. Min 2003].

- Proactive nature of Opportunistic Relaying, reception energy cost is fixed.

\[
\begin{align*}
|a_{s,i}|^2 & \quad |a_{i,d}|^2 \\
|a_{s,j}|^2 & \quad |a_{j,d}|^2
\end{align*}
\]

Source  Destination

\[\text{Direct Relayed}\]
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:

It can be shown that opportunistic relaying is superior to other approaches in the field.
What if TOTAL power allocated to the relays was fixed?

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

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

\[
\varepsilon[\check{n}_{D,2}, \check{n}_{D,2} | H_{R \rightarrow D}] = N_0 \left( 1 + \sum_{i=1}^{M} \frac{P_{RD} |a_{RD}|^2}{P_{SRi} + N_0} \right) = \omega^2 N_0
\]

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What if TOTAL power allocated to the relays was fixed?

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

\[ y = \begin{bmatrix} \sqrt{P_{SD}} h_{SD} & 0 \\ \frac{1}{\omega} \sqrt{P_{SD}} h_{SD} & H_{21} \end{bmatrix} x + n \]  

(21)

\[ y = H x + n \]  

(22)

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

(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).

CDF of Mutual Information

Selection one random relay
Selecting all relays
Opportunistic Relaying
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).
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)

\[ h_i = \min\{ |a_{si}|^2, |a_{id}|^2 \} \]

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

Here \( \lambda \) has the units of time. For the discussion in this work, \( \lambda \) has simply values of \( \mu s e c s \).

\[ h_b = \max\{ h_i \}, \quad \iff \]

\[ T_b = \min\{ T_i \}, \quad i \in [1..M]. \]
Worst case scenario:

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

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

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

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

Worst case scenario:

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

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: 
\[
c = r_{max} + |n_b - n_j|_{max} + 2d_s + dur + 2n_{max}
\]

- \( n_j \): 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 $T_b \equiv Y_1$, 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)
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:

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

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

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

Ratio $\frac{\lambda}{c}$ needs to be as high as possible. $\lambda$ and $c$ are user controlled.
Overhead: Collision Probability (3)

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:

\[ Pr(\text{any } T_j < T_b + c \mid j \neq b) \equiv Pr(Y_2 < Y_1 + c) \] (36)

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

\[ 1/h(1) < 1/h(2) < \ldots < 1/h(M) \]

\[ Pr(Y_2 < Y_1 + c) = Pr\left(\frac{1}{h(2)} < \frac{1}{h(1)} + \frac{c}{\lambda}\right) \] (37)

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

However \( \lambda \) needs to be kept small:

\[ E[T_j] = E[\lambda/h_j] \geq \lambda/E[h_j] \] (38)
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)

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

(40)

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

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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:

\[
\Pr(Y_2 < Y_1 + c) = 1 - I_c
\]

(41)

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

(42)

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

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 \( c/\lambda \approx 1/200 \Rightarrow \Pr(\text{Collision}) \leq 0.6\% \) for policy I.

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

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 $M=6$
Overhead: Collision Probability (6)

Assymetry and collision probability

4 different topologies for M=6
...and a Remark...

$$b = \arg \max \{ \min \{ \text{SNR}_{si}, \text{SNR}_{id}\} \} = \max \{ \text{SNR}_{sid} \}, \quad i \in [1..M]$$  \hspace{1cm} (43)
...and a Remark...

\[ b = \arg \max_i \min\{\text{SNR}_s, \text{SNR}_i\} = \max\{\text{SNR}_s\}, \quad i \in [1..M] \] (45)

\[ b = \arg \max_i \min\{\text{SINR}_s, \text{SINR}_i\} = \max\{\text{SINR}_s\}, \quad i \in [1..M] \] (46)
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Implementation: Hardware

- 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 low cost embedded Software Defined Radios (SDRs).
- We built a room size cooperative diversity demo.
Implementation: Demo Setup

right view

left view

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Implementation: Demo Setup

left view

right view

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Implementation: Signal Structure

- Signal structure of each frame
  - Preamble 32 bits (on-off keying)
- Direct transmission of 16 frames
- Direct and best relay transmission (16 + 16 = 32 frames)
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Coordination, Cooperation and Time Keeping

Relays (or receiver) might be busy or in sleep mode!

Time keeping could simplify required *scheduling*.

*Time keeping as the basis of scalable communication.*

Extensive work 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).

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- Improving **accuracy** (error) and **precision** (variance of error), compared to existing approaches.
- Computation efficient (since it is recursive) -
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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 $\equiv$ Entrainment.

It is relevant to natural phenomena of synchronization (fireflies, cardiac neurons etc.)
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Bigger Picture:

- No more *bad reception*...
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- Improved battery duration...

- Improved spectral efficiency (bps/Hz).
- Tx/Rx energy savings.
- Towards more scalable wireless networks...
- Additionally:
  - No performance loss compared to simultaneous transmissions and space-time coding.
  - Cross-layer research is needed.
  - Centralized/decentralized network time-keeping contributions.
  - Method was implemented in low-cost hardware.

Applications: WiFi, Zigbee, Tetra...
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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..."
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In memory of Stephen A. Benton (1941-2003)
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aggelos@mit.edu, Ph.D. Thesis Defense, MIT June 2005.  – p. 49/50
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