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Protocol design and characterization for ad hoc networks with multiple antennas

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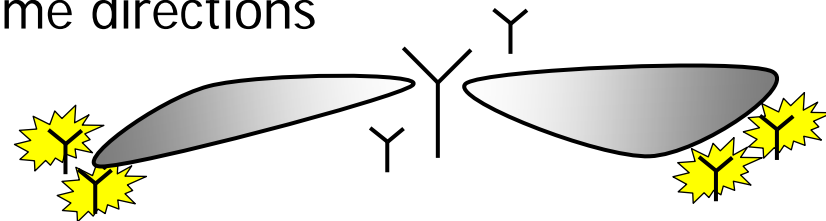
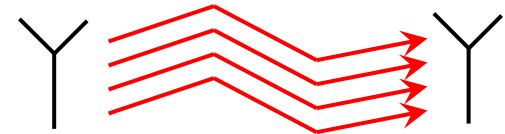
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Outline

- Background
- Protocols for MIMO ad hoc networks
 - PHY performance approximation
 - MAC/routing interactions
- Directional antennas in ad hoc networks
 - Cooperative strategy for deafness prevention
 - Cooperative-MAC design and characterization
- Cooperative Hybrid ARQ in MIMO ad hoc networks
 - Cooperation among nodes
 - Effects of routing on protocol design criteria
- Conclusions

Multiple antennas in ad hoc networks

- Have been recently proven to yield significant benefits
 - Higher bit rates
 - Spatial reuse and improved parallelism
 - Longer communication reach
- MIMO communications
 - Special signal processing allows greater diversity gain or Spatial Multiplexing of multiple signals
 - 👍 Greater channel capacity available
 - 👎 Higher complexity at the receiver
- Directional communications
 - Exploit higher transmit/receive antenna gain and null signal propagation toward some directions



Random access and MIMO ad hoc nets

- Last year: focus on the main aspects that need to be revisited if MIMO or directional antennas are used
 - Collision avoidance vs. collision control
 - Communication schemes that exploit directionality or MIMO to protect transmissions and increase neighborhood awareness
- This year
 - Joint study of multiuser detection, MAC and routing: which changes need to be made to increase performance?
 - Directional antennas: how to increase awareness of neighboring communications through a correctly designed signaling scheme
 - Study of the interaction between a Hybrid-ARQ based MAC and routing in MIMO ad hoc networks: enabling node cooperation

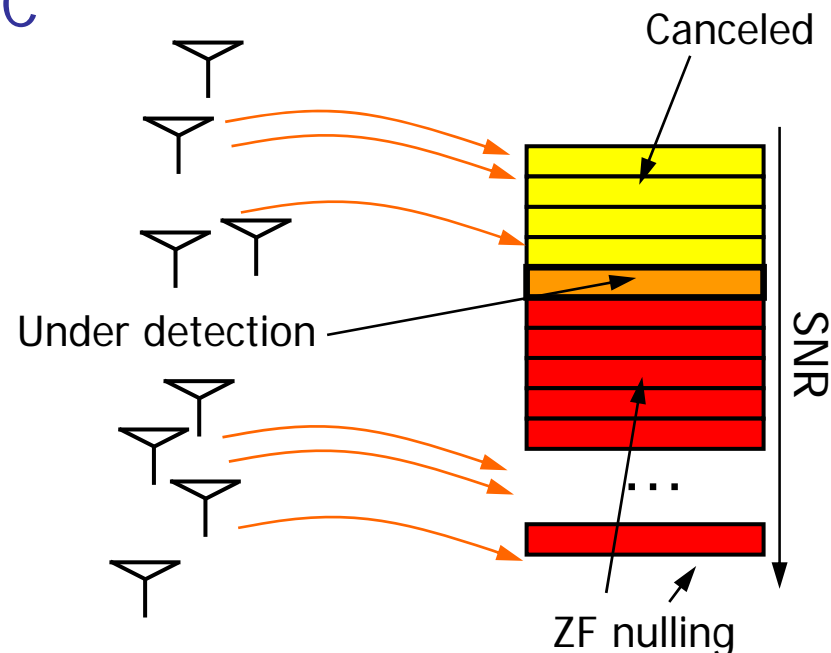
V-BLAST and MIMO ad hoc networks

V-BLAST

- Spatial Multiplexing at the transmitter plus layered detection
- Incoming signals have highly different attenuations (better case for multiuser detection)
- Greater overall bit rates and transmission parallelism

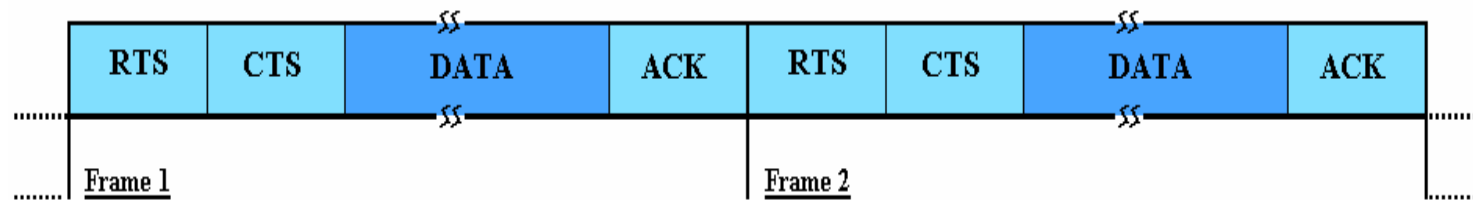
Interaction of V-BLAST and MAC enables

- Selection of the signals that must be detected and/or canceled
 - Throughput/protection tradeoff
- Flexible policies for transmission requests
- Adaptive policies for granting communications



Frames and RTS/CTS policies

- Framed transmissions to allow adaptation to neighboring traffic (for both throughput and interference protection)
- RTS slots used to declare transmit needs (heard by all receivers)
- Receivers use the CTS to limit own traffic and avoid overload
 - Incoming traffic estimates can be derived from the RTSs
- DATA packets are sent according to info in CTSs
- NO NEED for symbol synchronization (it's a complexity issue...)



- Problem: how to choose which signals are worth decoding/canceling
- How is this choice modified by routing needs?

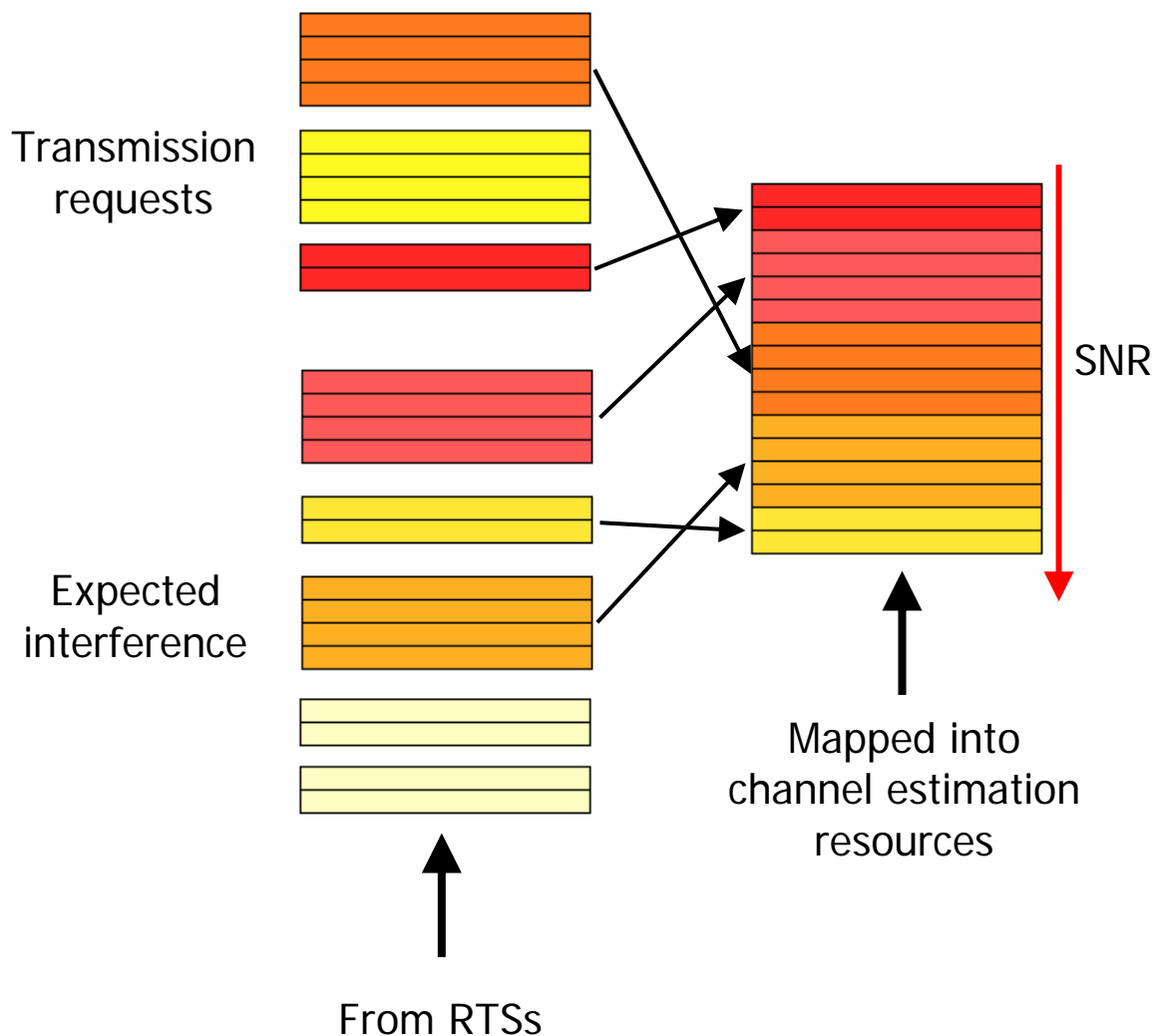
Example of CTS policy: FT

Follow Traffic (FT) policy

- Always grant at least one wanted request
- Take other requests in order of decreasing power, and grant them if they are wanted
 - Otherwise, account for the fact that they are interferers to cancel
- Terminate when no more channels can be estimated

Favors greater power

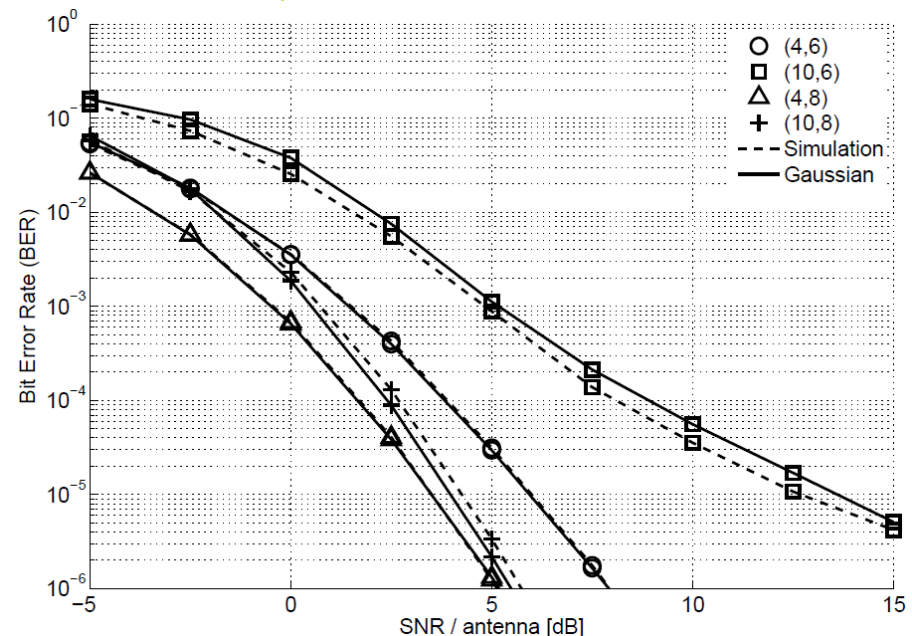
- Cancels strong interf.
- Does not grant transmission of multiple weak signals



PHY level approximation

$$\gamma(k_i) = \frac{\overbrace{\sigma_s^2 \left| \mathbf{w}(i)^H \mathbf{R}_{\cdot, k_i} \right|^2}^{\text{Extracted signal power}}}{\underbrace{\frac{N_0}{2} \left\| \mathbf{w}(i)^H \mathbf{H}^H \right\|^2}_{\text{Space-filtered noise power}} + \underbrace{\sigma_{\text{int}}^2(k_i)}_{\text{Unestimated interfering PDUs' power}} + \underbrace{\sum_k \left| \mathbf{w}(i)^H \mathbf{R}_{\cdot, k} \right|^2 \sigma_e^2(k)}_{\text{Error signal power (due to imperfect cancellations)}} + \underbrace{\sum_j \left| \mathbf{w}(i)^H \mathbf{R}_{\cdot, j} \right|^2 \sigma_s^2(j)}_{\text{Power of still uncanceled PDUs}}}$$

- Reproduce the behavior of a multiuser detector without the complexity of a fully-detailed simulation model
- Power of residual errors after cancellation approximated as Gaussian
- One-shot calculation of the SINR of the current detection



Effect of channel estimation errors

Relative error model

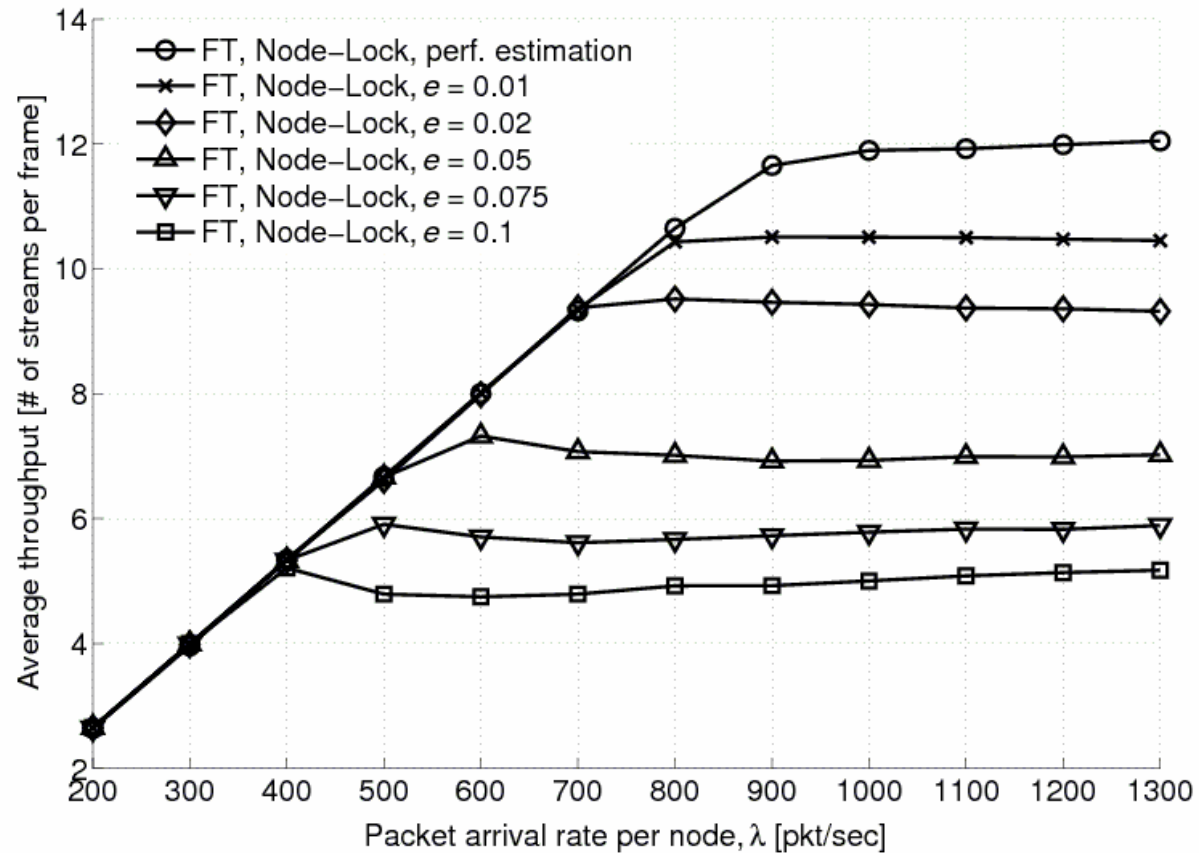
- The standard deviation of the channel estimate is a fraction e of the absolute value of the real channel gain

$$\hat{\mathbf{H}} = \mathbf{H} + e\mathbf{\Omega}$$

$$\mathbf{\Omega}_{ij} = \omega_{ij}|h_{ij}|$$

- ω_{ij} is a zero-mean unit-variance circ. Gaussian r.v.

- Throughput decreases for increasing channel errors

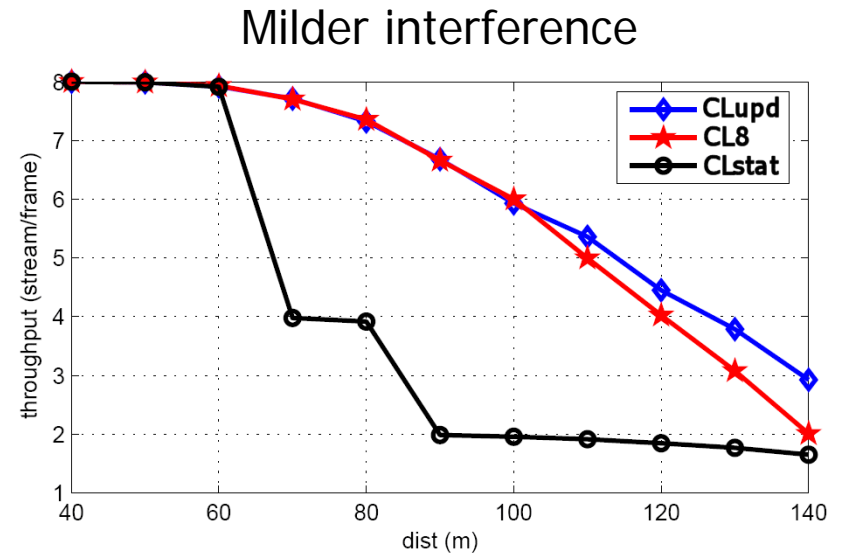
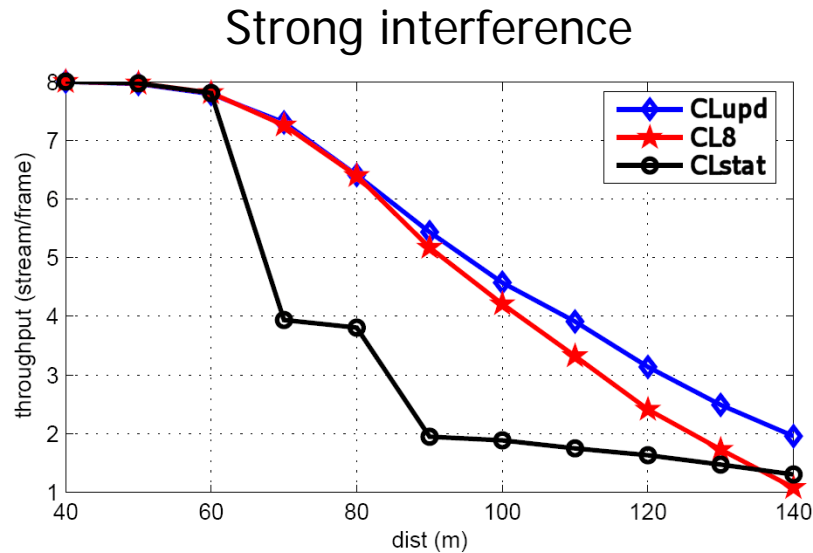


RTS composition and node class

- Previous studies allow to understand the relationship between
 - The desired performance at the receiver
 - The level of spatial multiplexing at the transmitter
- Straightforward policy (distance-based):
 - Based on the average received power, choose the number of antennas ("class") to meet some target packet error rate
 - A transmitter will set up links that do not break this constraint for any of the receivers addressed in a certain frame
- Adaptive policy:
 - Change the class of a node depending on a suitable reliability metric, such as the success ratio toward that node

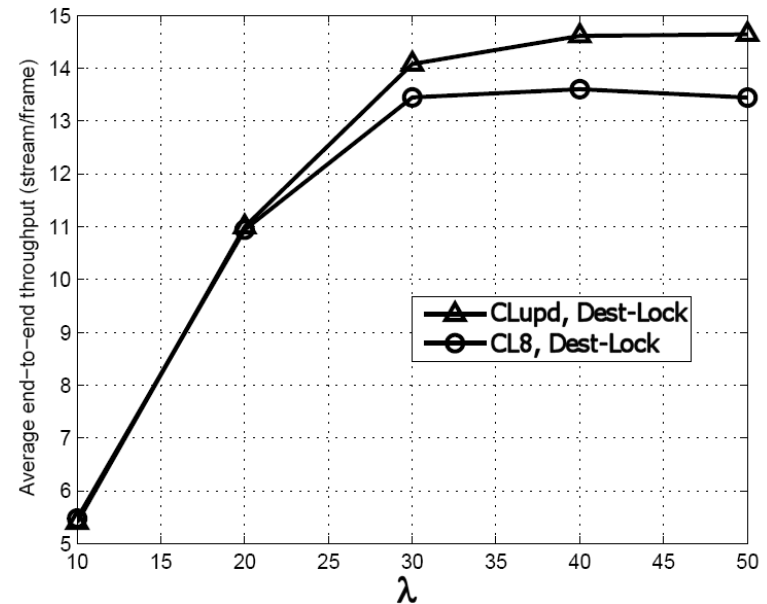
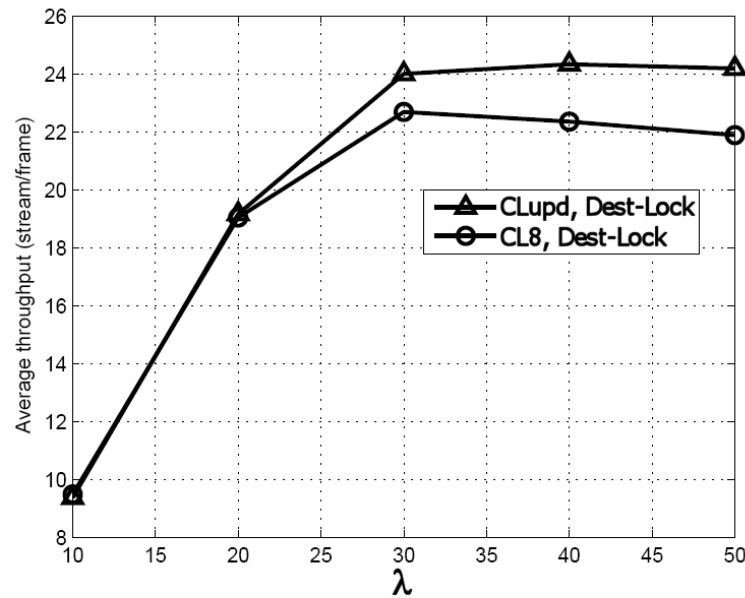
$$\text{New class} \longrightarrow r_{new} = a \frac{N_{ACK}}{N_{SENT}} + (1 - a) r_{old} \longleftarrow \text{Old class}$$

Effects on throughput performance



- CLstat = static, average power- (*i.e.*, distance-) based class
- CL8 = always try to transmit with 8 antennas
- CLupd = update the class of each node according to the changes in the reliability of the link
- Adaptation yields a smoother throughput decrease, while still preserving the beneficial properties of FT

Experiments with shortest path routing



- Routing scenario: nodes use pre-computed shortest-path routes
- Class adaptation helps offering better local and end-to-end throughput
- Interaction of shortest-path routing and FT
 - FT privileges high-power transmissions (to protect against strong interf.)
 - Links on shortest-path routes are typically long-reach, low-power ones
- Further improvements achieved with a dynamic choice of the next hop

Cross-layer routing/MAC/PHY: conclusions

- Need to specifically address the interaction between MAC and routing
- FT (in general a link activation policy) should be designed to incorporate both routing and PHY information
- Such a policy is currently being designed
- Results obtained through an effective simulation tool that models networking protocols in full detail and is based on a good PHY level approximation
- Publications

- [1] M. Levorato, S. Tomasin, P. Casari, M. Zorzi; "An Approximate Approach for Layered Space-Time Multiuser Detection Performance and its Application to MIMO Ad Hoc Networks"; IEEE International Conference on Communications, (ICC), Istanbul, Turkey, June 11, 2006 - June 15, 2006
- [2] P. Casari, M. Levorato, M. Zorzi; "DSMA: an Access Method for MIMO Ad Hoc Networks Based on Distributed Scheduling"; accepted for publication in ACM International Wireless Communications and Mobile Computing Conference (IWCMC), Vancouver, Canada, July 3, 2006 - July 6, 2006
- [3] Marco Levorato, Paolo Casari, and Michele Zorzi, "On the Performance of Access Strategies for MIMO Ad Hoc Networks," *in Proc. IEEE GlobeCom*, San Francisco, CA, November 2006, pp. 1–5.
- [4] M. Levorato, S. Tomasin, P. Casari, and M. Zorzi, "Physical Layer Approximations for Cross-Layer Performance Analysis in MIMO-BLAST Ad Hoc Networks," *IEEE Transactions on Wireless Communications*, accepted for publication.

Introduction: Deafness [5],[6]

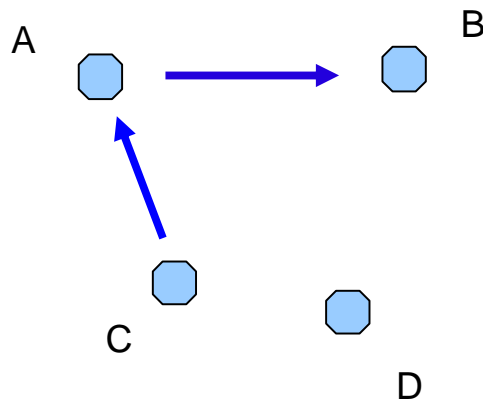
Definition: A node is said to be **deaf** if it does not answer an RTS message addressed to it

Omni-directional scenario

- caused by collisions of RTS frames
- handled via Binary Exponential Backoff (BEB)

Directional scenario

- to achieve SM nodes can access the medium also if other transmissions are in place



a node might send an RTS to a *busy* neighbor

- BEB contention not tailored for this condition

+ interference, + link failures, + collisions, + energy consumption

Major limit to the performance of directional ad hoc networks

Circular Handshaking

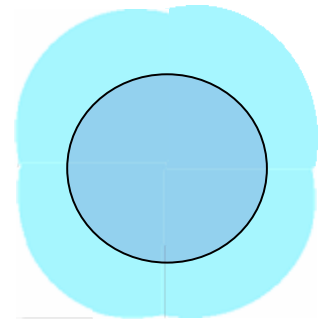
- Proposed by Korakis et al. in the CRCM protocol
T. Korakis, G. Jakklari, I. Broustis, S. Krishnamurthy and L. Tassiulas,
“Handling asymmetry in gain in directional antenna equipped ad hoc networks”,
IEEE PIMRC 2005.
- Delivery of handshake frames covers the whole horizon by means of a sequence of suitably spaced directional transmissions

Pros:

- Extended coverage range
- All the neighbors that are listening to the channel are informed of the link under construction

Cons:

- Increased latency
- Increased power consumption
- Increased overhead

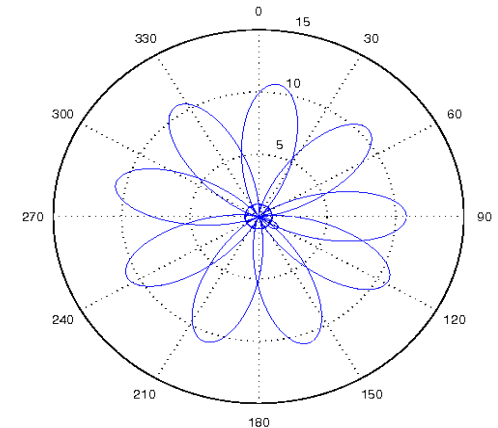


Multiple Receptions

- N samples of the incoming signal are collected


$$\mathbf{r} = [r_1 \ r_2 \ \dots \ r_N]^T$$

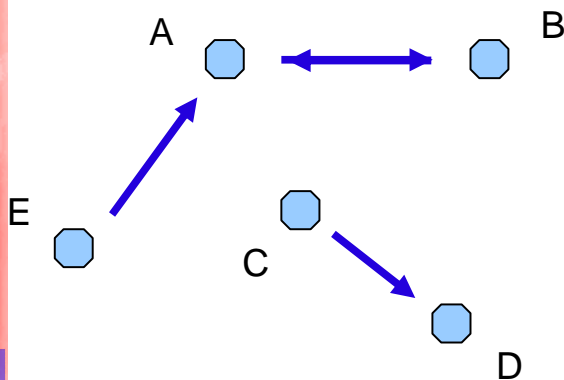
- If the signals are suitably combined, a directional reception is obtained
- Receives omni-directionally yet with increased range
 → solves the *asymmetry in gain* problem at the receiver




- Simple solution but has not been considered so far in the design of MAC protocols for directional antennas
- Up to M packets can be received simultaneously provided they
 - impinge on different lobes
 - have comparable power level (near-far problem)
- Benefits for deafness reduction
 - increased number of handshake frames received
 - a node can listen to the channel also during the reception of a data packet

Cooperation

Circular handshaking and Multiple Receptions do not completely address deafness  **COOPERATION**



1. A initiates tx to B
2. C negotiates the channel with D
 - E (idle) updates CR thanks to *circular hsk*
 - B updates CR thanks to *circular hsk + multiple receptions*
 - A cannot update the CR

 3. At the end of A's transmission, B and E send a *directional cooperative frame* to A to inform it of the C-D link

A can update its register

Cooperation

The *Cooperation* scheme has three potential drawbacks

1. Cooperative frames may generate *interference*

Not a major issue:

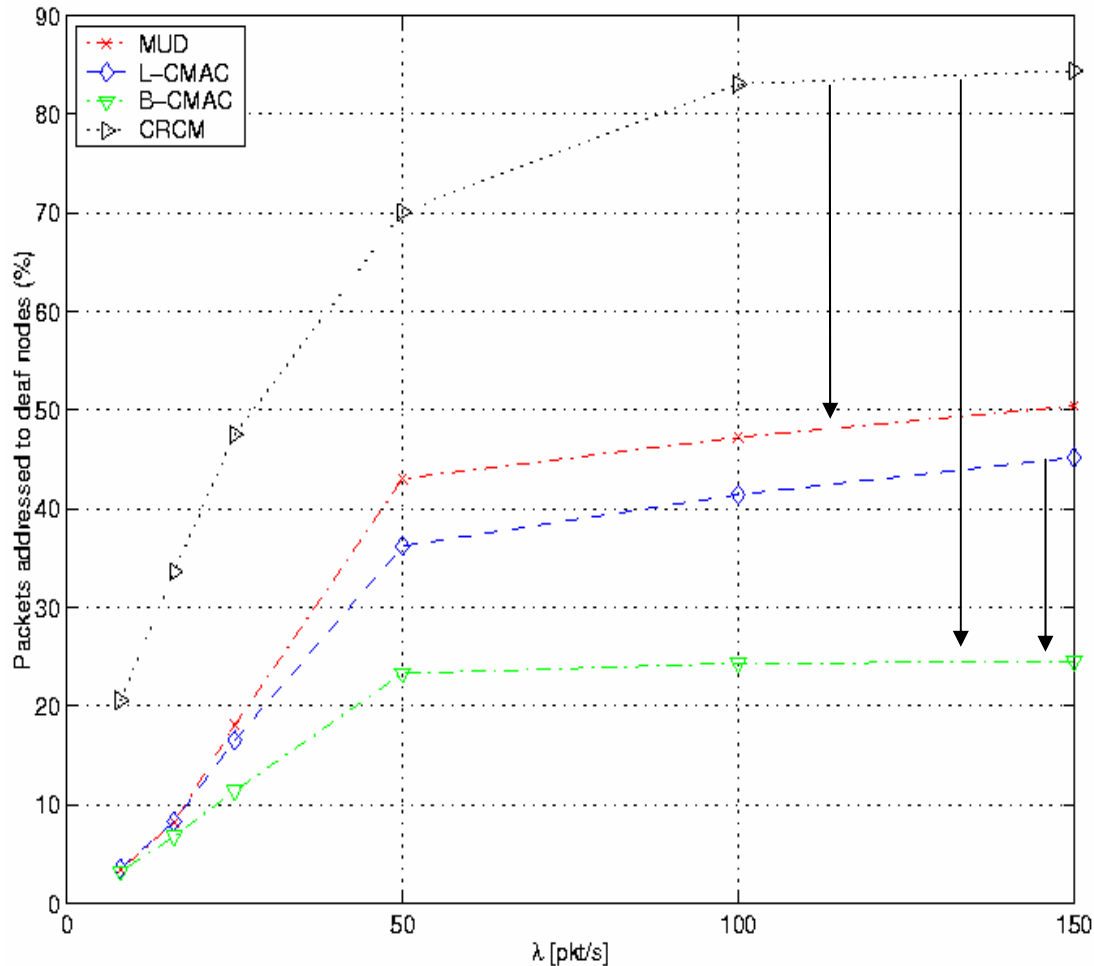
- directional transmissions
- power control
- counterbalanced by the benefits

2. Some *overhead* is introduced

3. Finite size of cooperative frames limits the number of communications that can be reported

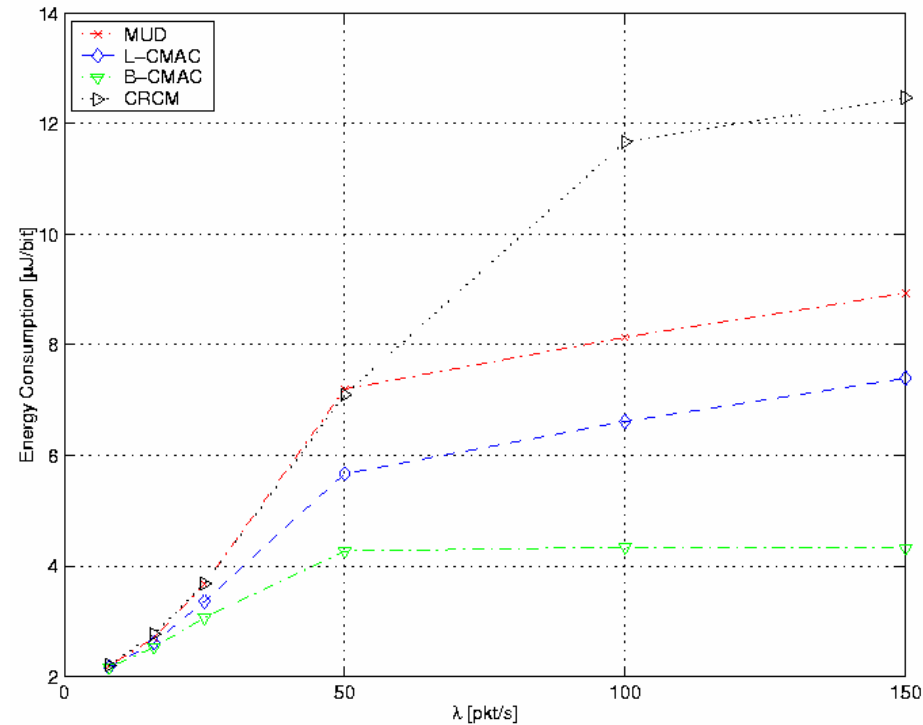
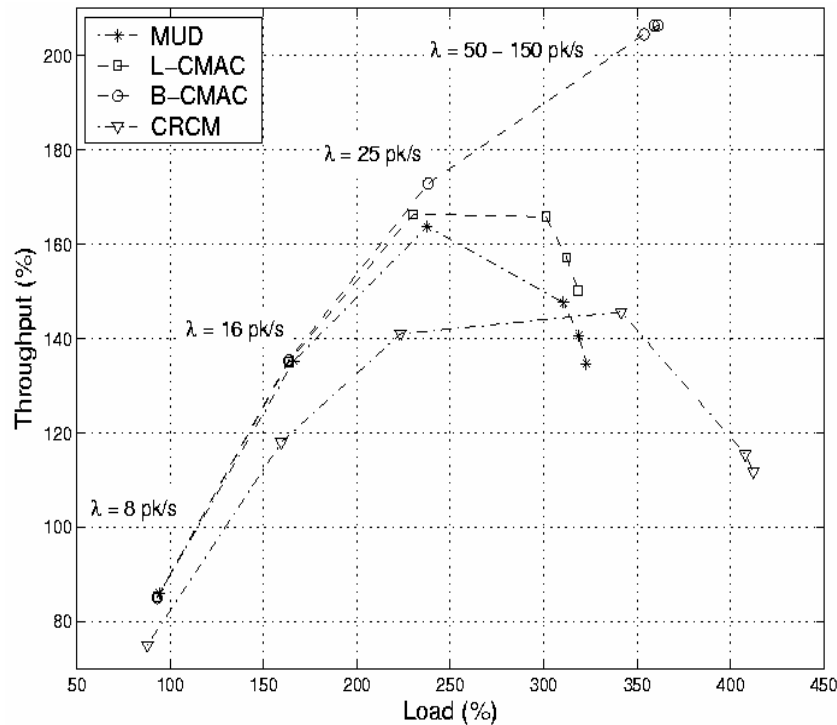
- tradeoff between overhead and deafness reduction
- only few links can be set up: short *COOP* packet
- B-CMAC (ideal coop info at no cost) vs. L-CMAC (single info in *COOP* packets, interference included)

Simulations: Deafness

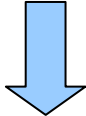


- Multiple receptions offer significant improvement
- Cooperation cuts deafness by a factor of 4 wrt CRCM
- B-CMAC twice as good as L-CMAC

Simulations: Throughput and Energy



- Cooperation offers 14-41% more throughput and 66% power savings

Accurate CR

 stable network

- Highly informative cooperative packets (B-CMAC) lead to great improvement

Conclusions

- Network Cooperation is a simple yet effective way to avoid deafness
- Important performance improvements:
 - 66% less transmit energy
 - 40% more throughput
- Significant difference between B- and L-CMAC
 - Cooperation may help significantly
 - The more the amount of cooperative information, the lower the impact of deafness

● Publications

- [5] F. Rossetto, M. Zorzi; "On gain asymmetry and broadcast efficiency in MIMO ad hoc networks," International Conference on Communications (ICC), Istanbul, Turkey, June 11, 2006 - June 15, 2006
- [6] A. Munari, F. Rossetto, M. Zorzi, "A new Cooperative Strategy for Deafness Prevention in Directional Ad Hoc Networks," IEEE International Conference on Communications (ICC) 2007, Glasgow, 24-28 June 2007.
- [6b] A. Munari, F. Rossetto, M. Zorzi, "Cooperative Cross Layer MAC Protocols for Directional Antenna Ad Hoc Networks ," ACM Mobile Computing and Communications Review, accepted.

Cross-layer cooperative MIMO system

We design a Cooperative system aimed at the improvement of the performance of ad hoc networks with multiuser detection

Network features:

- Nodes access the channel without performing carrier sensing
- Source-destination pairs perform a handshake phase (to avoid packet transmissions to unavailable destinations)
 - Unlike in CA systems where the handshake is needed to avoid simultaneous transmissions
- Asynchronous transmissions (unlike the previously presented V-BLAST network)
- Correlated block-fading channel model

Cross-layer cooperative MIMO system

Due to interfering transmissions being started and completed, the channel conditions are highly variable



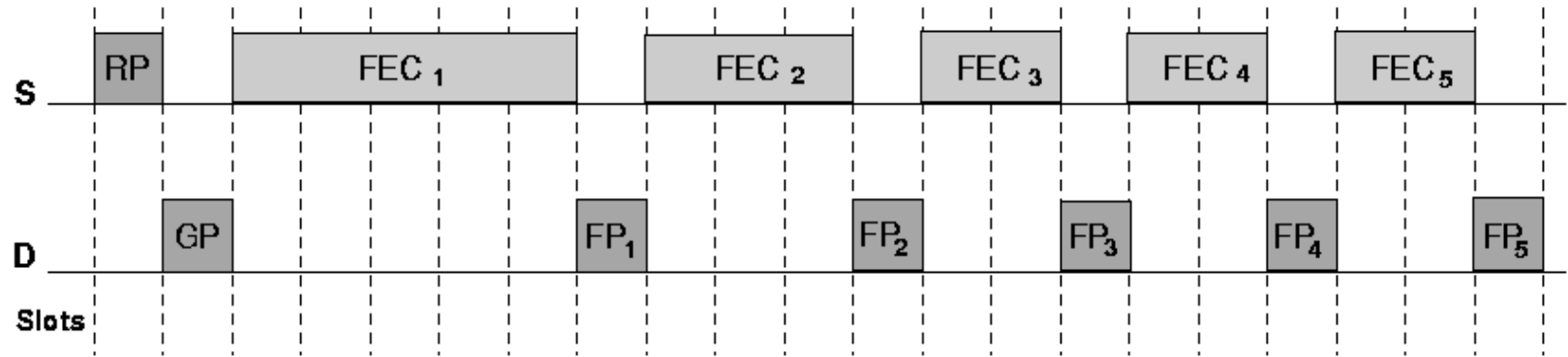
The coding rate needed to ensure transmission reliability can not be effectively estimated during the handshake



To counteract this effect we design a Hybrid ARQ protocol that enables nodes to dynamically adapt their coding rate to the perceived channel conditions

To increase efficiency and reliability we allow nodes to cooperate, exploiting the intrinsic broadcast nature of the wireless channel and MUD potential

Cross-layer cooperative MIMO system

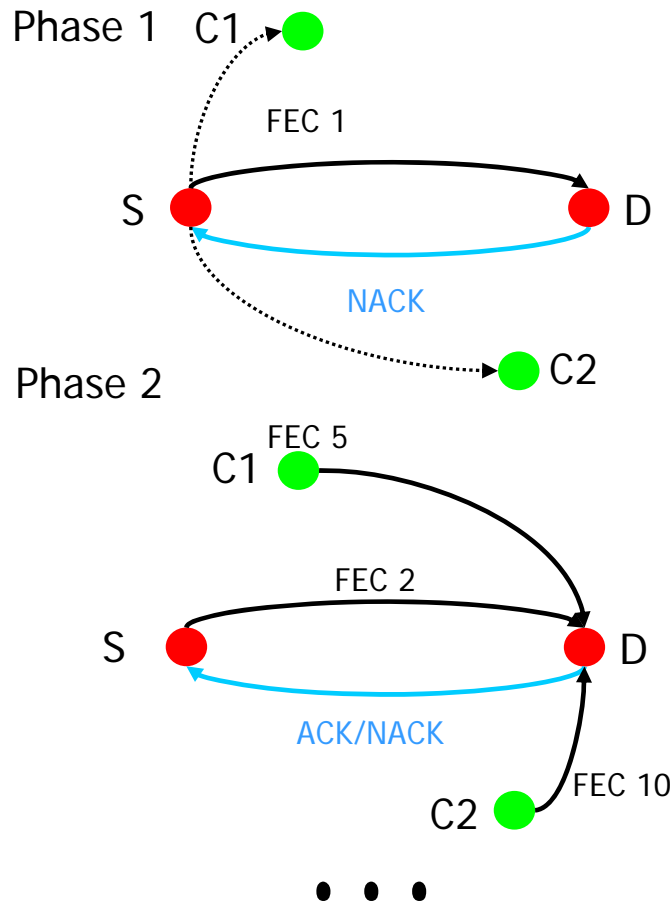


S – source node D – destination node C – cooperator node

- Packets are encoded with a low-rate code
- Transmission is divided into phases
 - In each phase the source transmits a different fragment of the codeword, and the destination sends out a feedback packet
- The fragment size choice could be aware of the channel conditions of the previous phases
- Upon a failure a further phase is performed
- Transmission ends when a success is reported or the maximum number of allowed phases is reached

Cross-layer cooperative MIMO system

Distributed HARQ protocol



- After the handshake, S sends a codeword fragment to D, that responds with a feedback packet
- Idle neighboring nodes may decode the frame
- If D reports a failure a further phase is performed
- Idle nodes that correctly decode the frame and have higher SNR to D than S, encode the frame and send randomly chosen fragments
- Cooperation is dismissed after a positive acknowledgment from D or if the maximum number of allowed phases is reached
- Cooperators and source transmissions are performed simultaneously
- D exploits MUD to decode the incoming fragments
- No need for coordination
- No TDMA for cooperation → low latency

Tradeoff between increased instantaneous per transmission load and transmissions duration

Cross-layer cooperative MIMO system

Considered Implementation

- Nodes with array of N antennas
- Spatial multiplexing at the transmitter and V-BLAST (LASTMUD) receiver
- Linear Erasure Packet Coding (Reed-Solomon)
 - The packet is divided in k blocks and encoded, obtaining n blocks
 - To decode the whole packet, the receiver must correctly decode at least k blocks
- The number of blocks sent in each phase is equal to the number of blocks missing for the correct decoding

Considered protocols

- **LPCS:** non-cooperative protocol
- **LPCCS:** all idle nodes that correctly received the packet in the first phase and that match the SNR constraint may become cooperating nodes (but don't have to, especially if they have their own packets to send)
- **FLPCCS:** (forced LPCCS) an idle node that correctly decodes an RTS/CTS exchange (and matches the SNR constraint) is forced to maintain the idle state until it fails to decode a sub-packet or the ACK is sent
- **ILPCCS:** (idealized LPCCS) only the best K_c nodes among those available are chosen for cooperation (ranking based on received SNRs)

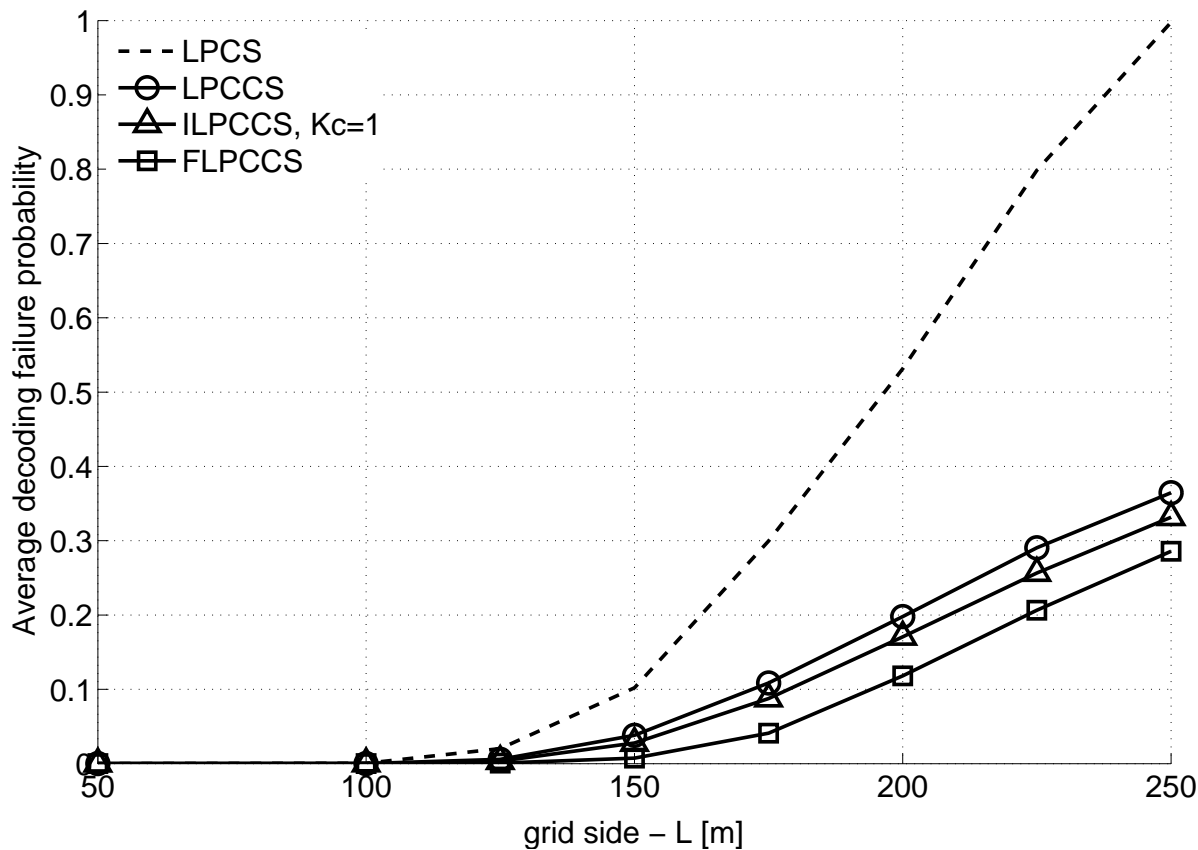
We performed:

fully-detailed PHY-MAC simulation of an $L \times L$ grid of nodes

analysis for the three-nodes case

Cross-layer cooperative MIMO system

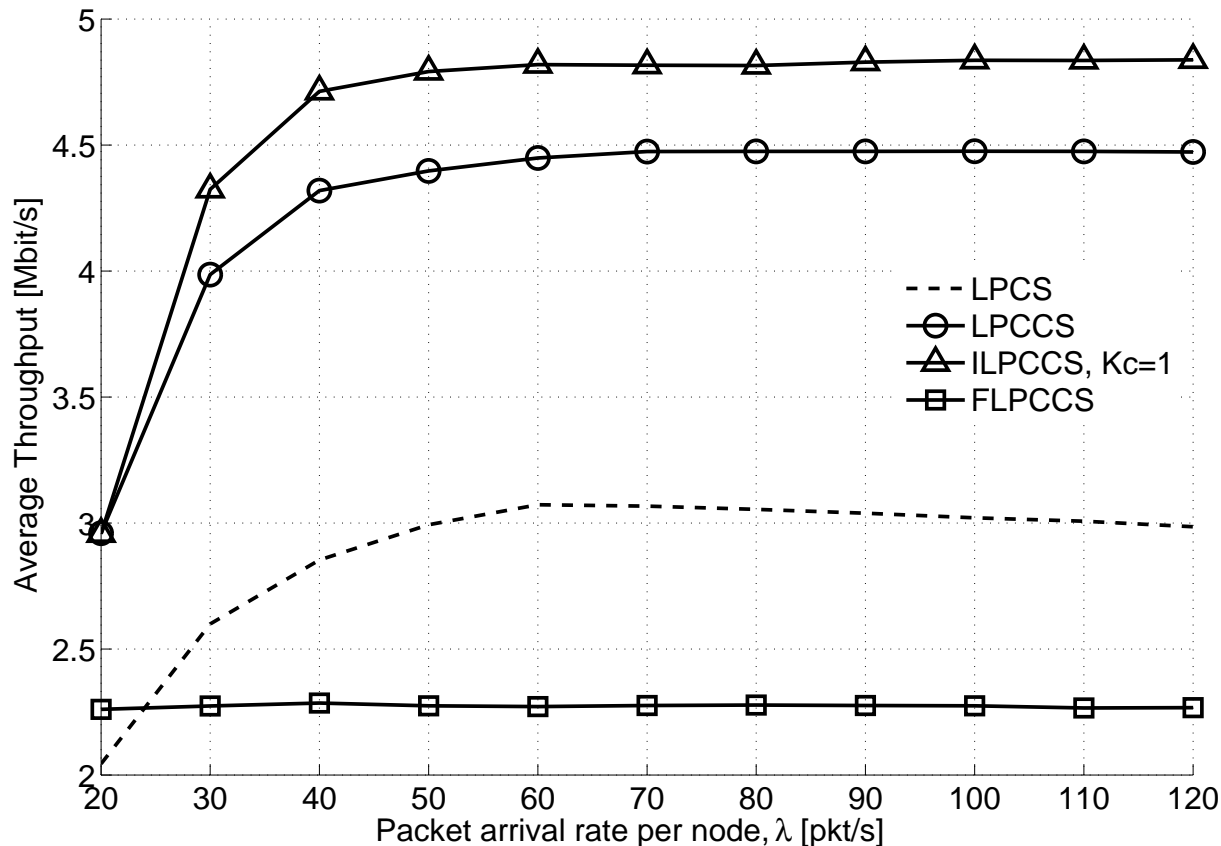
Average decoding failure ratio (after all permitted phases) as a function of the grid side L , 6×6 nodes, $\lambda = 120 \text{pkt/s}$ per node.



- All the considered cooperative protocols highly improve the success rate
- FLPCCS has the lowest failure rate, due to the higher number of cooperators provided by this protocol. In this case the interference generated by cooperation is balanced by the lower number of transmissions associated with their own traffic of forced idle nodes
- ILPCCS ($K_c=1$) offers slightly lower performance in terms of failure than LPCCS, due to the lower number of sub-pkts per phase (just one cooperator per communication)

Cross-layer cooperative MIMO system

Average throughput as a function of the per node arrival rate λ



- FLPCCS achieves the worst performance in terms of throughput, due to the low communications parallelism (nodes forced to idle state)
- LPCCS and ILPCCS outperform LPCS, thanks to the higher delivery efficiency and success rate
- ILPCCS has better performance than LPCCS, due to the comparable failure rate, achieved with lower resource cost

Cooperative Routing

- The proposed protocol exploits cooperation only to increase the efficiency of single hop communications
- We are extending our scheme by introducing cooperation at the routing level as well
- Cooperation is used to dynamically change the path when the link between the current transmitter and the next relay is suffering harsh conditions

In particular:

- Transmission to in-range final destinations are performed with a protocol similar to that previously described
- If the current transmission is to a routing relay we design a different cooperative policy
 - If the current destination fails to decode the packet, one of the nodes that correctly decoded it and that has a number of hops to the final destination at most equal to the current destination is selected to be the routing relay
 - Then, the transmitting node releases the packet, and the forwarding to the next hop destination is performed by the selected node

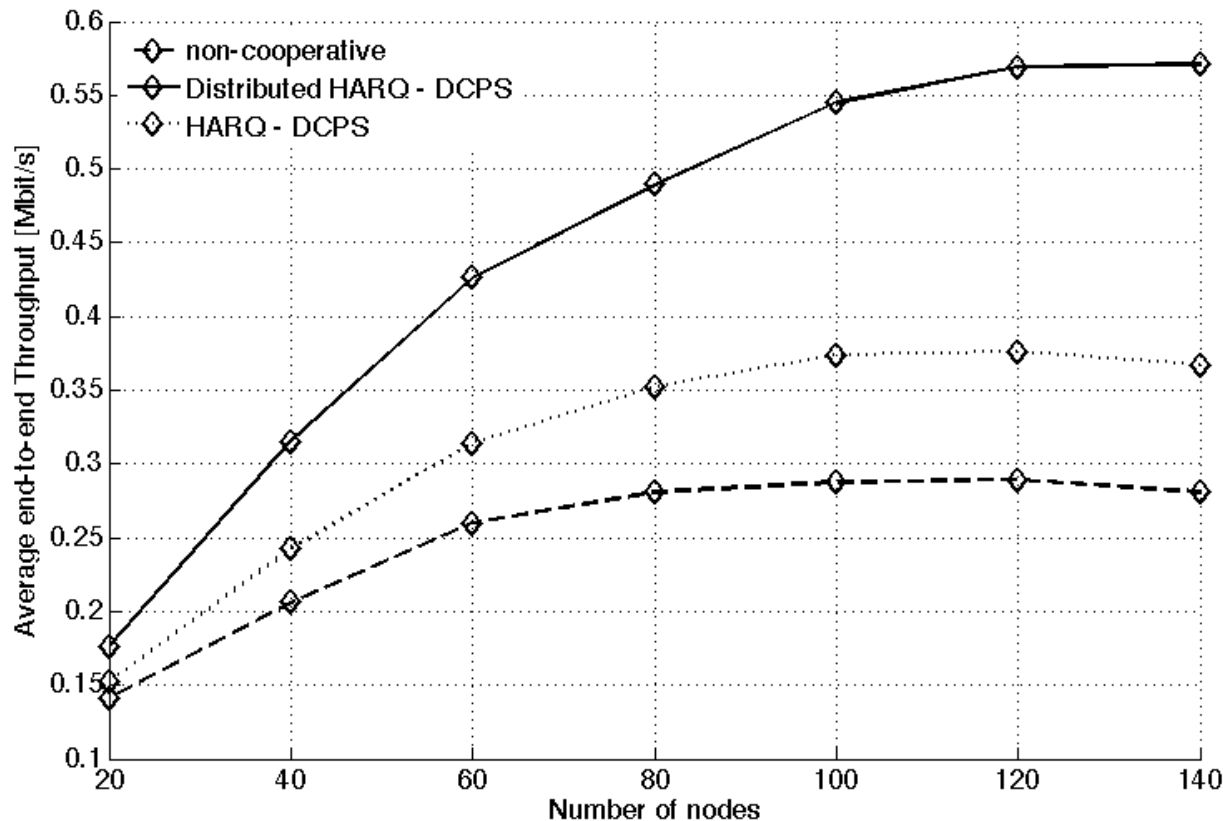
Cooperative Routing

Thus:

- We try to avoid inefficient transmissions over channels with poor instantaneous conditions, to both increase efficiency and decrease interference in the network
- Under bad channel conditions, and when none of the relay candidates is available, the distributed HARQ protocol is activated also when the current destination is not the final destination, to increase the advancement probability

We compare the proposed scheme, that implements dynamic cooperative path selection (DCPS) and distributed HARQ, with the non-cooperative case (fixed routing path and HARQ protocol) and a protocol that provides only dynamic cooperative path selection

Cooperative routing



- Dynamic path selection and cooperation improve end-to-end throughput
- The activation of higher efficiency links
 - Improves delivery
 - Reduces interference
- The integration of the distributed HARQ scheme with the dynamic cooperative path selection provides a substantial improvement.

- Other preliminary results show that this protocol achieves the best performance, in terms of throughput, delay, efficiency and failure rate in both one-hop and multi-hop communications

Cross-layer cooperative MIMO: conclusions

Conclusions:

- Adaptive HARQ is an effective error control technique in MUD ad hoc networks with simultaneous multiple access
- Cooperation in MUD networks, providing channel diversity, increases the overall efficiency
- Cooperation is particularly suited to MUD networks, due to the lower coordination needed
- The extension of cooperation to the routing level, integrated with PHY, MAC and error control, further improves the performance

Publications:

- [7] Marco Levorato, Stefano Tomasin, and Michele Zorzi, "Cooperative spatial Multiplexing for Ad Hoc Networks with Hybrid ARQ: Design and Performance Analysis", *IEEE Transactions on Communications*, accepted for publication.
- [8] Marco Levorato, Stefano Tomasin, and Michele Zorzi, "Coded Cooperation for Ad Hoc Networks with Spatial Multiplexing," *in Proc. of IEEE ICC*, Glasgow, Scotland, UK, June 2007.
- [9] Federico Librino, Marco Lavorato, and Michele Zorzi, "Distributed Cooperative Routing and Hybrid ARQ in MIMO-BLAST Ad Hoc Networks," *in Proc. of IEEE GlobeCom*, Washington, DC, November 2007, accepted.

Conclusions

● Lessons learned

- Efficient signaling and distribution of traffic information is very important to enable adaptation and efficient transmission
- Rate adaptation (through spatial multiplexing, coding, etc.) is a key feature of any non-collision avoidance system
- Cooperation (even beyond multi-hop routing) is a very promising way to improve overall communication efficiency

● Work in progress

- Design of a new integrated policy to jointly drive routing, MAC, and detections at the physical level
- Thorough evaluation of the performance in the presence of imperfect channel estimates
- Rate/interference control in cooperative systems

Publications (May06-Jul07)

- [1] M. Levorato, S. Tomasin, P. Casari, M. Zorzi; "An Approximate Approach for Layered Space-Time Multiuser Detection Performance and its Application to MIMO Ad Hoc Networks"; IEEE International Conference on Communications, (ICC), Istanbul, Turkey, June 11, 2006 - June 15, 2006
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