Intelligent Antenna Sharing in Cooperative Diversity Wireless Networks

Ph.D. Thesis Defense
June 2005

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Thesis Committee

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- Joe Paradiso,
  Associate Professor, MIT Media Lab.
- Moe Win,
  Associate Professor, MIT LIDS.

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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- Multiple Antennas at each radio help...

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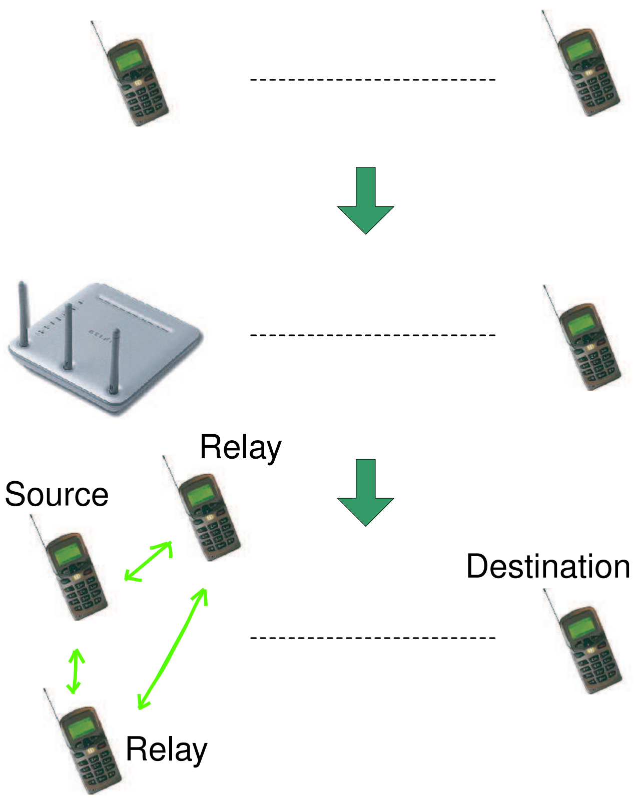
- Gupta and Kumar IT 2000 result: local communication helps...
- Multiple Antennas at each radio help...
- Could we merge the two above? More users $\stackrel{?}{=}$ *better* wireless communication?

Additional Problem Constraint: Low Complexity and Implementation



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.

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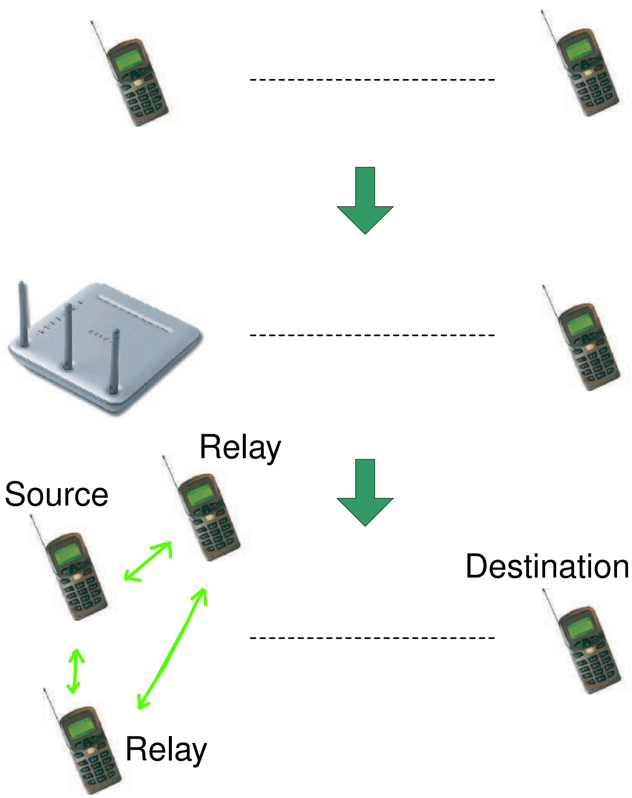

In general, multi-antenna systems increase:

- reliability (diversity gain).
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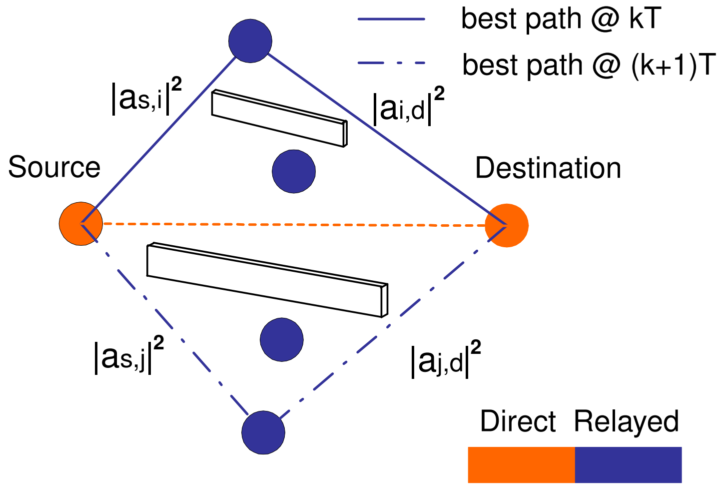
- Explore multiple antennas in the *Relay* channel, via *cooperative* relays.
- IMPLEMENTATION TODAY, with existing RF-front ends.

Main Difficulties



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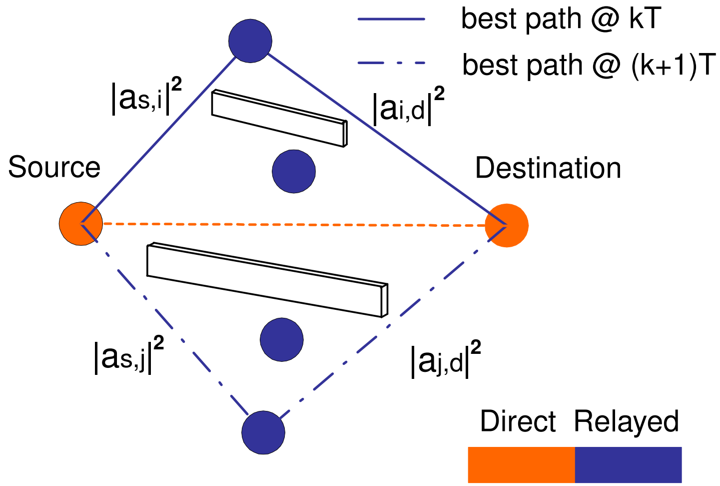

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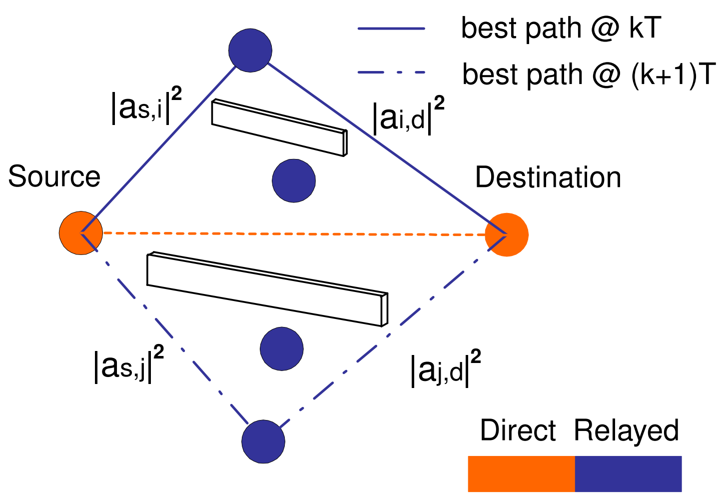

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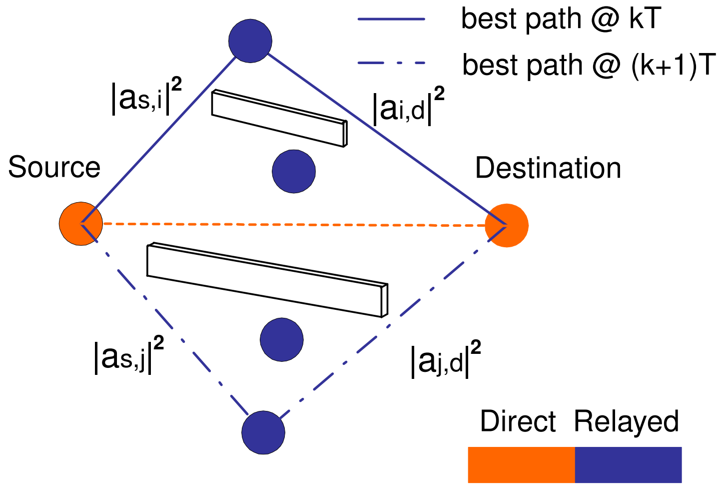

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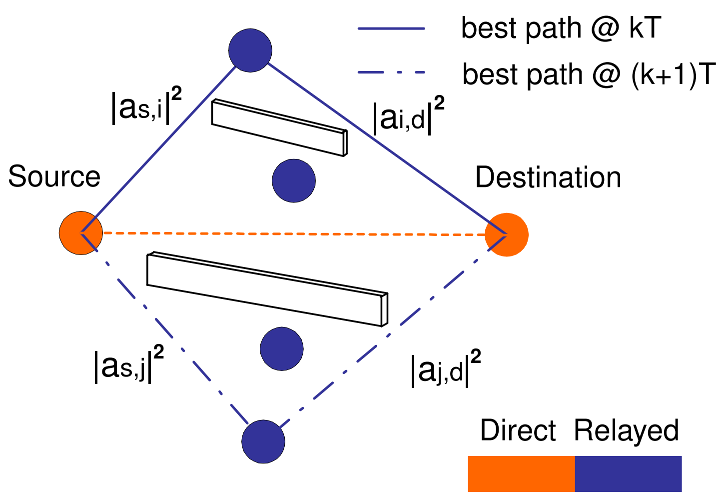

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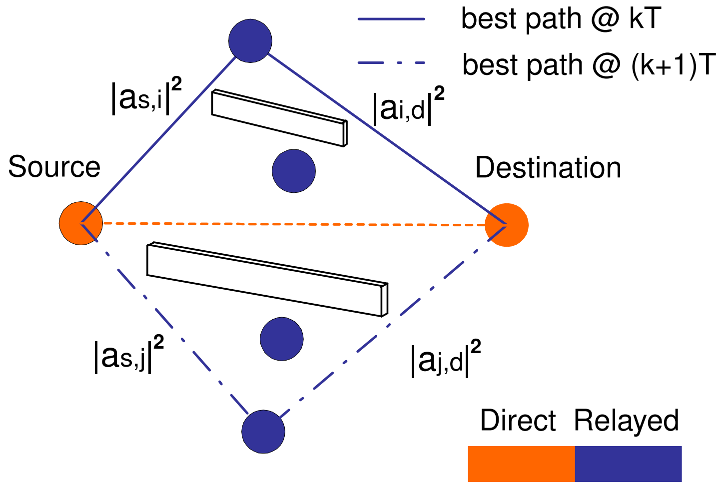

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- MIMO ST-coding $\neq$ coding for the Relay channel.
- Radio transceiver complexity.

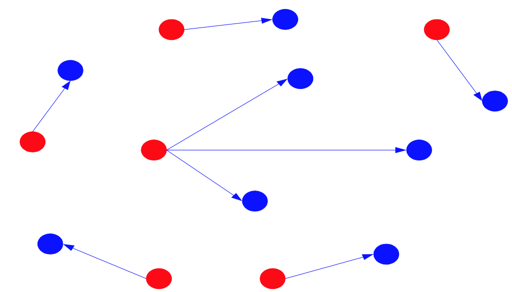
Outline

- 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. $\mathcal{E}[|a_{sd}|^2] = 1/d^v$
- Slow Fading (most difficult communication problem).



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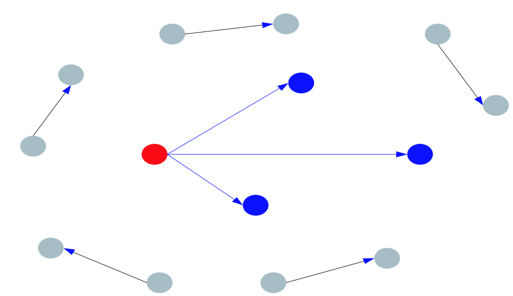
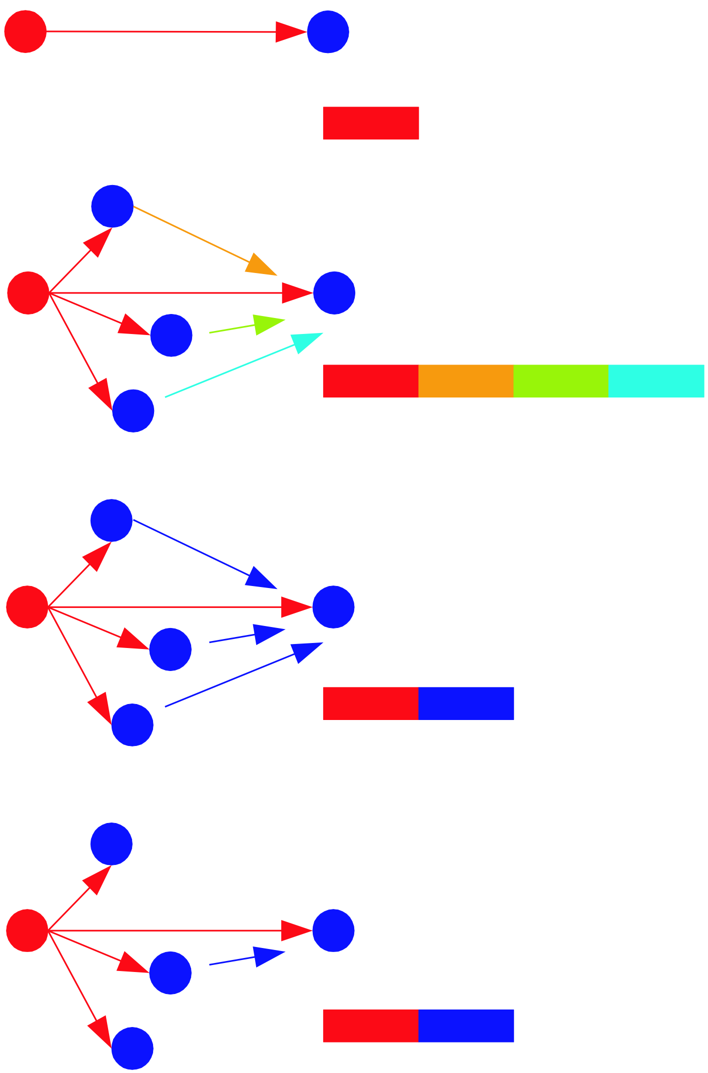


Approaches



- Non-cooperative communication.

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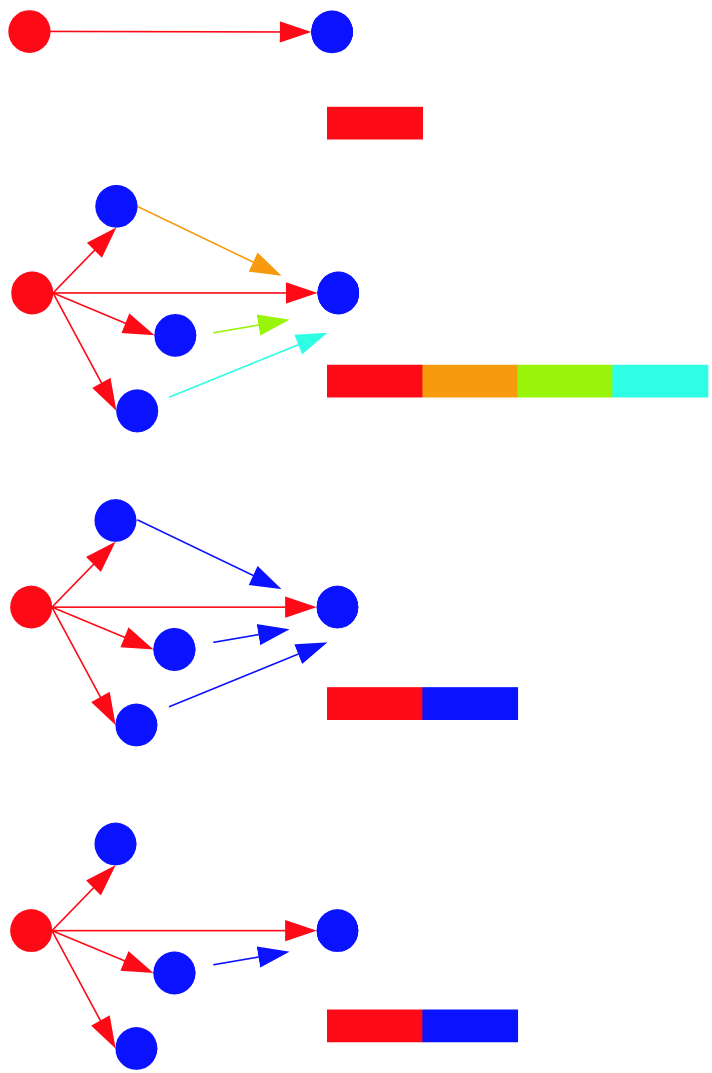

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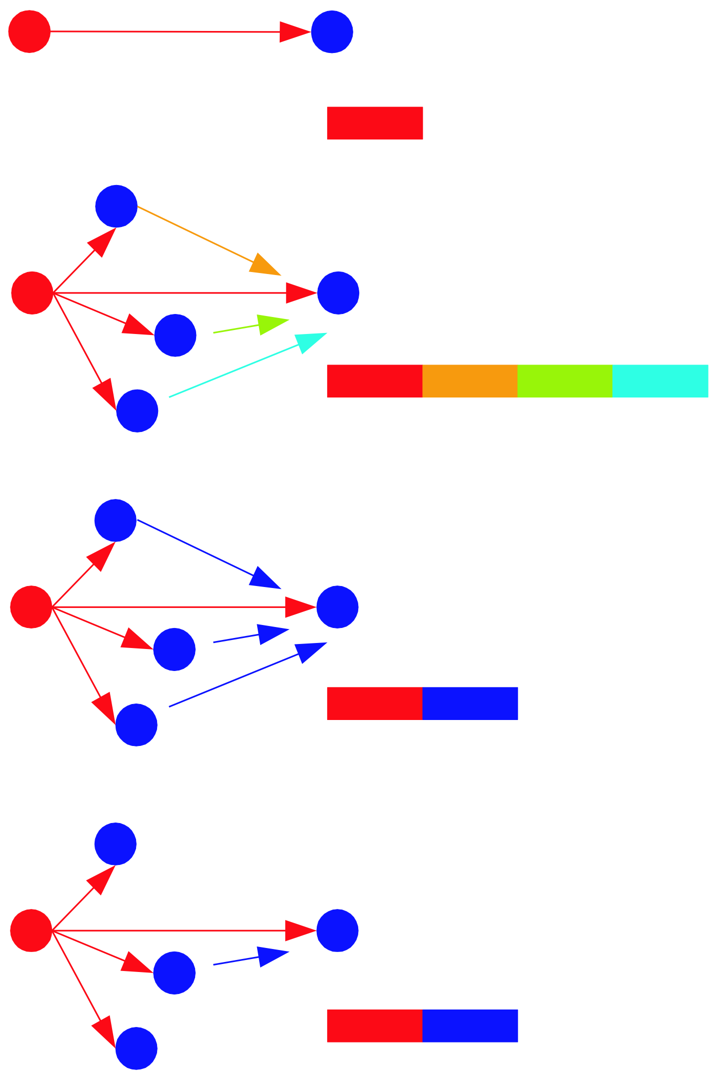

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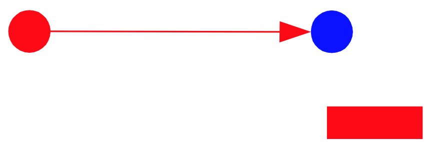

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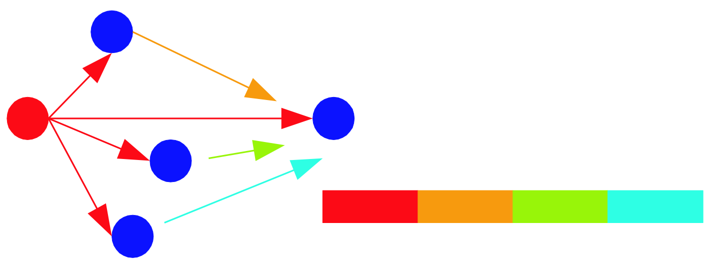

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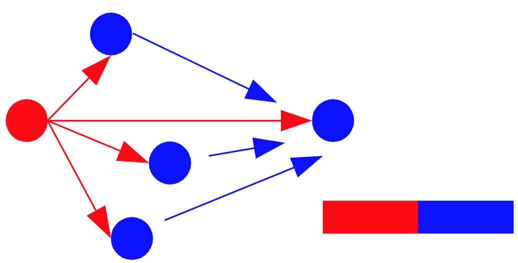

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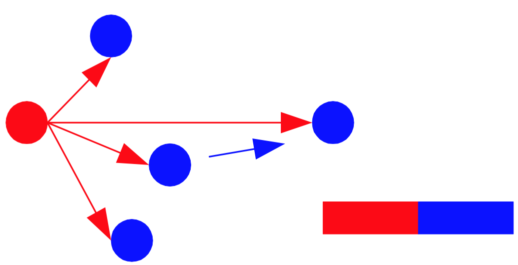

- Our Approach.
  - *Proactive* single relay selection.
  - *Instantaneous* channel conditions (instead of average).

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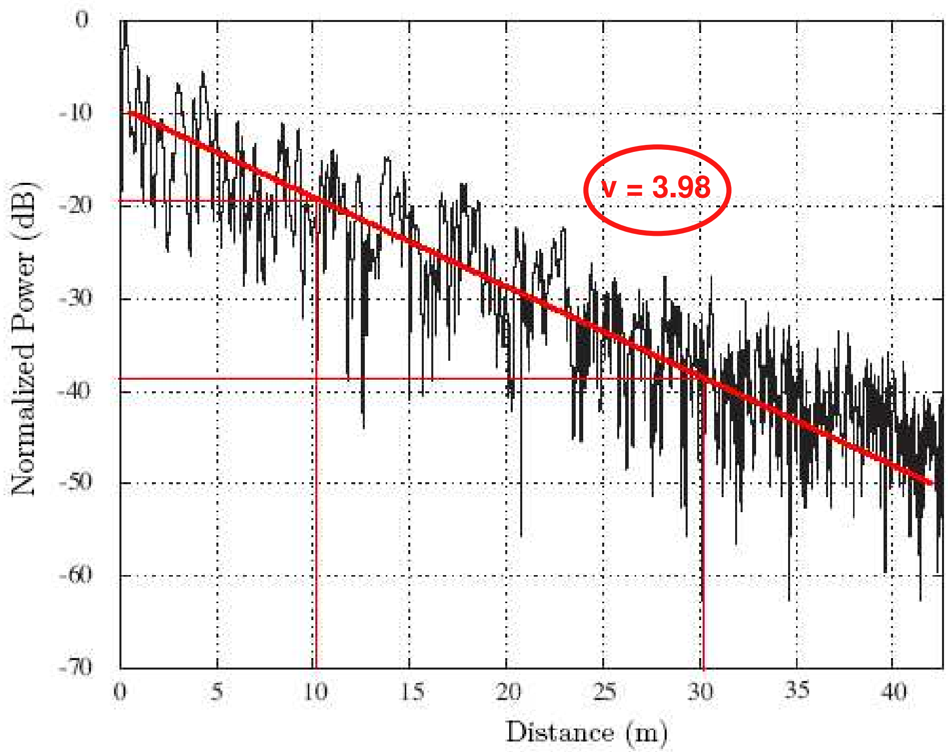
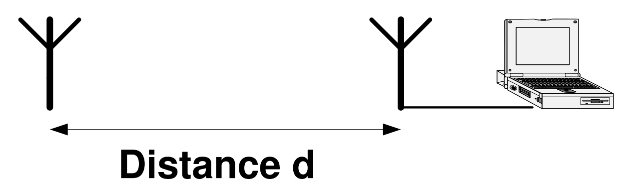
Wireless Channel Observations





- Receiver cares about signal strength (not distance).
- Selection based on distance or *average* SNR... is suboptimal.
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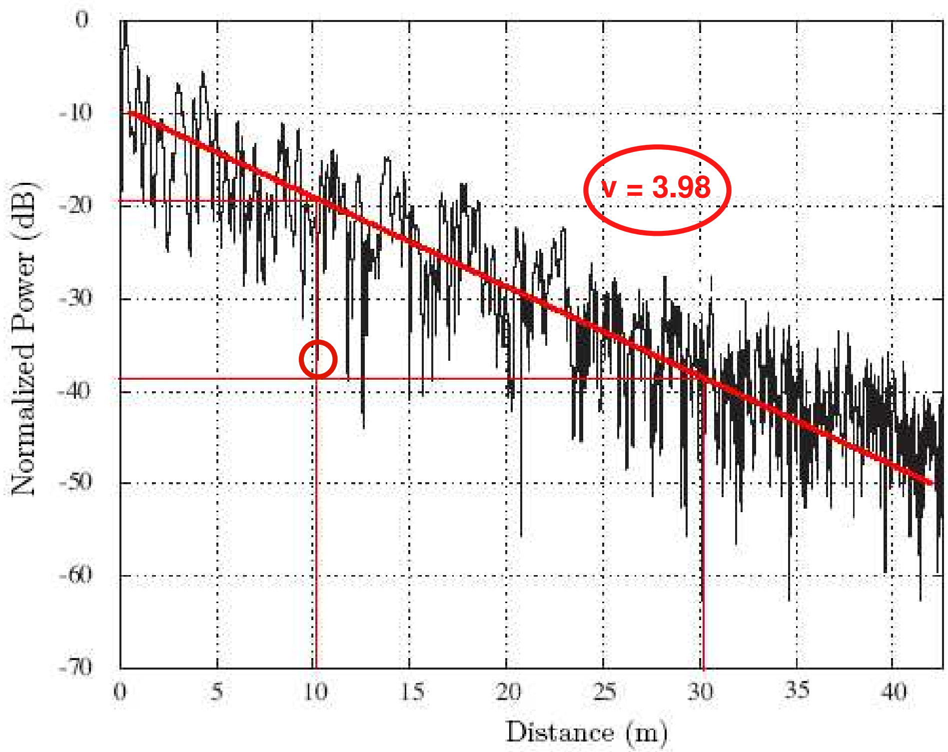

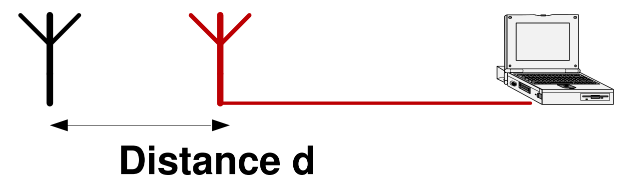

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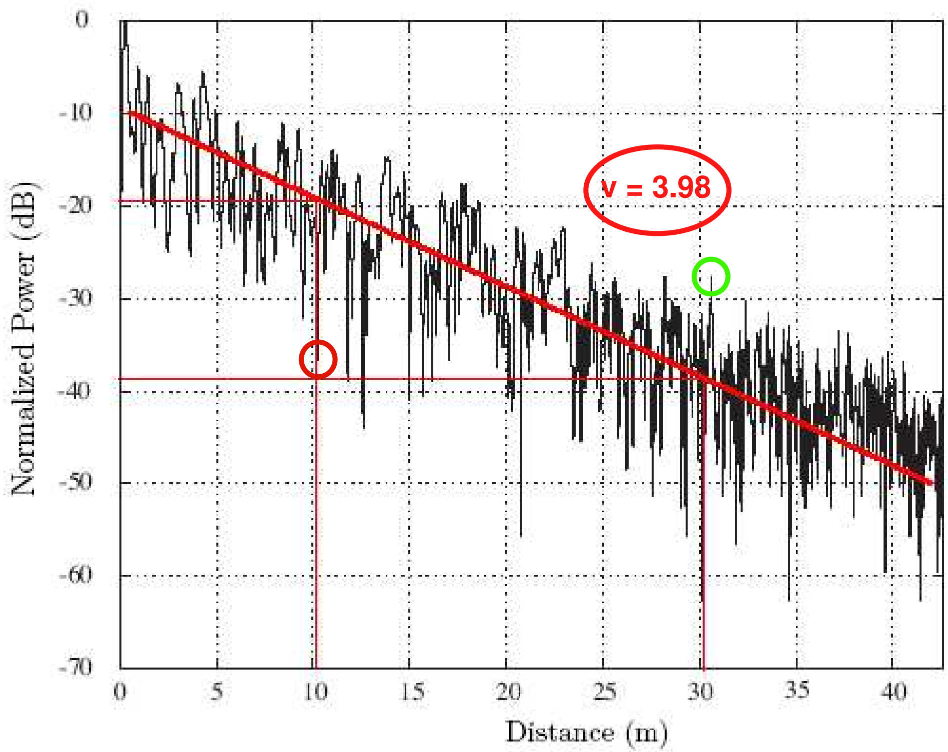

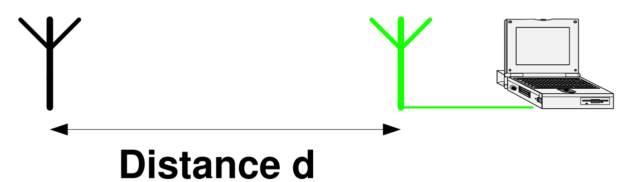

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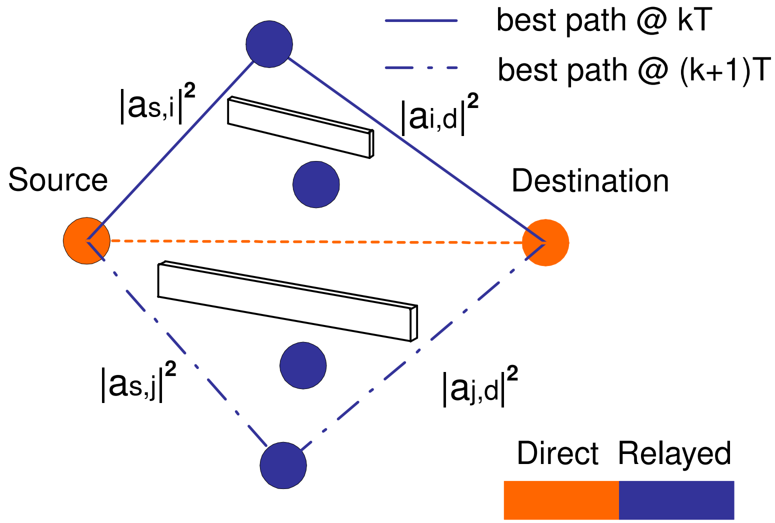
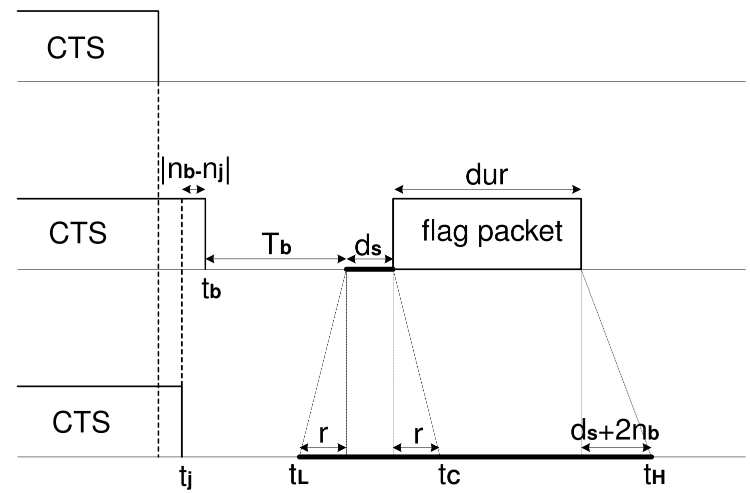
Our Approach: *Opportunistic Relaying*





$$Policy\ I: \quad h_i = \min\{|a_{si}|^2, |a_{id}|^2\} \qquad Policy\ II: \quad h_i = \frac{2}{\frac{1}{|a_{si}|^2} + \frac{1}{|a_{id}|^2}} = \frac{2\,|a_{si}|^2\,|a_{id}|^2}{|a_{si}|^2 + |a_{id}|^2}$$

$$T_i = \frac{\lambda}{h_i} \tag{1}$$

Here λ has the units of time. For the discussion in this work, λ has simply values of $\mu secs$.

$$h_b = \max\{h_i\}, \iff \tag{2}$$

$$T_b = \min\{T_i\},\ i \in [1..M]. \tag{3}$$

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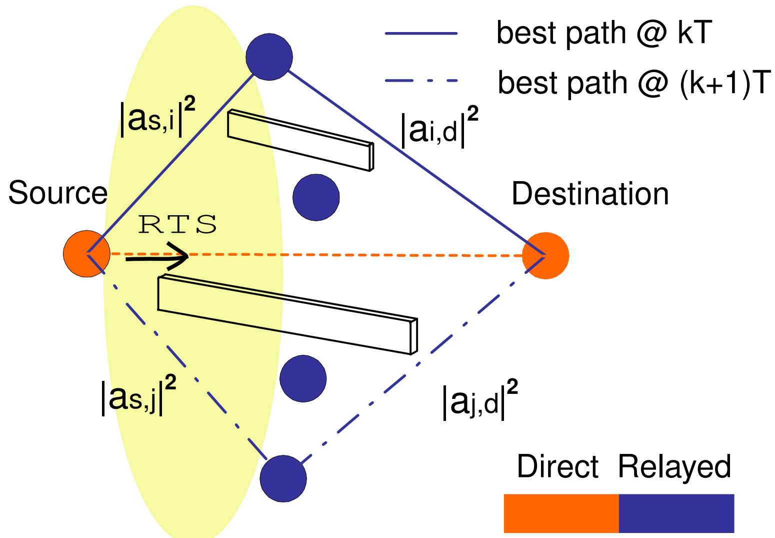

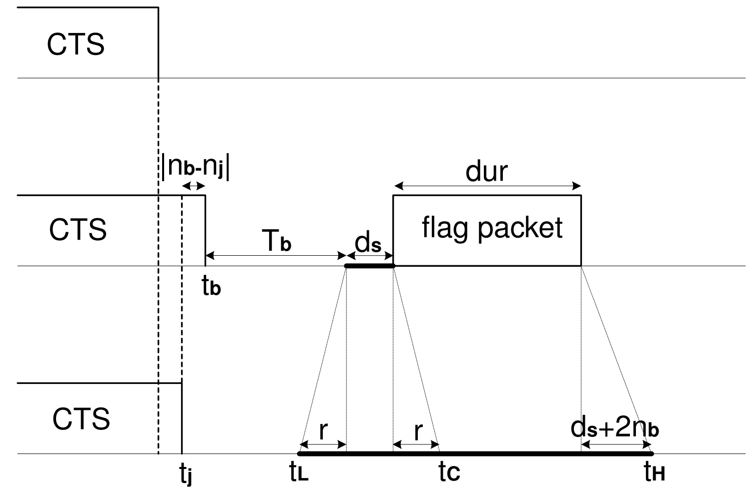

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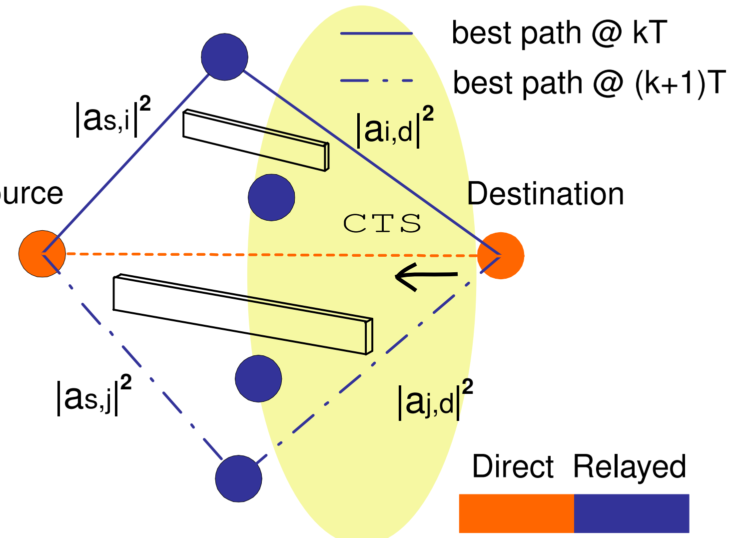

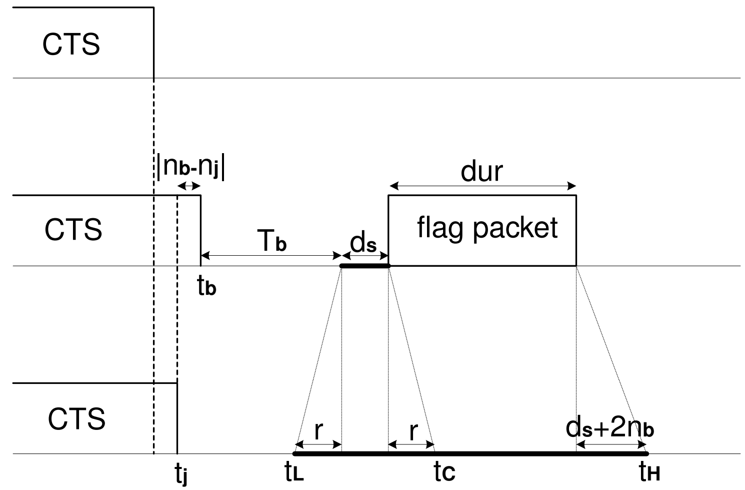

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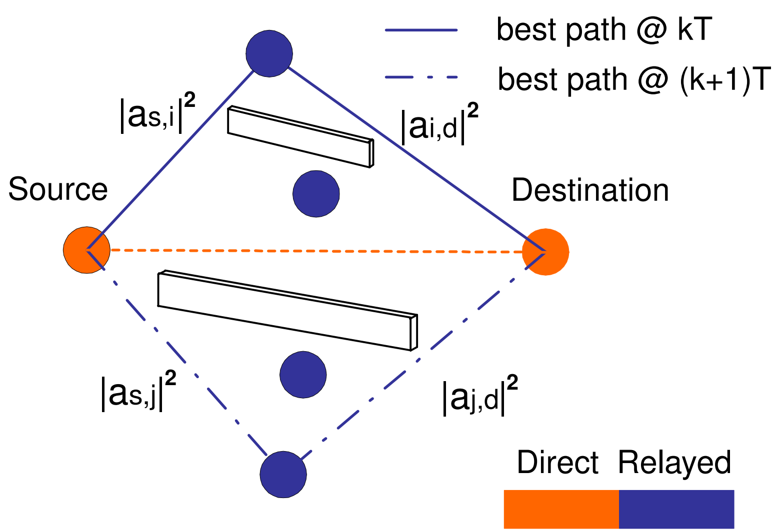

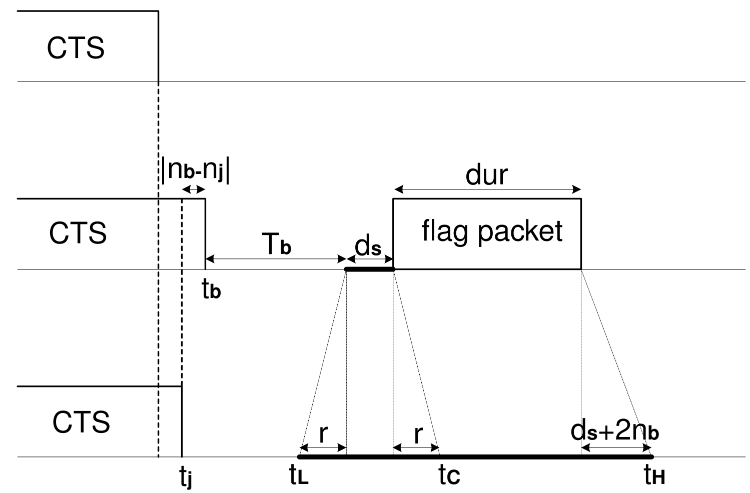

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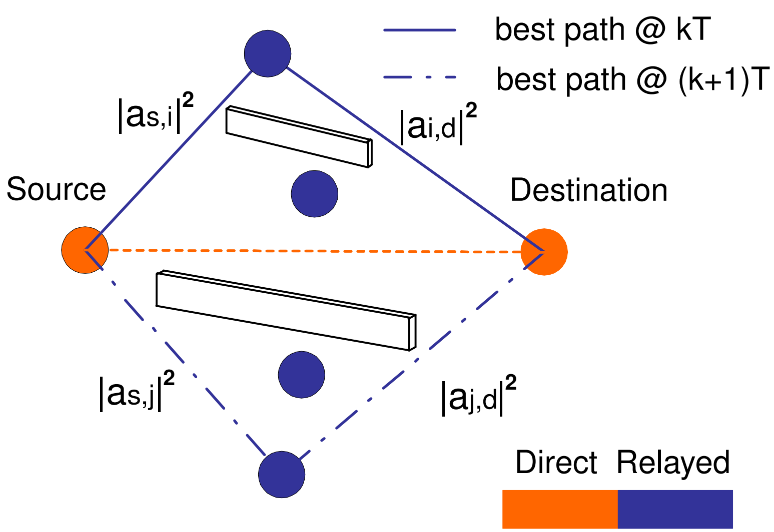
Discussion: a note on CSI and time synchronization



- 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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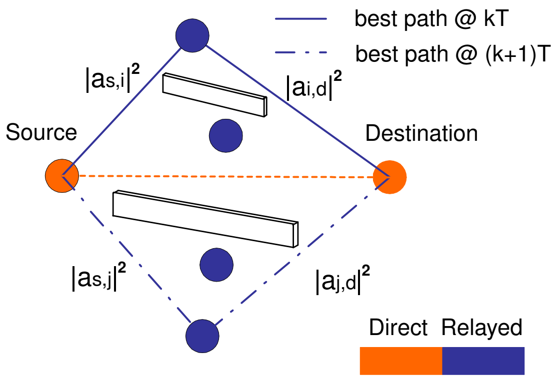
Outage Performance (1)



- Outage event between source s and destination d:

$$\log(1 + |a_{sd}|^2\ SNR) \leq \rho \Leftrightarrow |a_{sd}|^2 \leq (2^\rho - 1)/SNR \Leftrightarrow \gamma_{sd} \leq \Theta$$

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

$$b = \underbrace{arg}_{i}\ max\{min\{\gamma_{si}, \gamma_{id}\}\}, \quad i \in [1..M] \tag{13}$$

- Probability of outage via "best" relay:

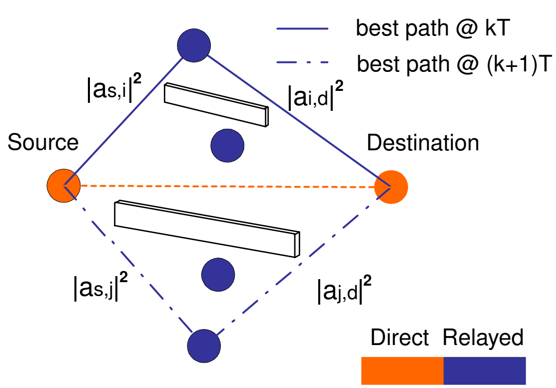
$$P_r(\gamma_{sb} < \Theta_2 \bigcup \gamma_{bd} < \Theta_2), \quad \Theta_2 = 2\ (2^{2\rho} - 1)/SNR \tag{14}$$

Outage Performance (2)

- The above outage probability of opportunistic relaying is calculated for the case of Rayleigh Fading:

$$P_r(\gamma_{sb} < \Theta_2 \bigcup \gamma_{bd} < \Theta_2) = \prod_{i=1}^{M}(1 - exp(-\Theta_2\,(\frac{1}{\overline{\gamma}_{si}} + \frac{1}{\overline{\gamma}_{id}}))) \tag{15}$$

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



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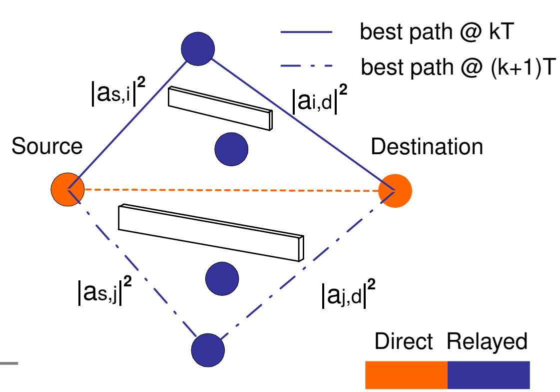

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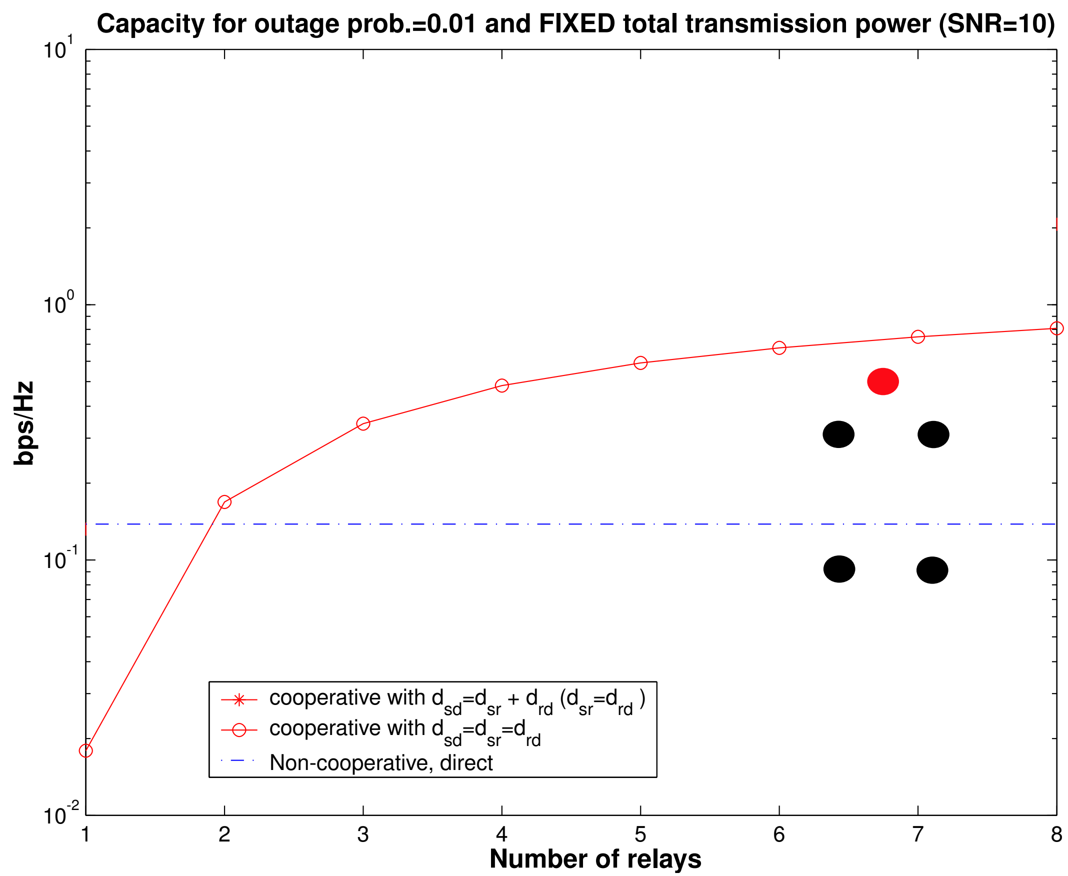

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- Opportunistic relays do help, even under a total tx power constraint!

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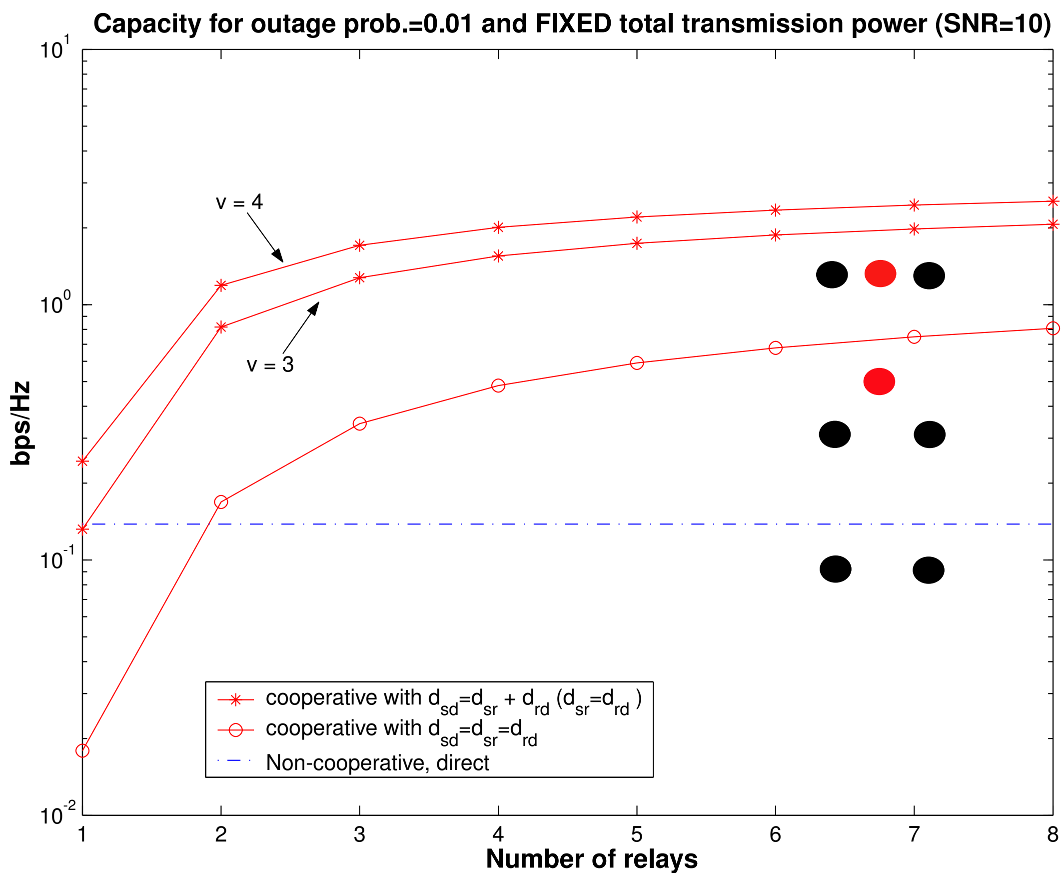

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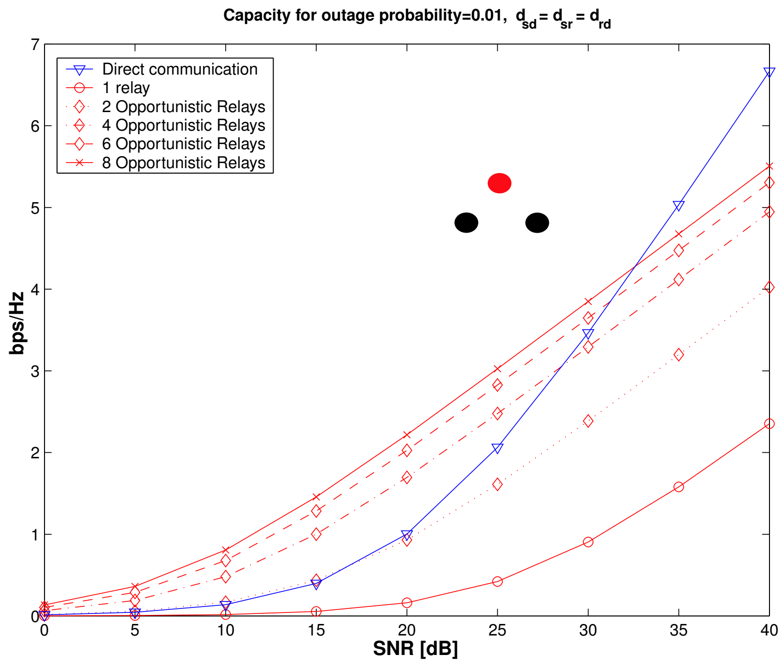

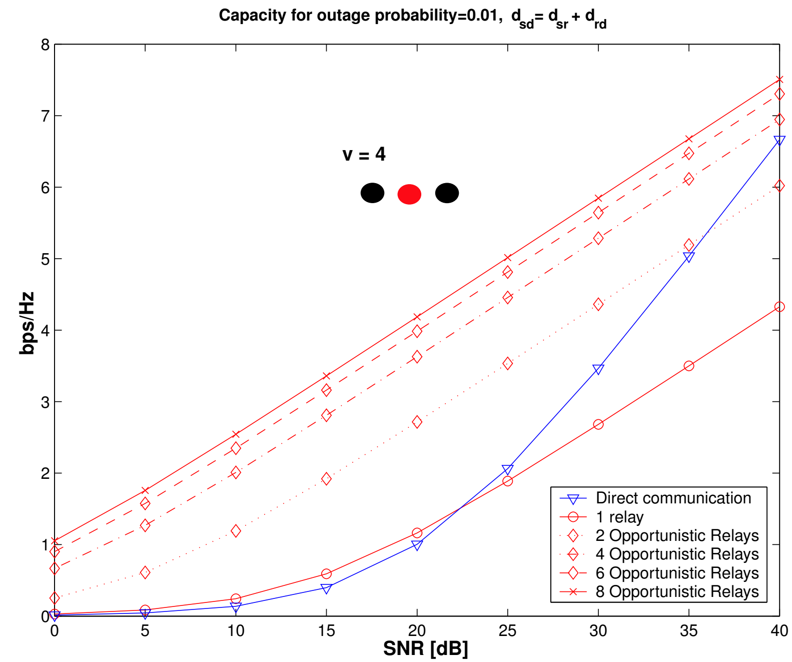

- $Pr^{out} = \delta.$

$$\rho_{opport} = \frac{1}{2} \log_2(1 - ln(1 - \delta^{1/M}) \frac{SNR}{2} \overline{\gamma}_{sid}) \quad (18)$$

$$\rho_{direct} = \log_2(1 - ln(1 - \delta) \, SNR \, \overline{\gamma}_{sid}) \quad (19)$$

Diversity-Multiplexing Tradeoff (1)

$$d \triangleq -\lim_{SNR \to \infty} \frac{\log P_e(\rho)}{\log SNR} \qquad r \triangleq \lim_{SNR \to \infty} \frac{\rho(SNR)}{\log SNR}$$

- 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 $r \in (0, 0.5)$.

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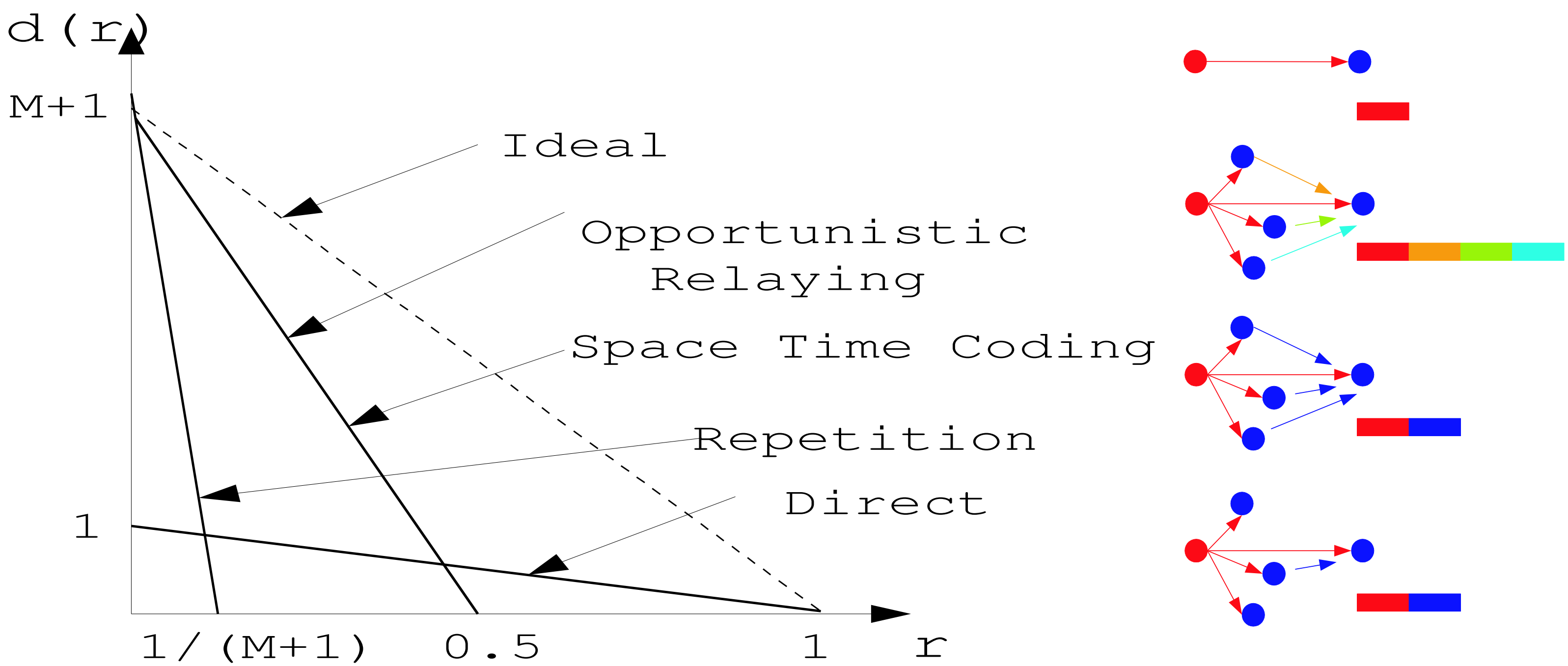
- **Theorem 1***: Under opportunistic relaying, the decode and forward protocol with M intermediate relays achieves the same diversity multiplexing tradeoff, as in Theorem 0.
- **Theorem 2***: Opportunistic amplify and forward achieves the same diversity multiplexing tradeoff stated in Theorem 0.

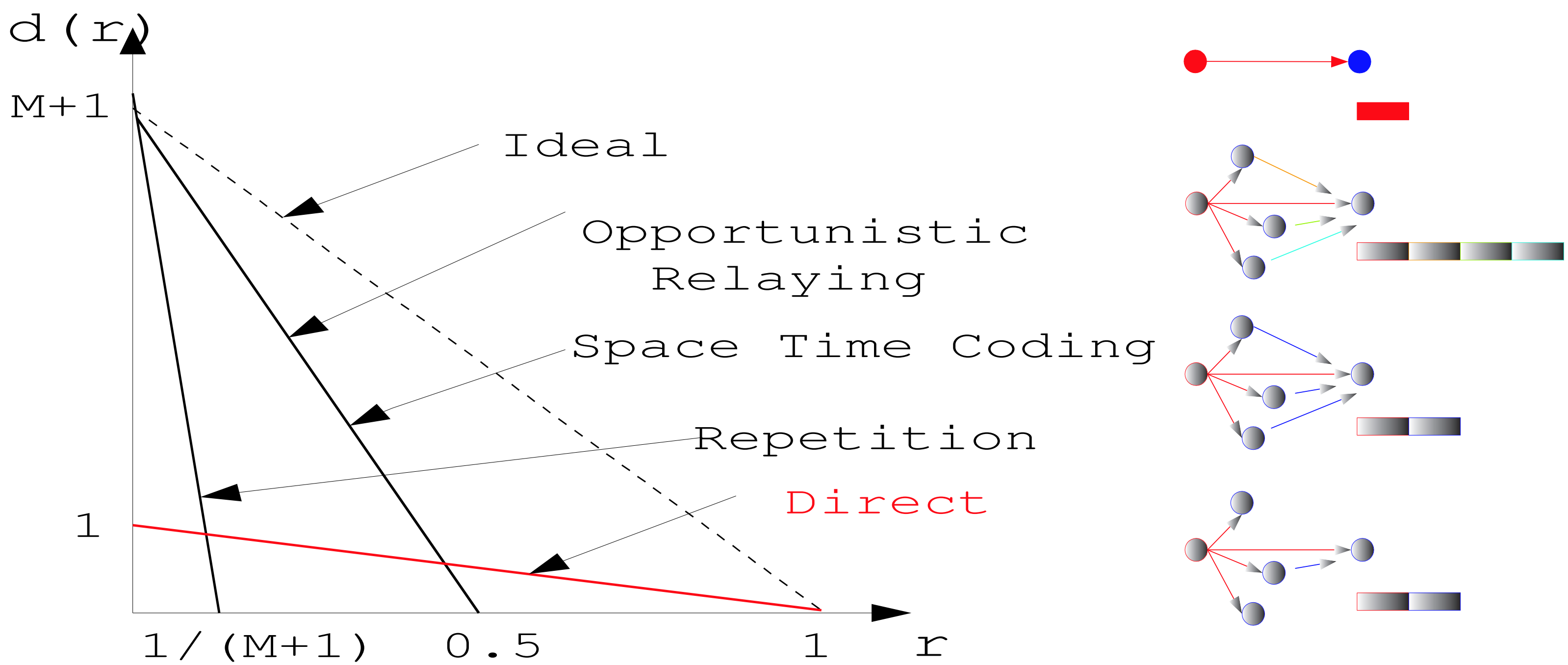
  *: In cooperation with Ashish Khisti.

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!

Diversity-Multiplexing Tradeoff (2)



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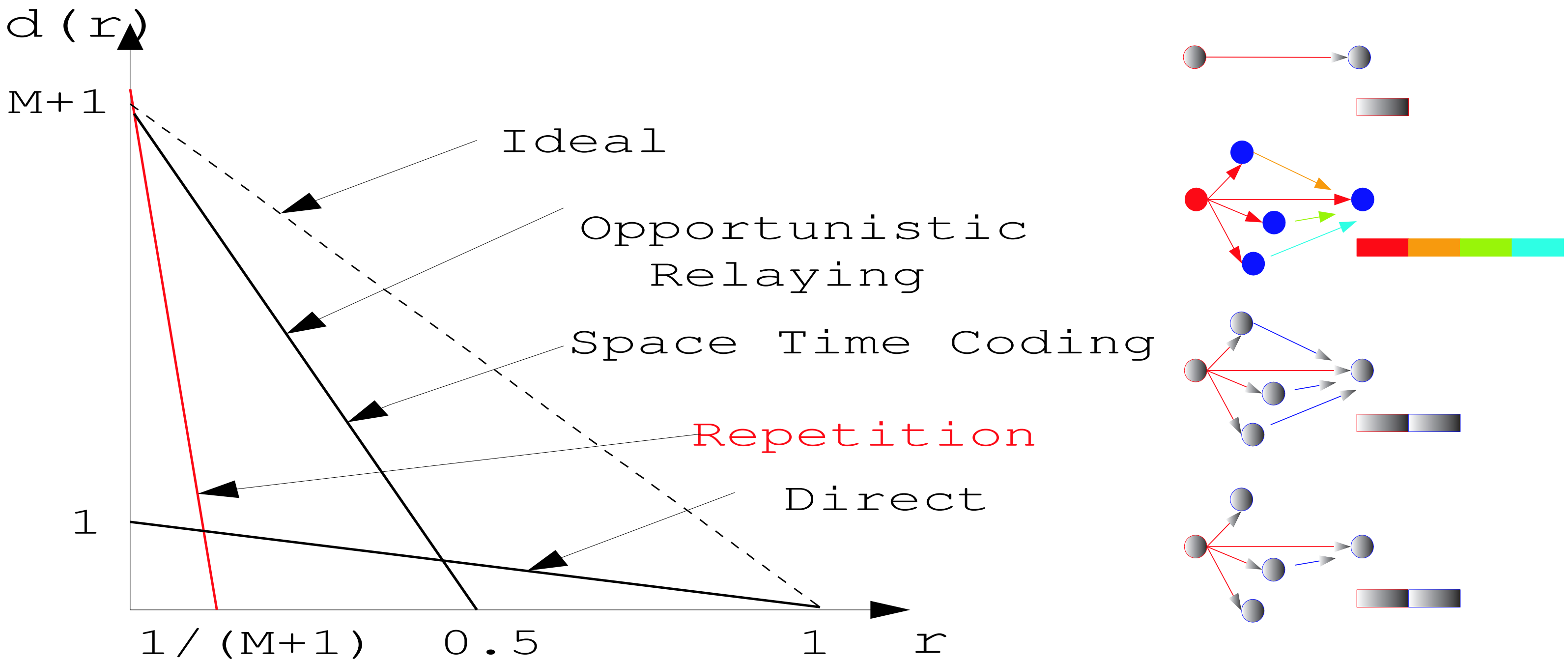

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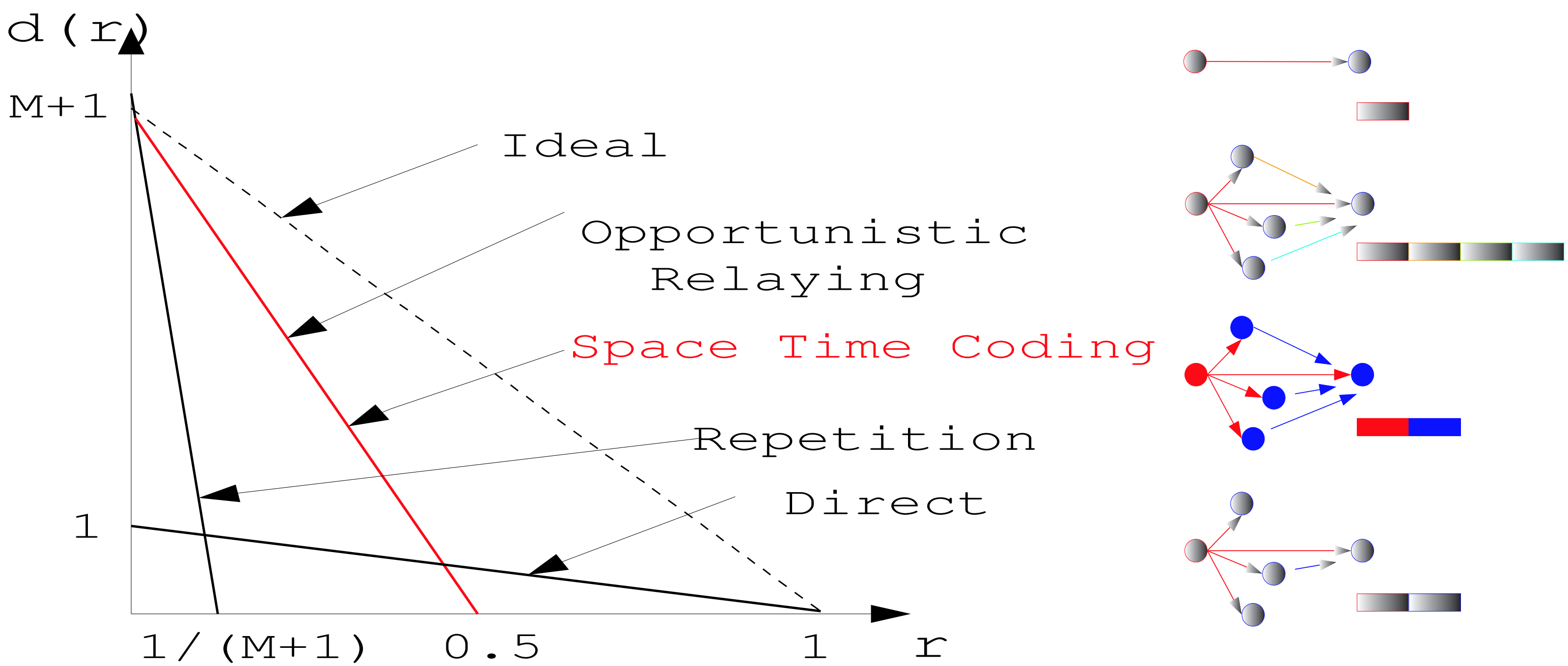

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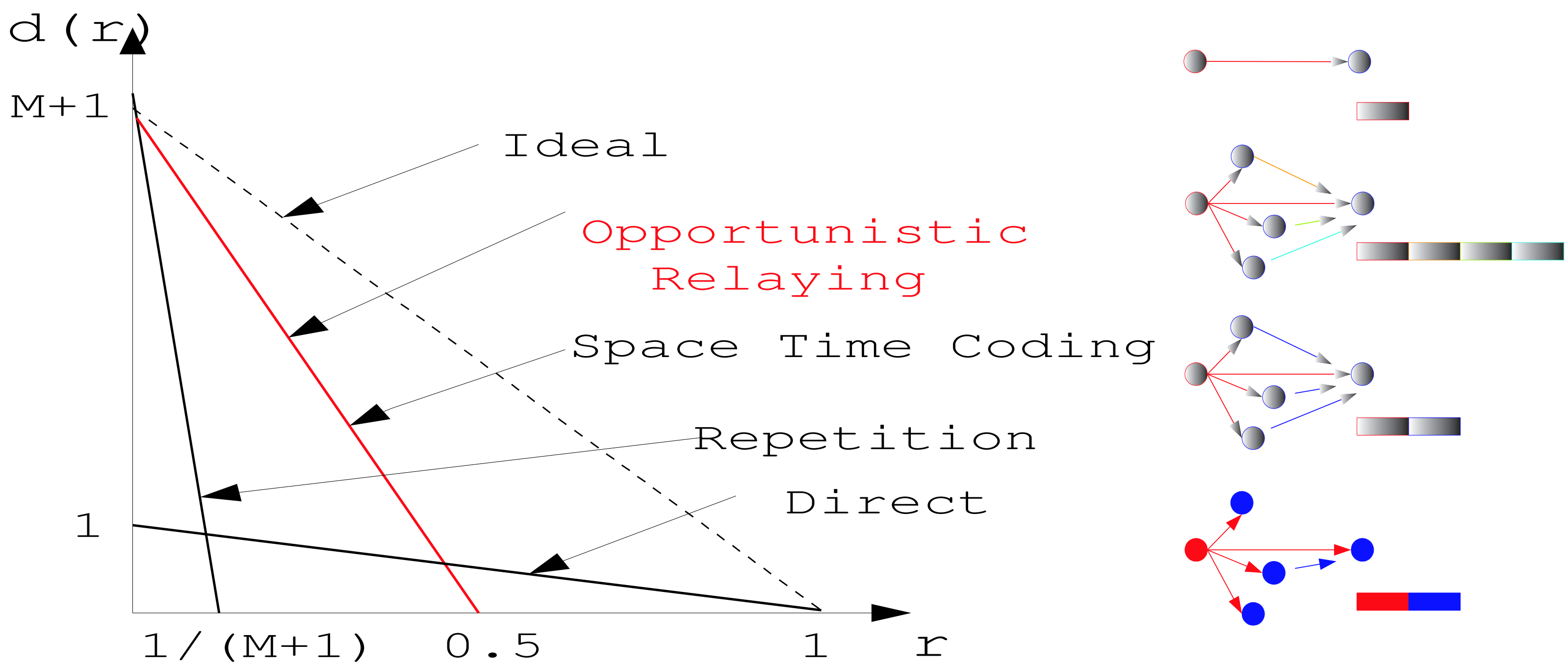

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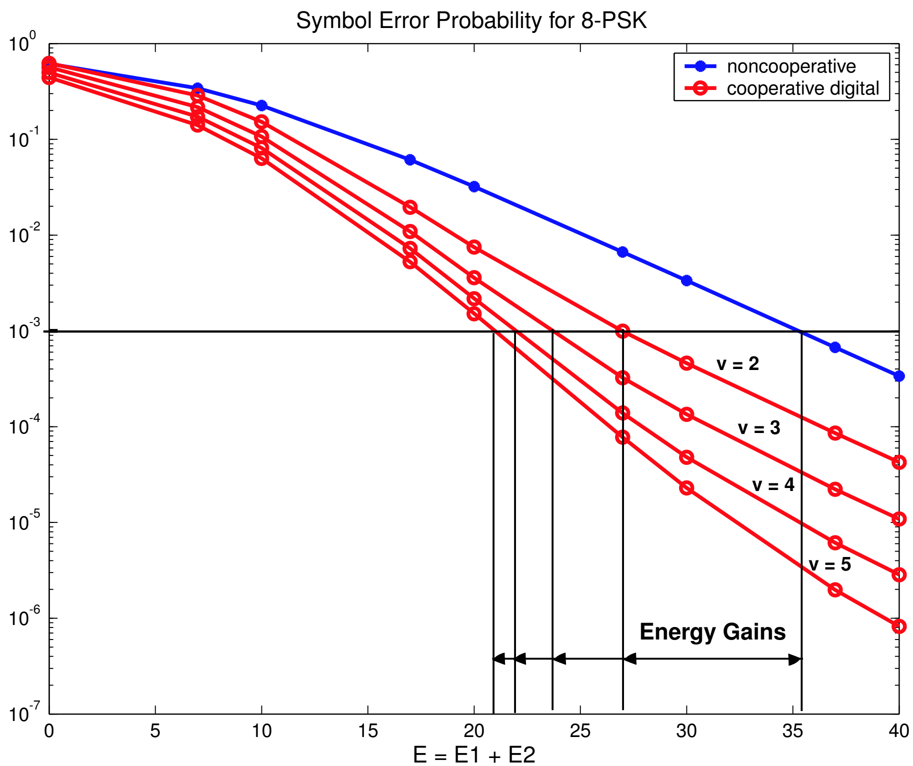
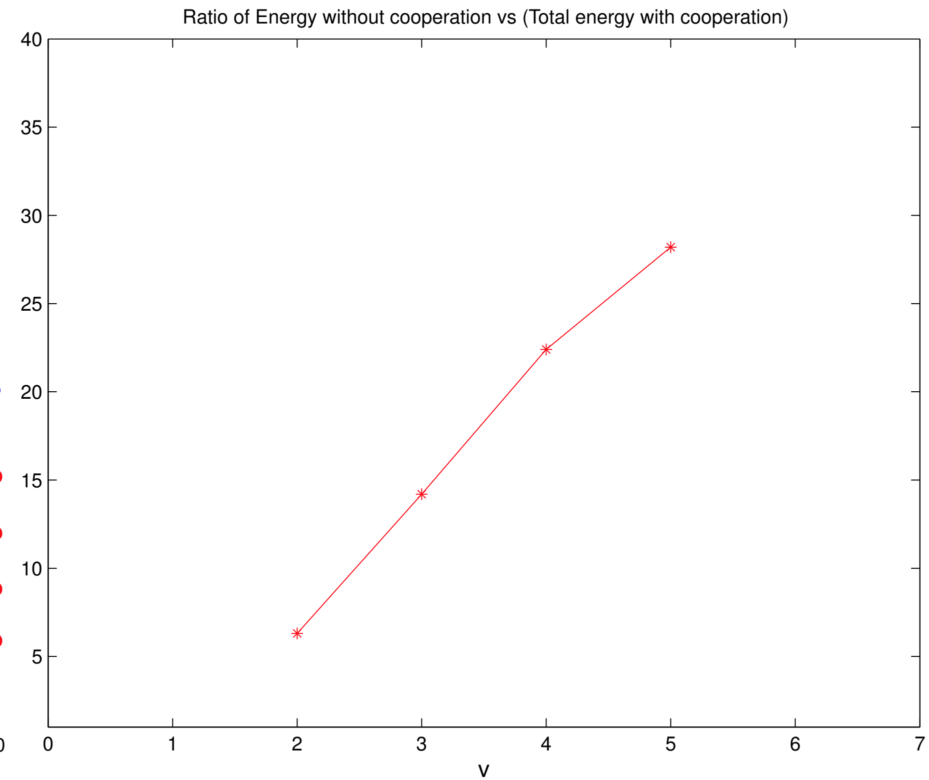
Results: Transmission Energy Gains

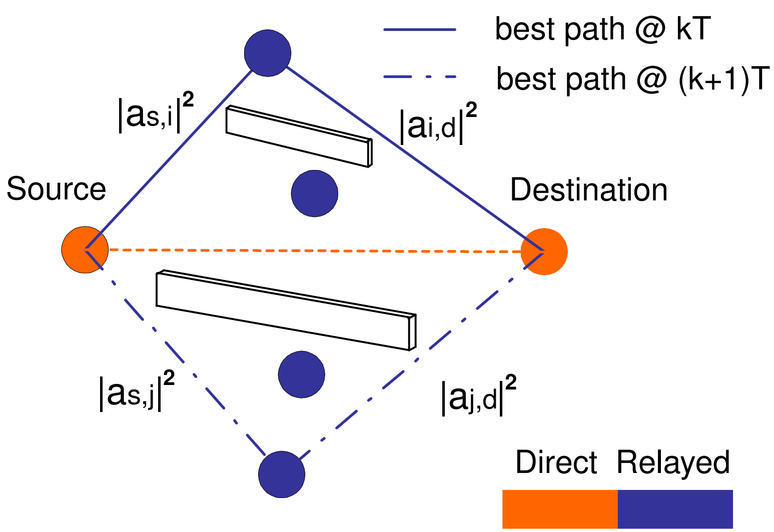




- Energy gains counterbalance the decrease of rate by a factor of 2.
- For the example above, 50% throughput increase is possible (8-PSK uncoded cooperative vs 2-PSK uncoded direct).

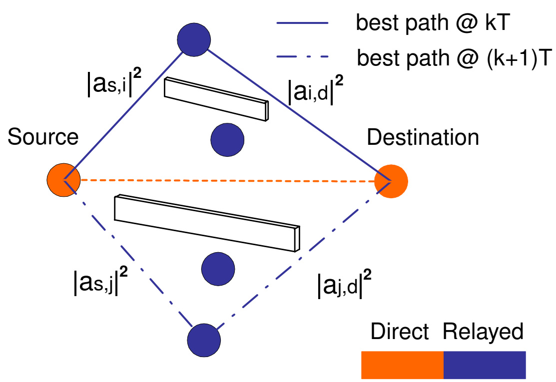
Results: Reception Energy Gains

- 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.



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.

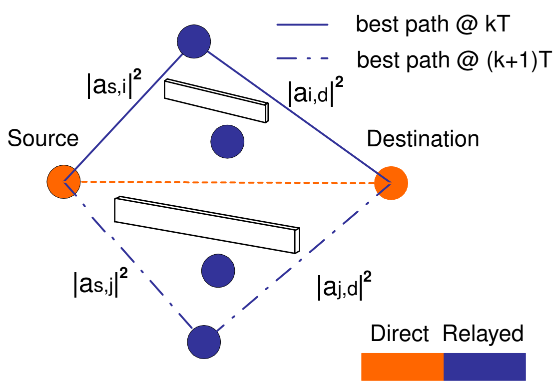


Results: Power Allocation Optimality (1)

- What if TOTAL power allocated to the relays was fixed?
- For amplify and forward networks, the equivalent system equation can be shown to be:

$$\begin{bmatrix} y_{D,1} \\ \frac{y_{D,2}}{\omega} \end{bmatrix} = \left[\begin{array}{c|c} \sqrt{P_{SD}}\, a_{SD} & 0 \\ \hline \frac{1}{\omega} \sum_{i=1}^{M} \frac{\sqrt{P_{SRi}}\sqrt{P_{RiD}}}{\sqrt{P_{SRi}+N_0}}\, a_{SRi}\, a_{RiD} & \frac{1}{\omega} \sqrt{P_{SD}}\, a_{SD} \end{array}\right] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_{D,1} \\ \frac{\tilde{n}_{D,2}}{\omega} \end{bmatrix}$$

$$\mathcal{E}[\tilde{n}_{D,2}\, \tilde{n}^*_{D,2}\, |H_{R\to D}] = N_0 \underbrace{(1 + \sum_{i=1}^{M} \frac{P_{RiD}\, |a_{Rid}|^2}{P_{SRi} + N_0})}_{\omega^2} = \omega^2 N_0 \quad (20)$$



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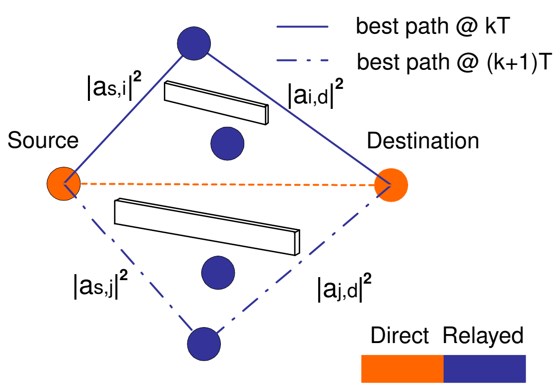
- What if TOTAL power allocated to the relays was fixed?
- For amplify and forward networks, the equivalent system equation can be shown to be:

$$\mathbf{y} = \begin{bmatrix} \sqrt{P_{SD}}\, h_{SD} & 0 \\ H_{21} & \frac{1}{\omega}\sqrt{P_{SD}}\, h_{SD} \end{bmatrix} \mathbf{x} + \mathbf{n} \quad (21)$$

$$\mathbf{y} = \mathbf{H}\,\mathbf{x} + \mathbf{n} \quad (22)$$

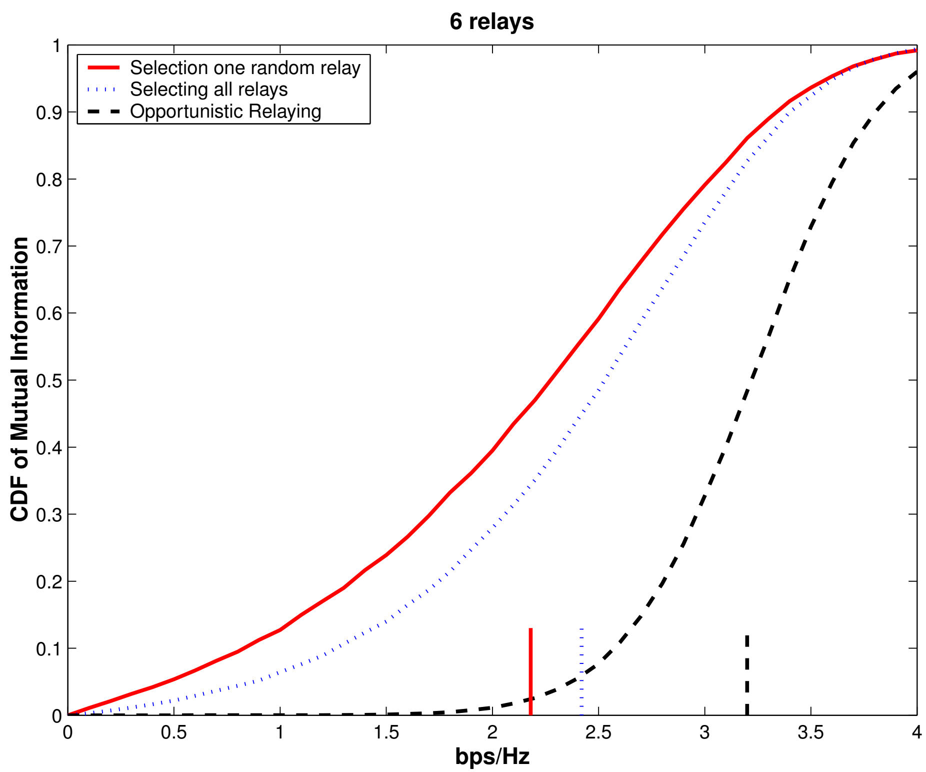
$$I_{AF} = \frac{1}{2}\,\log_2(1 + \frac{P_{SD}}{N_0}\,|h_{SD}|^2 + \frac{|H_{21}|^2}{N_0}) \quad (23)$$



Results: Power Allocation Optimality (2)

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).



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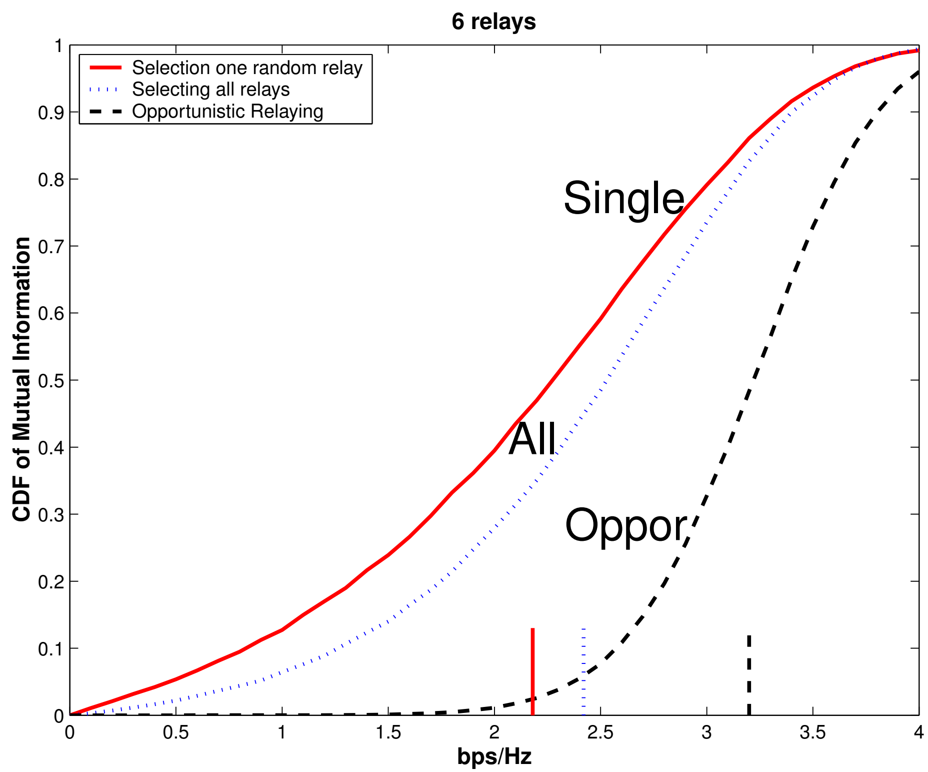
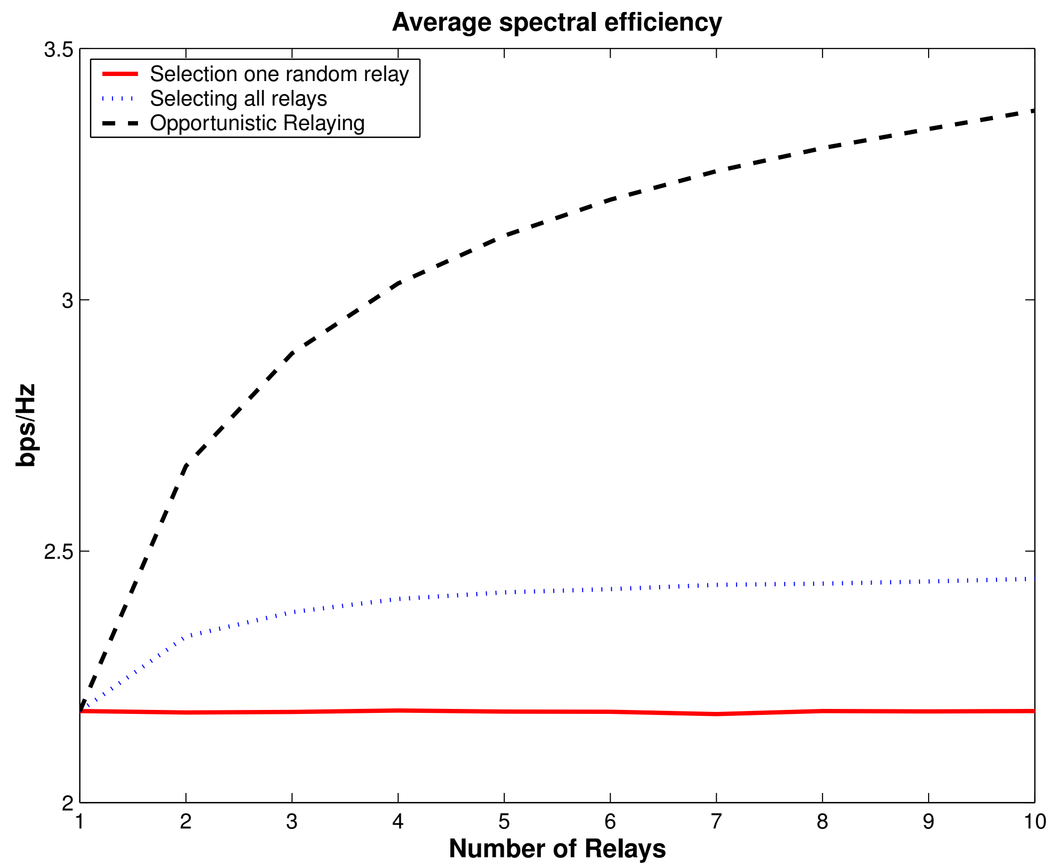


Results: Power Allocation Optimality (3)



- 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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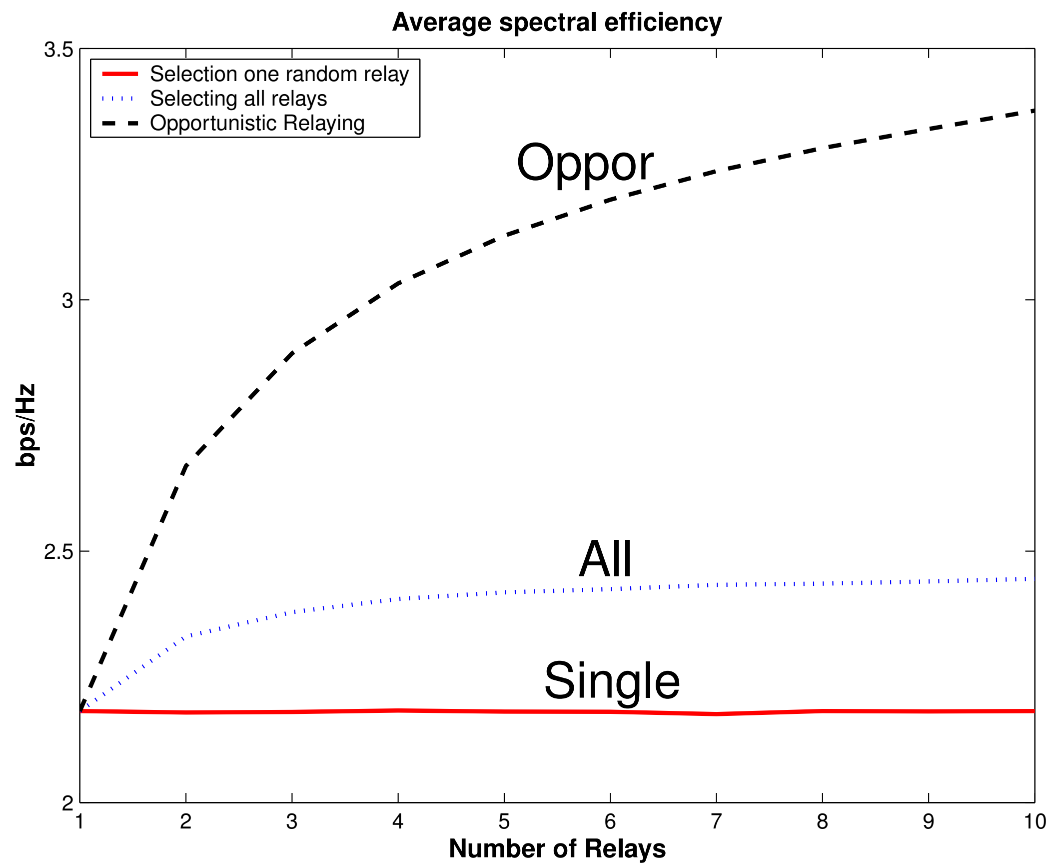

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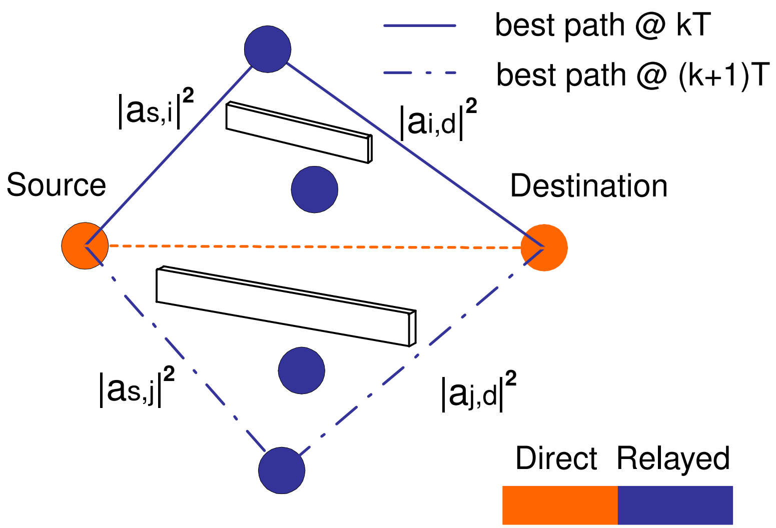
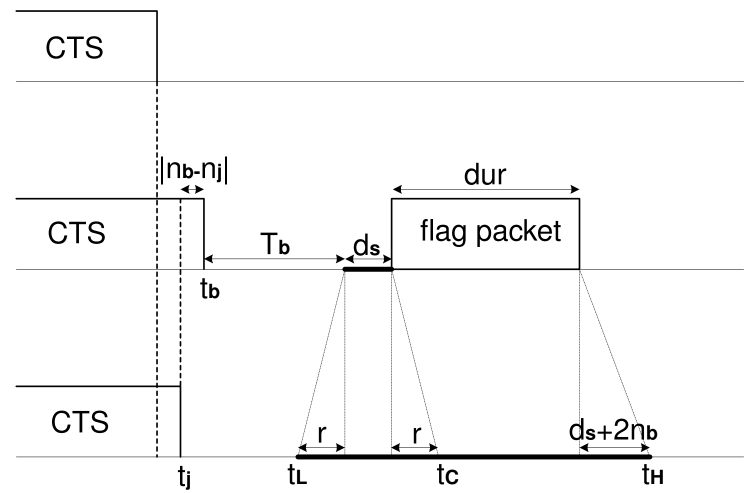
Overhead: Collision Probability (1)





$$Policy\ I: \quad h_i = \min\{|a_{si}|^2, |a_{id}|^2\} \qquad Policy\ II: \quad h_i = \frac{2}{\frac{1}{|a_{si}|^2} + \frac{1}{|a_{id}|^2}} = \frac{2\,|a_{si}|^2\,|a_{id}|^2}{|a_{si}|^2 + |a_{id}|^2}$$

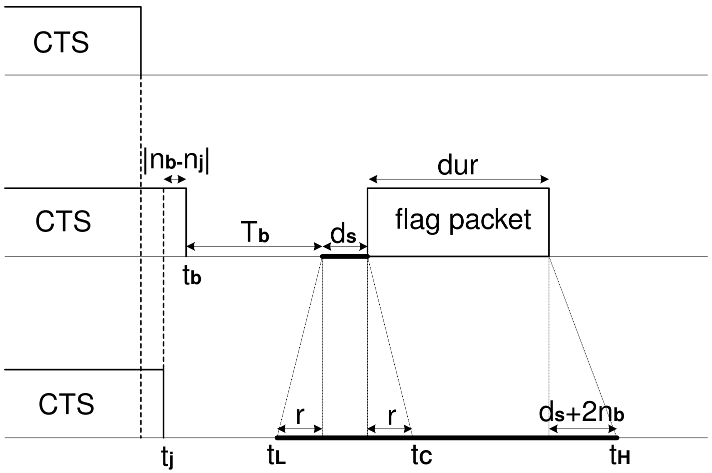
$$T_i = \frac{\lambda}{h_i} \tag{24}$$

Here λ has the units of time. For the discussion in this work, λ has simply values of $\mu secs$.

$$h_b = \max\{h_i\}, \iff \tag{25}$$

$$T_b = \min\{T_i\},\ i \in [1..M]. \tag{26}$$

Overhead: Collision Probability (2)

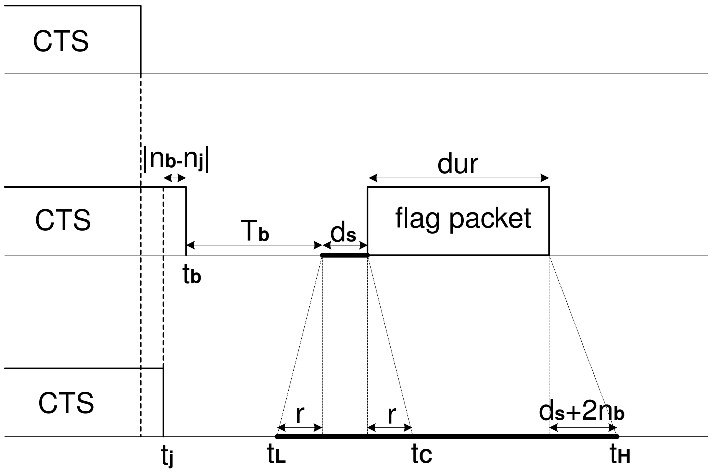


Worst case scenario:

$$Pr(Collision) \leq Pr(any\ T_j < T_b + c \mid j \neq b)$$
$$where\ T_b = \min\{T_j\},\ j \in [1, M]\ and\ c > 0.$$

$$(a)\ No\ Hidden\ Relays:\ c = r_{max} + |n_b - n_j|_{max} + d_s$$
$$(b)\ Hidden\ Relays:\ c = r_{max} + |n_b - n_j|_{max} + 2d_s + dur + 2n_{max}$$

Overhead: Collision Probability (2)



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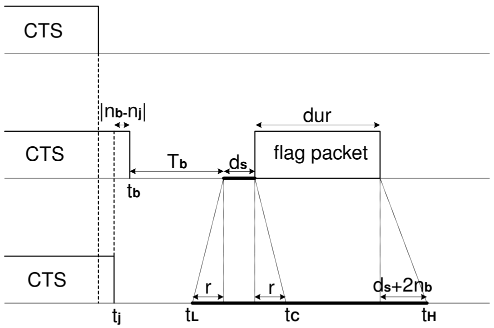
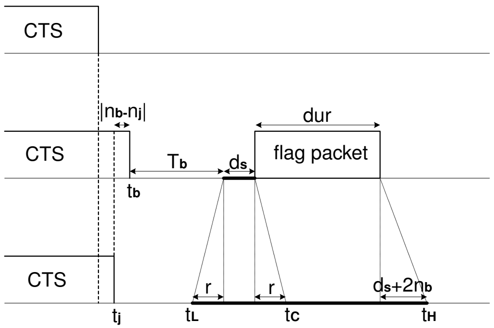
- n_j: propagation delay between relay j and destination. n_{max} is the maximum.
- r: propagation delay between two relays. r_{max} is the maximum.
- d_s: receive-to-transmit switch time of each radio.
- dur: duration of flag packet, transmitted by the "best" relay.

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:

Overhead: Collision Probability (3)



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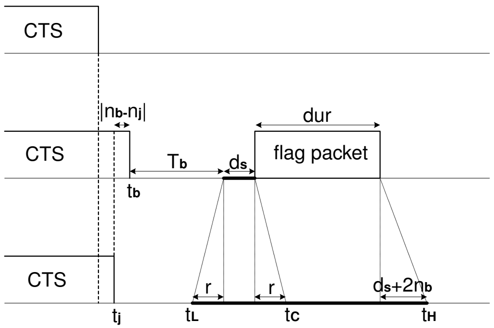
- $$Pr(any\, T_j < T_b + c \mid j \neq b) \equiv Pr(Y_2 < Y_1 + c) \tag{30}$$

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:

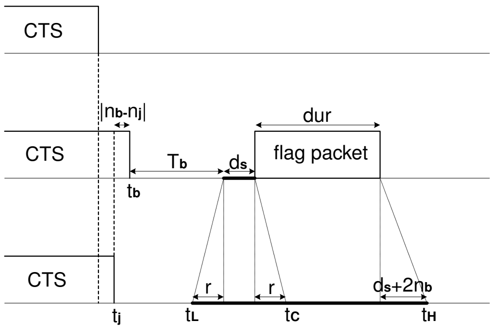
- $$Pr(any\, T_j < T_b + c \mid j \neq b) \equiv Pr(Y_2 < Y_1 + c) \tag{33}$$

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

$$Pr(Y_2 < Y_1 + c) = Pr(\frac{1}{h_{(2)}} < \frac{1}{h_{(1)}} + \frac{c}{\lambda}) \tag{34}$$

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

Overhead: Collision Probability (3)



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

- However λ needs to be kept small:

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

Overhead: Collision Probability (4)

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:

$$Pr(Y_2 < Y_1 + c) = 1 - I_c \tag{39}$$

$$I_c = M\ (M-1)\ \int_c^{+\infty} f(y)\ [1 - F(y)]^{M-2}\ F(y-c)\ dy \tag{40}$$

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

Overhead: Collision Probability (4)

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:

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

- 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 $T_c \simeq 200$ milliseconds.

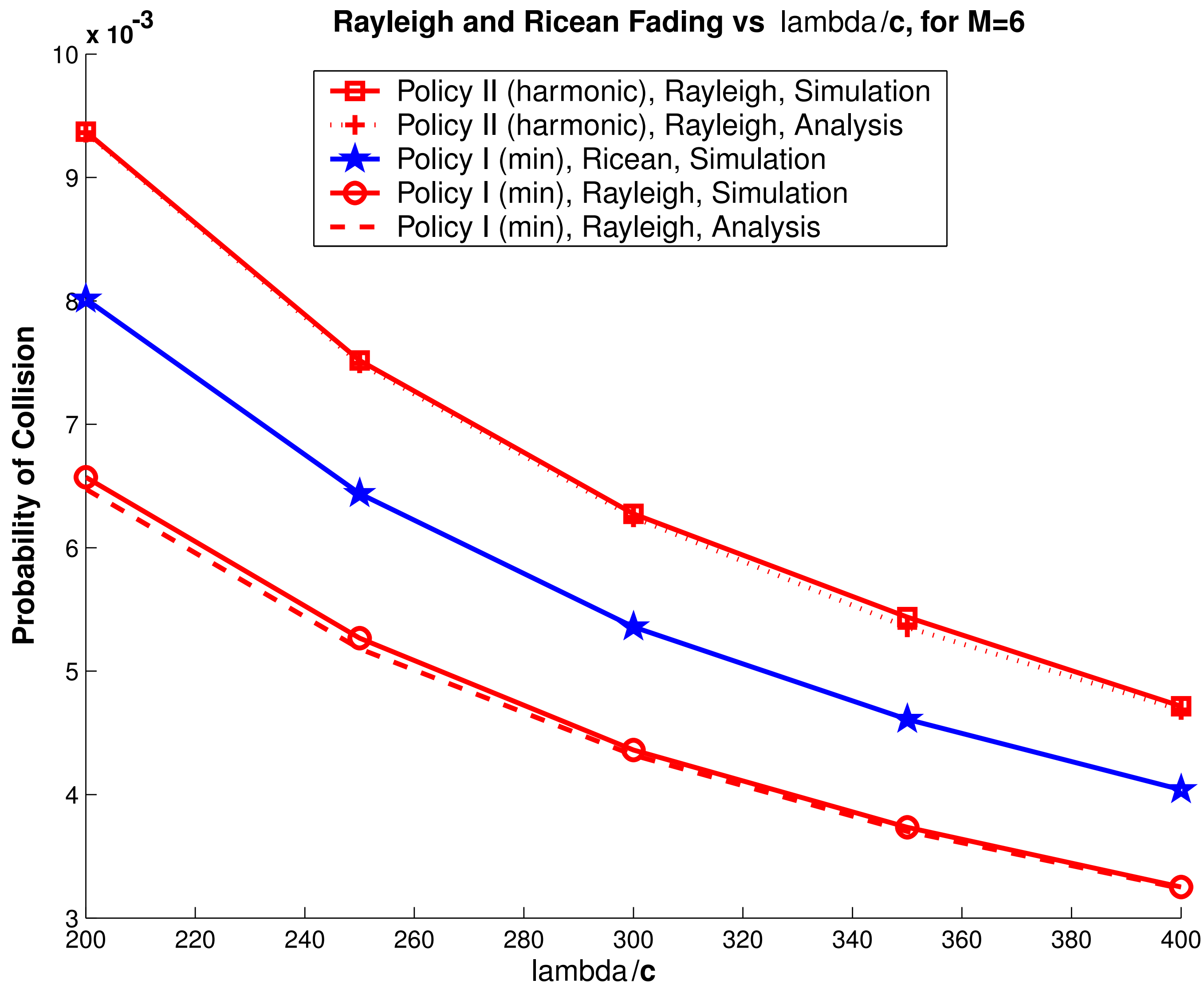
  For $c/\lambda \approx 1/200 \Rightarrow Pr(Collision) \leq 0.6\%$ for policy I.

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

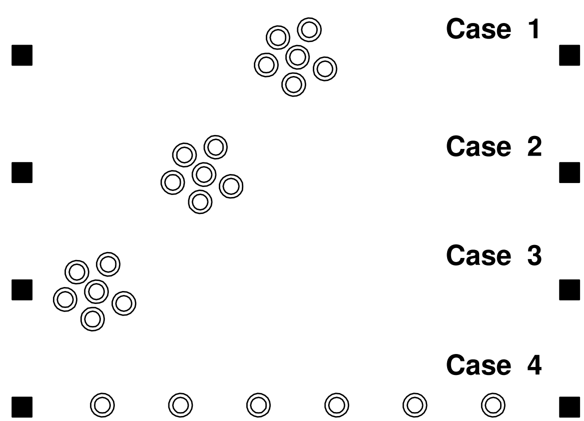
  For $c \approx 1\mu s \Rightarrow \lambda \approx 200\mu s \simeq \frac{1}{1000}Tc$.

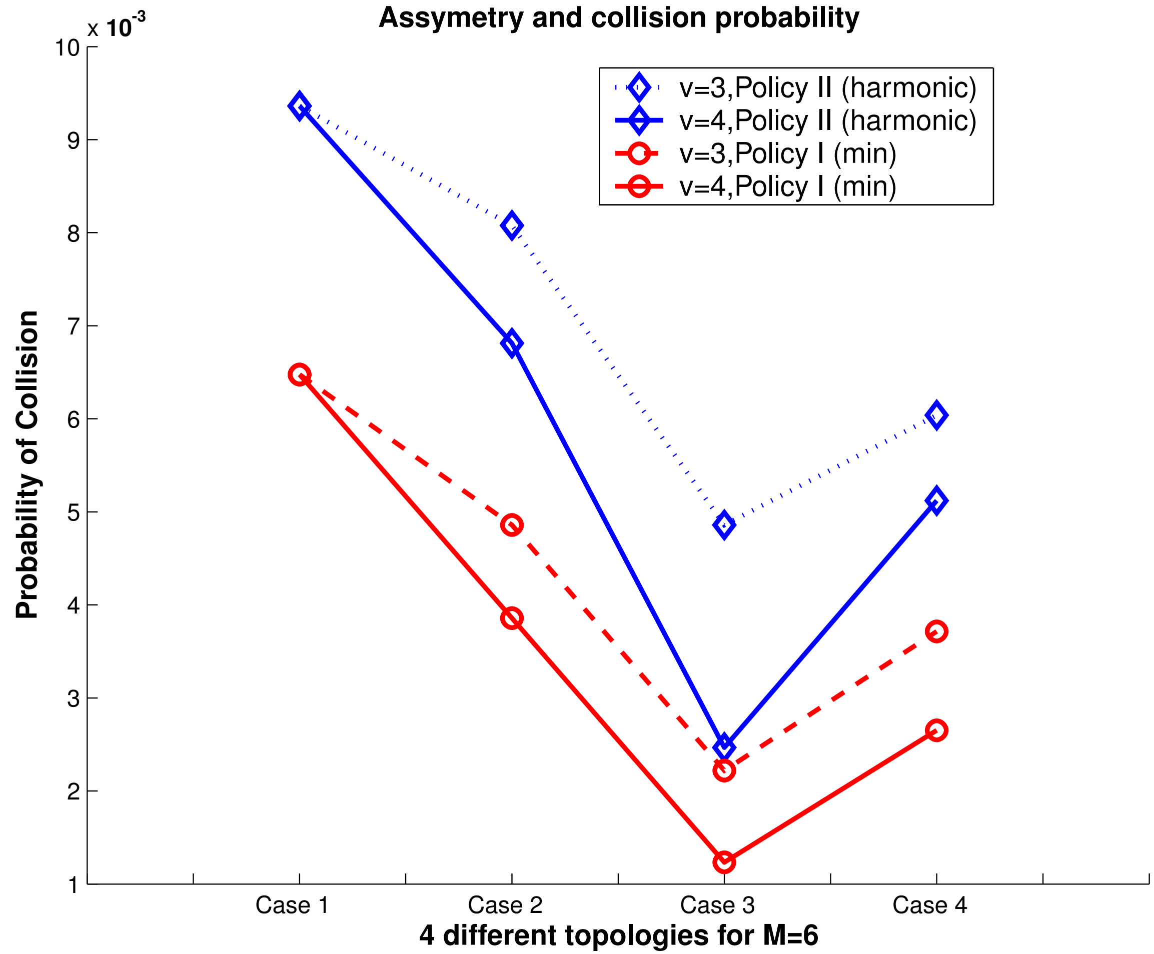
Rigorous analysis earns you trips around the world...

Overhead: Collision Probability (5)

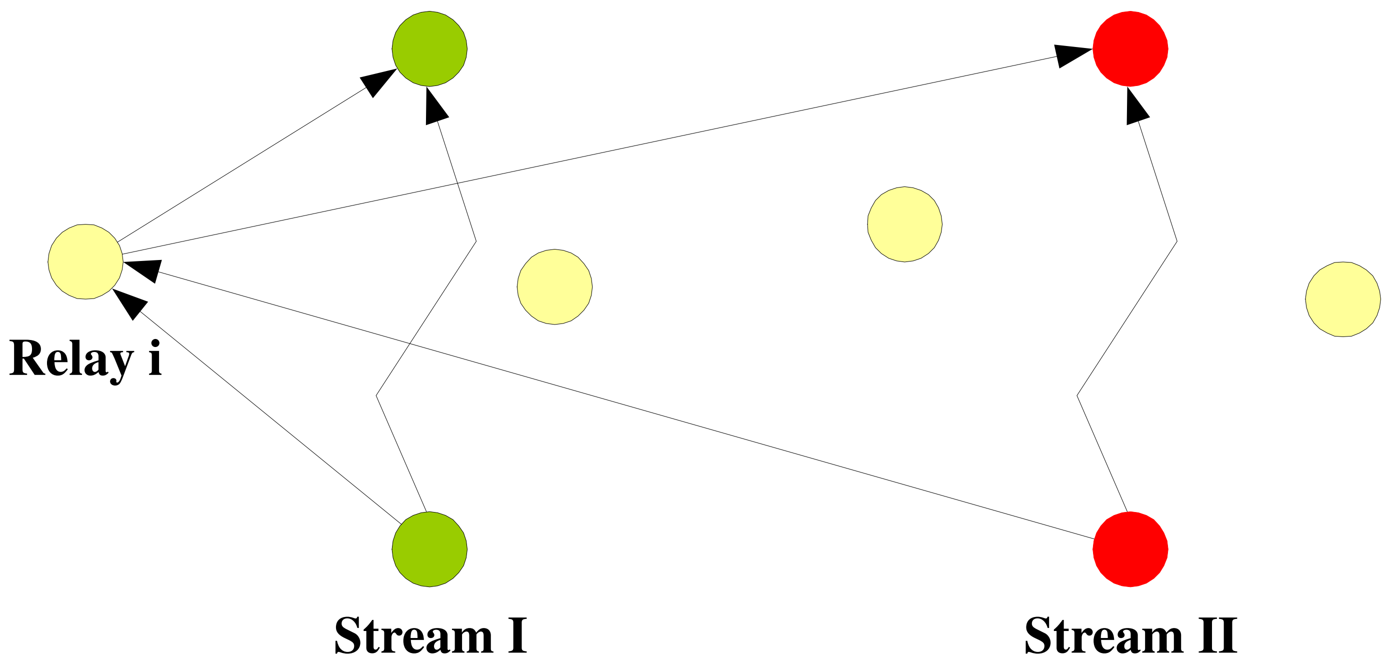


Overhead: Collision Probability (6)





...and a Remark...



- $$b = \underbrace{arg}_{i}\ max\{min\{SNR_{si}, SNR_{id}\}\} = max\{SNR_{sid}\}, \quad i \in [1..M] \tag{43}$$

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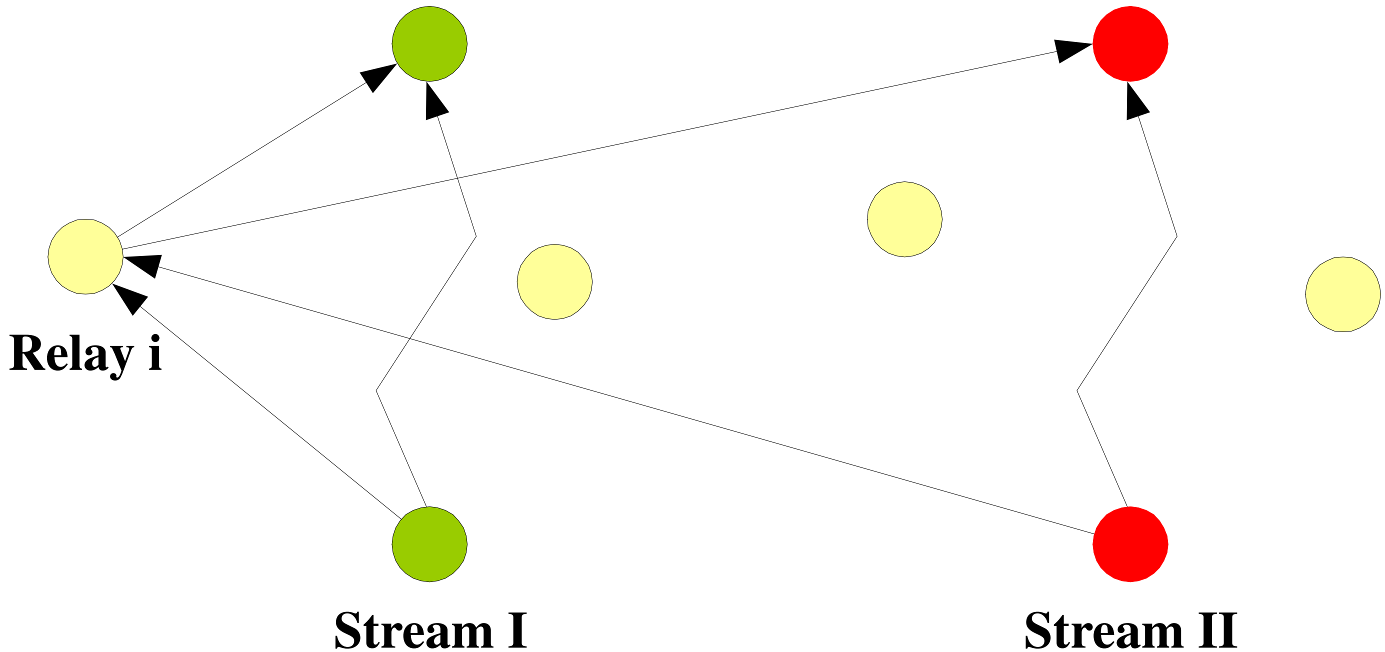


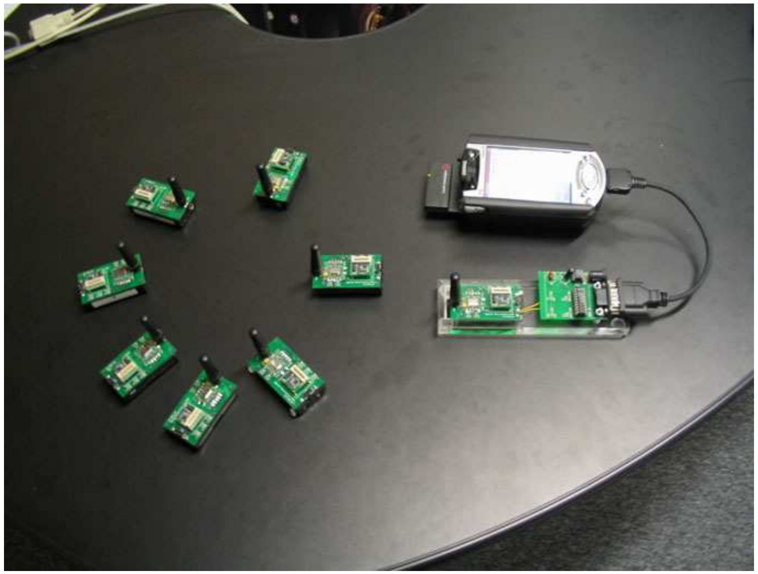
- $$b = \underbrace{arg}_{i}\ max\{min\{SNR_{si}, SNR_{id}\}\} = max\{SNR_{sid}\}, \quad i \in [1..M] \tag{45}$$

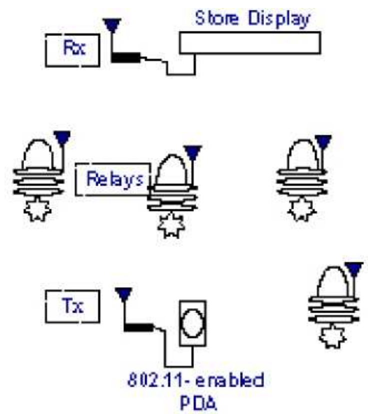
- $$b = \underbrace{arg}_{i}\ max\{min\{SINR_{si}, SINR_{id}\}\} = max\{SINR_{sid}\}, \quad i \in [1..M] \tag{46}$$

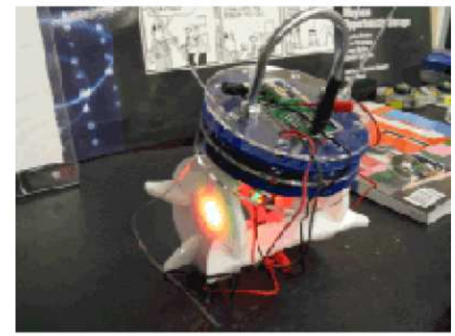
Outline

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

Implementation: Hardware

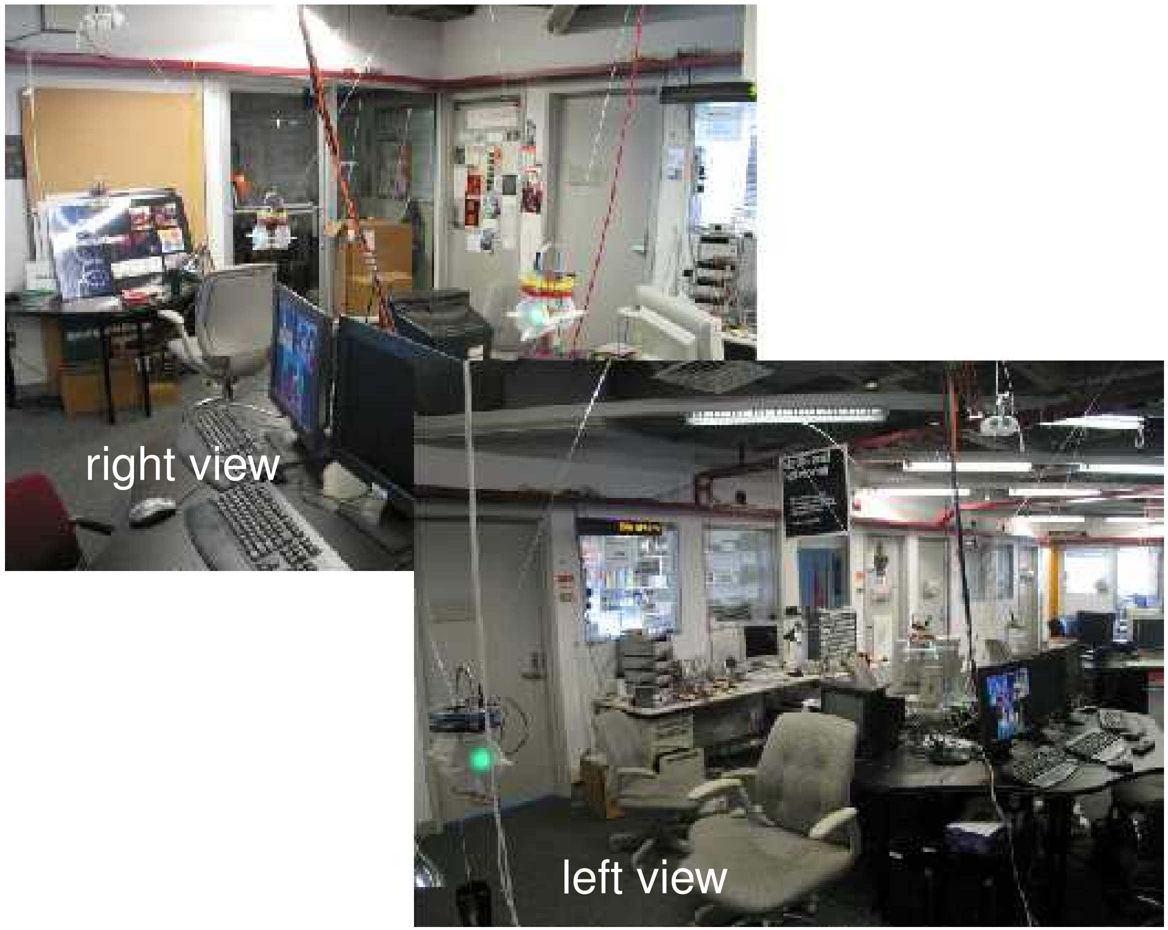






- Rethinking wireless:
  approach needs access to physical (layer 1), link (layer 2), routing (layer 3).
- COTS radios usually give limited access to all layers $\Rightarrow$
- We built our own low cost embedded Software Defined Radios (SDRs).
- We built a room size cooperative diversity demo.

Implementation: Demo Setup



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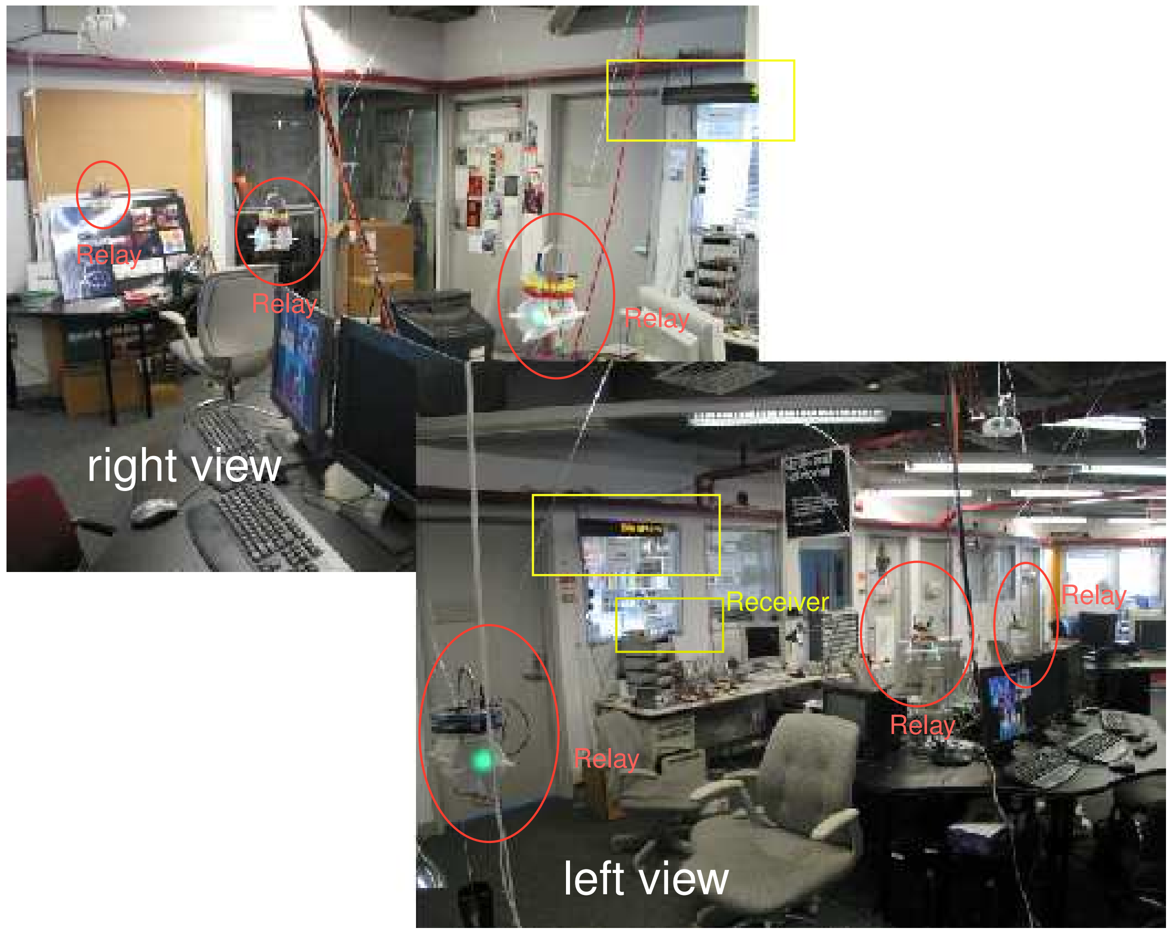
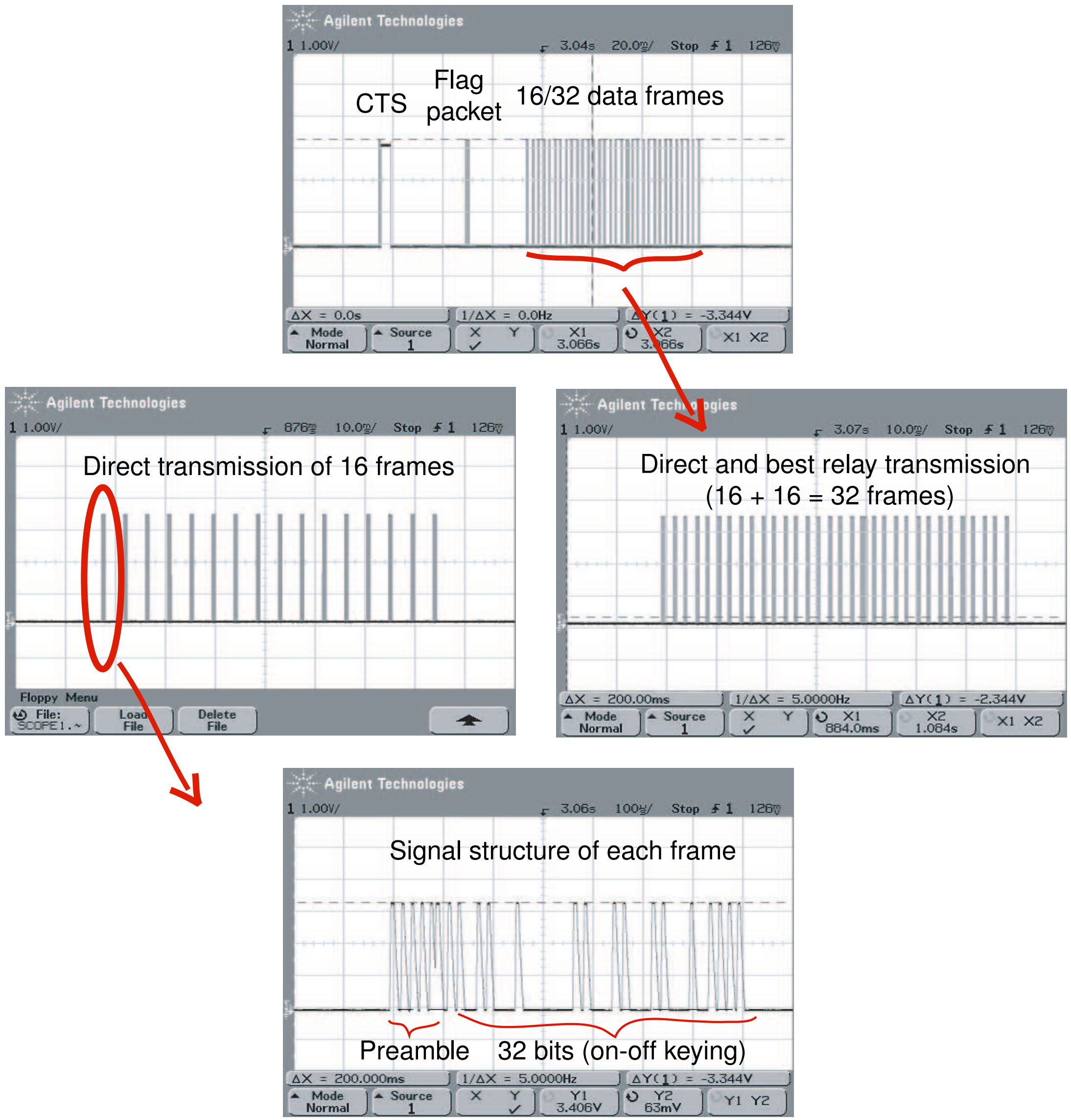


Implementation: Signal Structure



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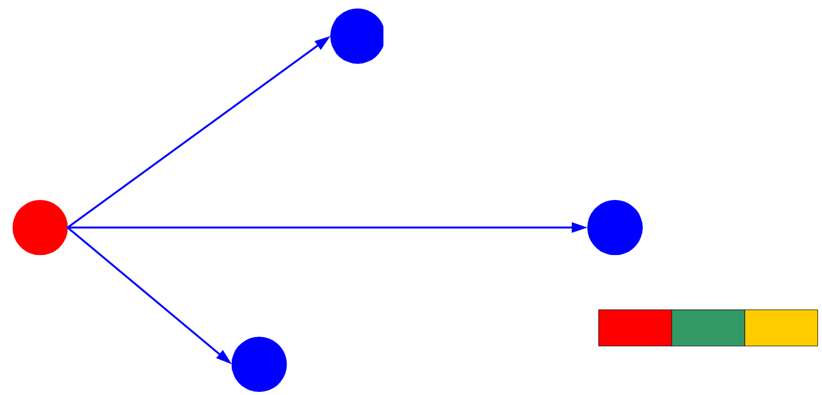
Coordination, Cooperation and Time Keeping

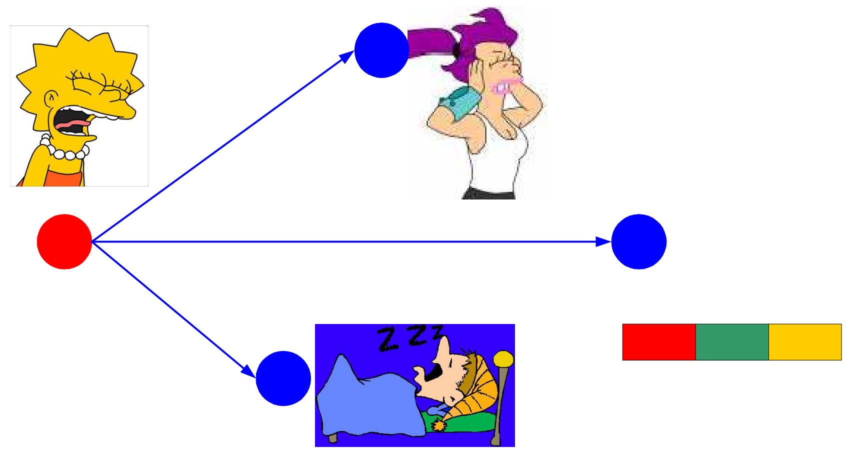


- Relays (or receiver) might be busy or in sleep mode!
- Time keeping could simplify required *scheduling*.
- *Time keeping as the basis of scalable communication*.

Extensive work on Network Time Keeping:

- centralized
- decentralized

Coordination, Cooperation and Time Keeping



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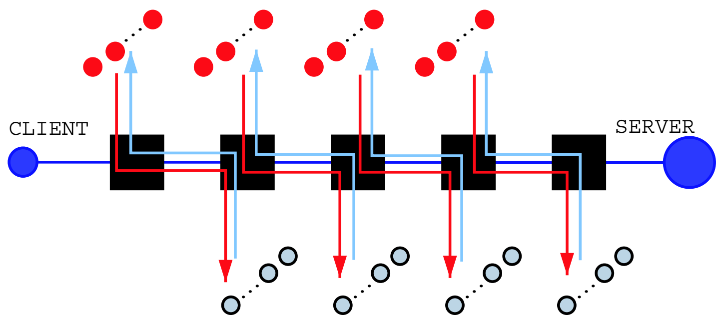
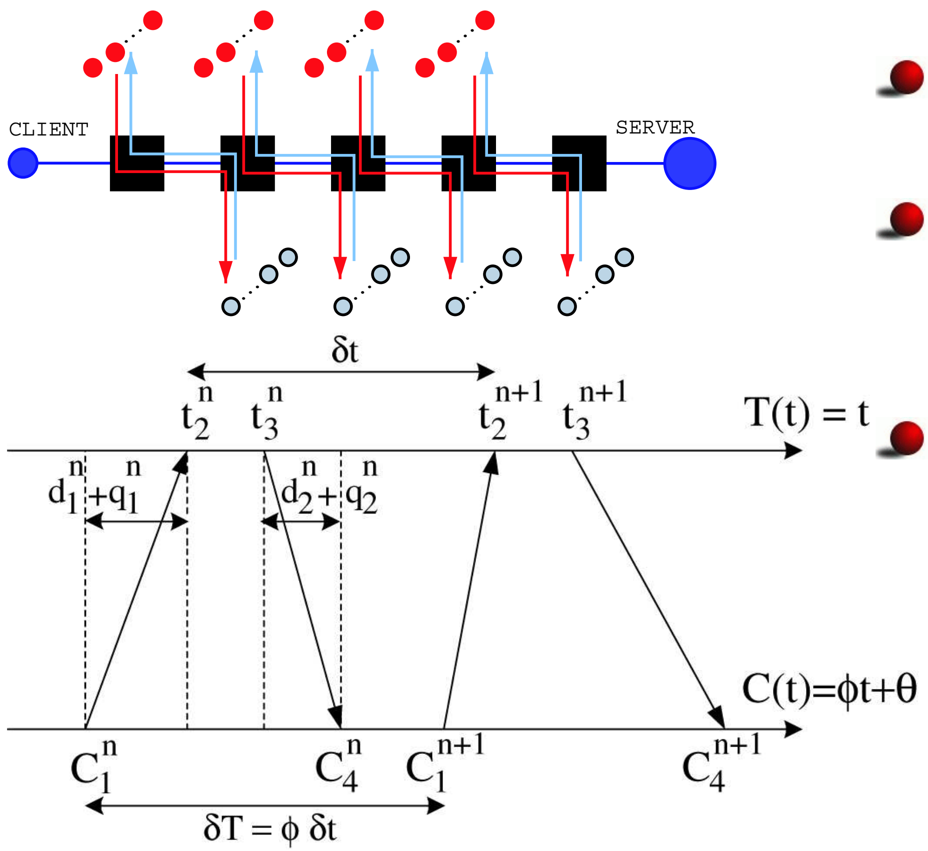
Centralized Time Keeping



- 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).

Estimation of ϕ and θ, with minimum communication BW and computation requirements.

Centralized Time Keeping



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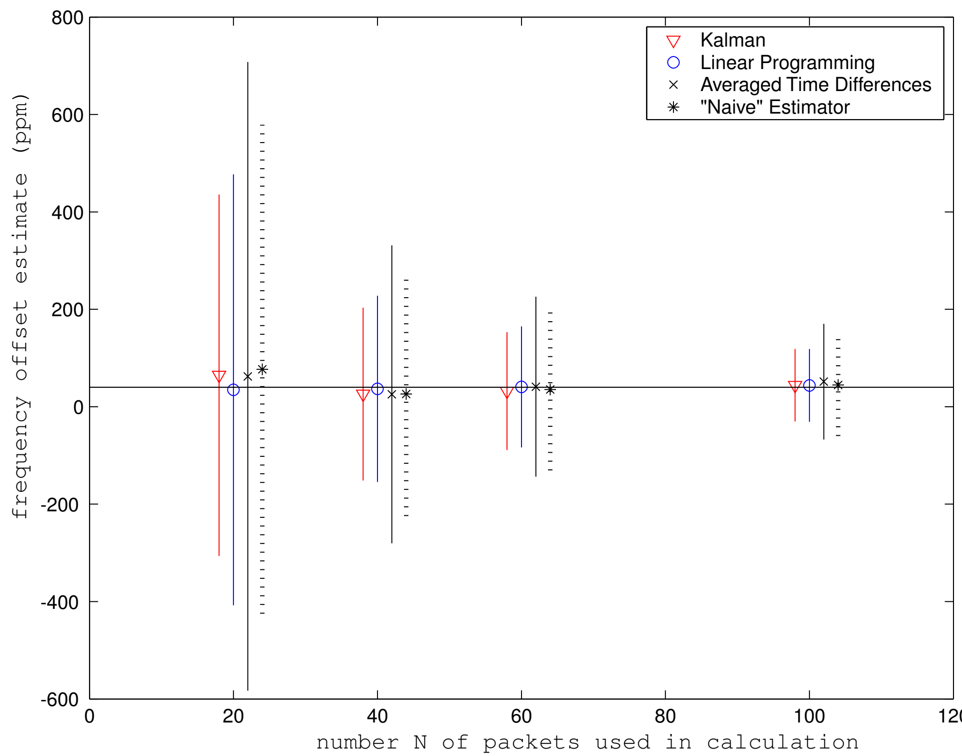
Centralized Time Keeping Results



- Improving *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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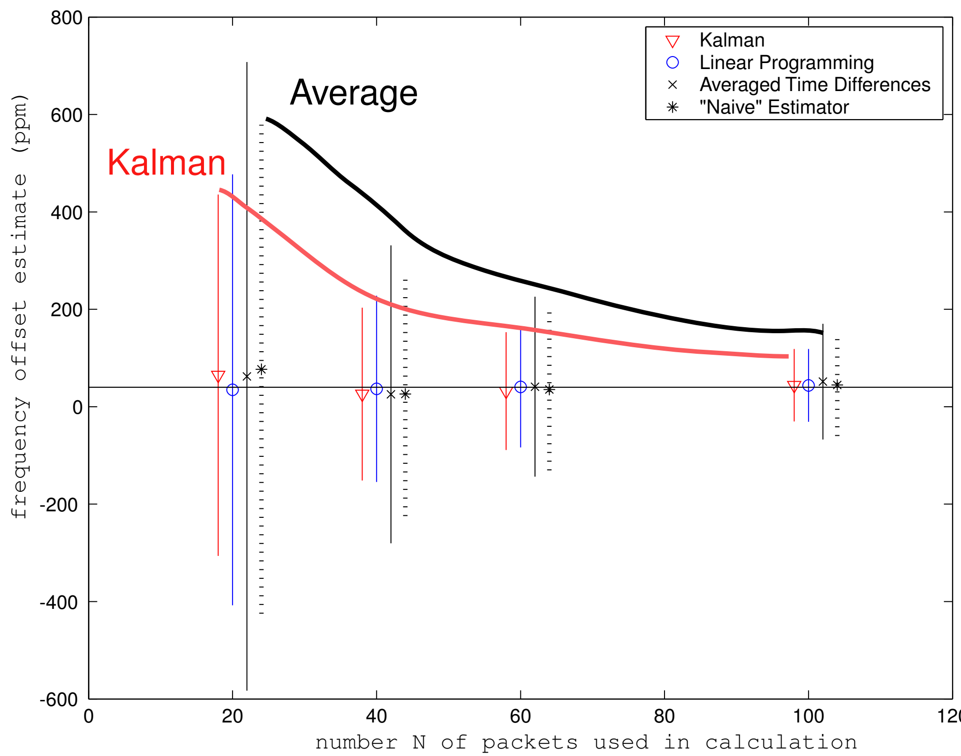

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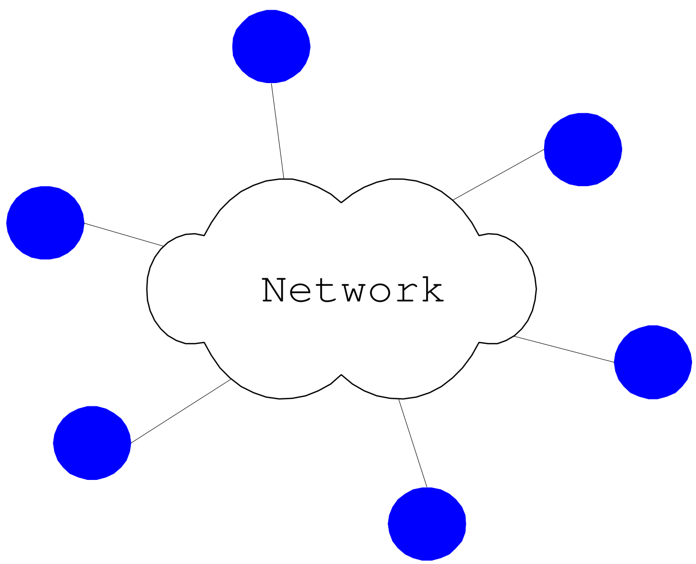
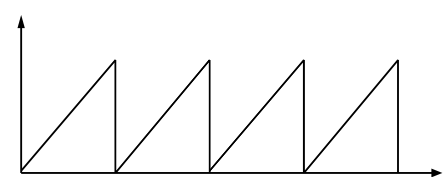
- Implemented and tested using existed NTP infrastructure.

Decentralized Time Keeping

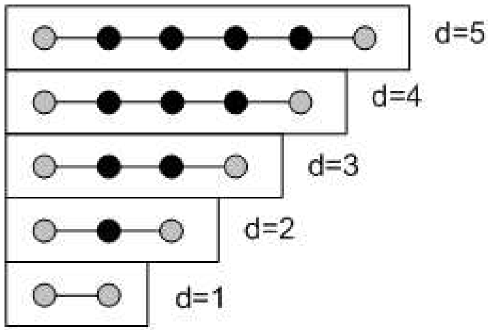


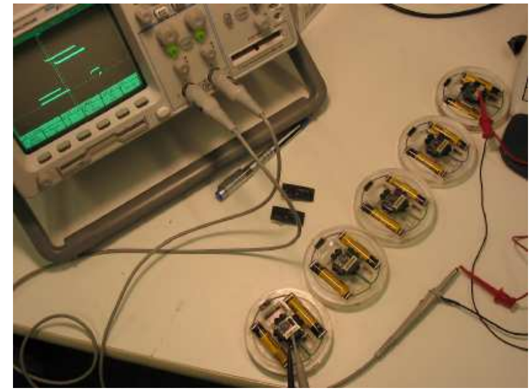
The network is the time server.

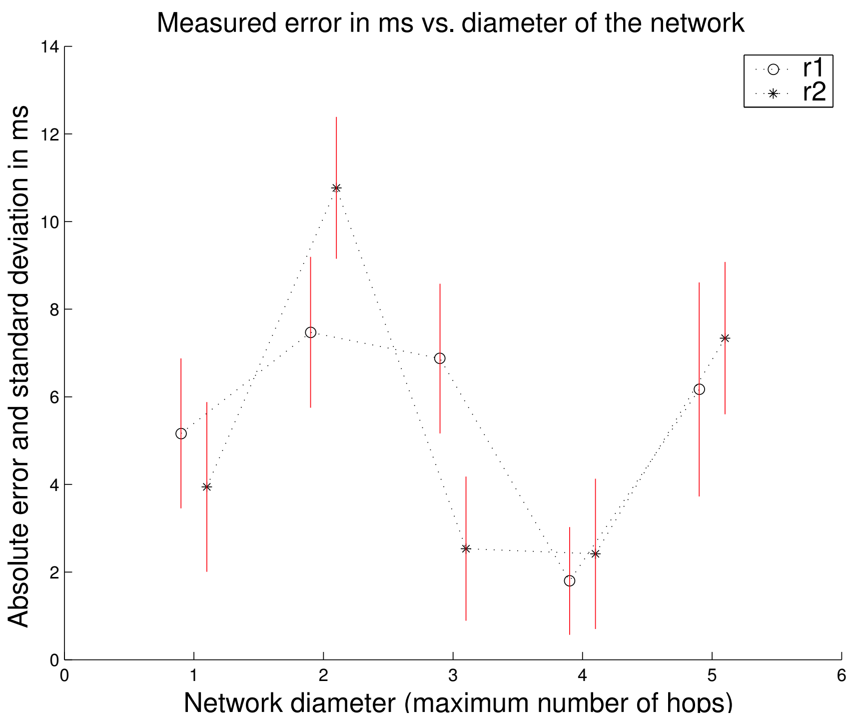
- Only local communication.
- Exchange timestamps and keep the highest (Lamport's idea).
- Redefine time as a periodic function!
- The network *re-calibrates* periodically and autonomously.



Decentralized Time Keeping Results







- Error could decrease with increasing Network diameter!

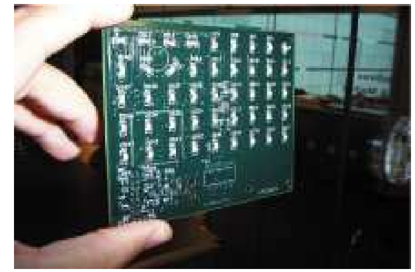
$$
\begin{aligned}
\epsilon(t_c) &= C_i(t_c) - C_j(t_c) = \\
&= \epsilon(t_0 + x) + (\phi_i - \phi_j)\,\Delta t \\
\Delta t &= t_c - (t_0 + x)
\end{aligned}
$$

- Error depends on communication BW.

$x =$
$propagation\,delay + transmission\,delay +$
$+\; operating\ system\ delay.$

Decentralized Time Keeping Demo






- Objective: play music in synchrony, display *heartbeat* at the edges...

Decentralized Time Keeping Demo (2)

- 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.)

Outline

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

Conclusions

Bigger Picture:

- No more *bad reception*...

Conclusions

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- Improved battery duration...

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Additionally:

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Papers

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A. Bletsas, A. Lippman, D.P. Reed, "A Simple Distributed Method for Relay Selection in Cooperative Diversity Wireless Networks, based on Reciprocity and Channel Measurements", accepted for publication, IEEE 61st Semiannual Vehicular Technology Conference May 30 - June 1 2005, Stockholm, Sweden.

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A. Bletsas, A. Khisti, D.P. Reed, A. Lippman, "A Simple Cooperative Diversity Method based on Network Path Selection", submitted for publication, IEEE Journal on Selected Areas of Communication, special Issue on 4G, January 2005, revised April 2005.

A. Bletsas, "Evaluation of Kalman Filtering for Network Time Keeping", accepted for publication, IEEE Transactions in Ultrasonics, Ferromagnetics and Frequency Control (TUFFC).

Acknowledgements

"Tolerating *ambiguity* is a sign of maturity..."

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

Acknowledgements

- Thesis Committee: Andy Lippman, Joe Paradiso and Moe Win.
- Colleagues at MIT: Ashish Khisti, Josh Lifton, David Reed and Joe Jacobson.
- My UROPs: Vimal Bhalodia, Amanda Lechman and Marios Michalakis.
- Colleagues outside MIT: Thucydides (Duke) Xanthopoulos.
- Office-mates: Dean Christakos, Ilia Mirkin and Dimitris Vyzovitis.
- Group Mates: Jamie Cooley, Jeff Hallbig, Casey Muller, Hector Yuen and the rest of the Viral Comm Gang: Arthur Petron, Kwan Hong Lee and Fulu Li.
- MIT people: Judith Donath, Neil Gershenfeld's Physics and Media Group, Hyundong Shin and Walter Bender.
- Necsys Crew: Paula Aguilera, Steve Berezansky, Jon Ferguson, Jeannie Finks, Will Glesnes, Tom Greene, Elizabeth Harvey-Forsythe, Henry Holtzman, Jane Wojcik, Chi Yuen.
- ML colleagues: Betsy Chimento, Tamara Hearn, Kevin Davis, Cornelle King, Sandy Sener and Stacie Slotnick.
- My sweet aunts here at Media Lab: Polly Guggenheim and Deborah Widener.
- Crazy Roomates: Maziar Tavakoli-Dastjerdi, Saul Griffith, Yael Maguire, John Maloney and Noah Vawter.
- To all my friends at Crete: Yiannis, Dia, Olga, Andonis, Costas, Mihalis.
- Friends here in Boston (including Greek Mafia): Thodoros Konstantakopoulos, Anna Stefanidou, Ioannis Kitsopanidis, Nikol Papadopoulou, Duke Xanthopoulos, Margarita Dekoli, Vasilis Ntziachristos, Christina Benou, Eirini Iliaki, Ioannis Kizanis, Anna Kondyli, Yiannis Zacharakis, George Themelis, Dimitris Rovas, Christina Samaraki, Georgia Konstadinopoulou, Karrie Karrahalios, Paris Smaragdis, Costas Pelekanakis, Thais Aleluia, Petros Bufunos, Thodoros Akiskalos, Christi Electris, Constadinos Caramanis, George Constadinidis, Maria-Katerina Nikolinakou, Angelina Aessopou, Wei Chai...
- Brother and his family here in Boston, sister and her family in Norway, Eleftheria and her family in Thessaloniki, and parents and grandaunt in Crete...

Thank you!

...to Eleftheria, Thodoris, Aimilia-Anastasia, Constadinos, Christina and to my family.