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Cooperative Wireless Networks

From Theory to Practice

A tutorial

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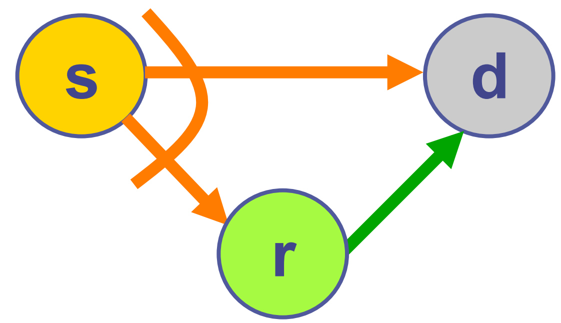
Introduction

- In 1971, Edward C. van der Meulen introduced the Relay Channel [1]
  - Broadcast
  - Sequential links: Forwarding
  - Parallel links: Multi-antenna system



- Why interesting?
  - Theoretical: Gains from energy, diversity, and coding mix
  - Practical:
    - Can assist communication in many scenarios: Adhoc, Mesh, WSN, Cellular, Vehicular
    - Can be combined with variety of techniques: MIMO, Network-Coding, Traffic offloading, Interference coordination
- **Currently: Relaying techniques are becoming practical**
  - **Still unclear: When to use which approach?**
  - **How will cooperative relaying affect real networks?**

Introduction: Cooperation in 2011 – What Is the Status?

- Theory:
  - No unified theory for capacity BUT for error rates
  - Capacity of the general relay channel not known BUT known for specific setups
  - Error rates of practical setups sufficiently studied

- Measurements and prototypes:
  - Simple, practical protocols (e.g., SDF) are a mature technology
  - With practical simplifications (e.g., combining, synchronization): Cooperation can be feasibly and efficiently implemented at L1 to L3
  - Relaying improves coverage: Implemented and shown for sensor networks, WLANs, and cellular networks; first field tests for LTE

- Standardization:
  - Simple relaying for coverage extension: Included in IEEE 802.16j at Layer 2 and in 3GPP TS 36.216 at Layer 3 (LTE Type 1/1a/1b relay)
  - Missing: MAC and PHY for cooperative relaying to increase capacity, e.g., LTE Type 2 relays

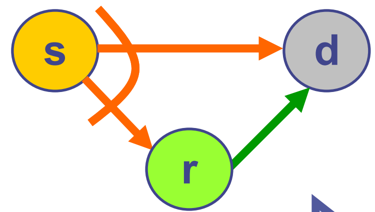
Introduction: What Is This Tutorial About?

- It's about making Cooperative Relaying practical

Analysis

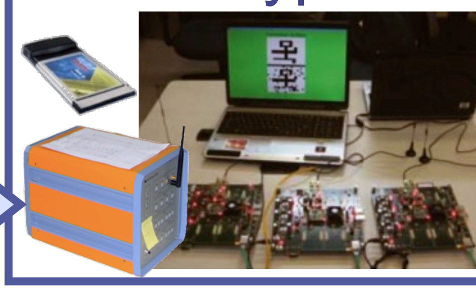
$$P^{\text{out}} \approx \frac{1}{L!}\Theta\left(\frac{2^{KR}-1}{\Gamma}\right)^{L}$$

$$C^{\epsilon} := R = \frac{1}{K}\log_2\left(\sqrt[L]{\frac{L!\epsilon}{\Theta}}\cdot\Gamma+1\right)$$



Tutorial

Prototypes

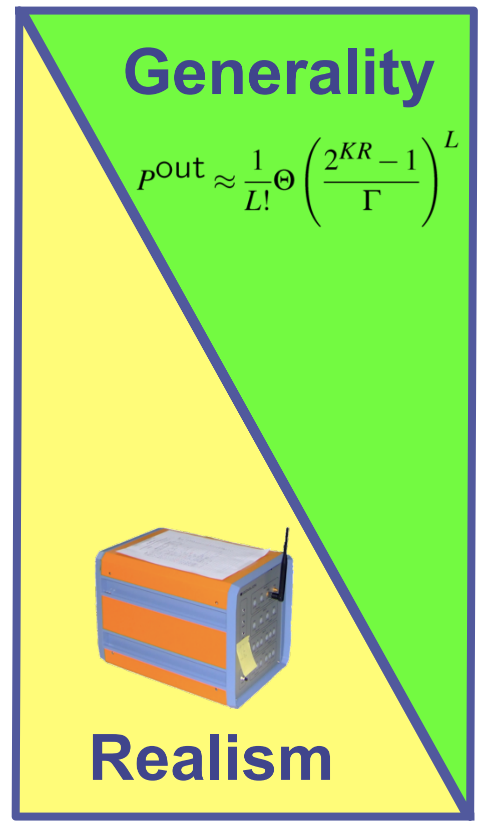


- To this end we:
  - Review the plethora of approaches and technologies in the field
  - Reveal the essence of common analytical models
  - Describe recent prototypes and measurements
  - Discuss beneficial scenarios and applications

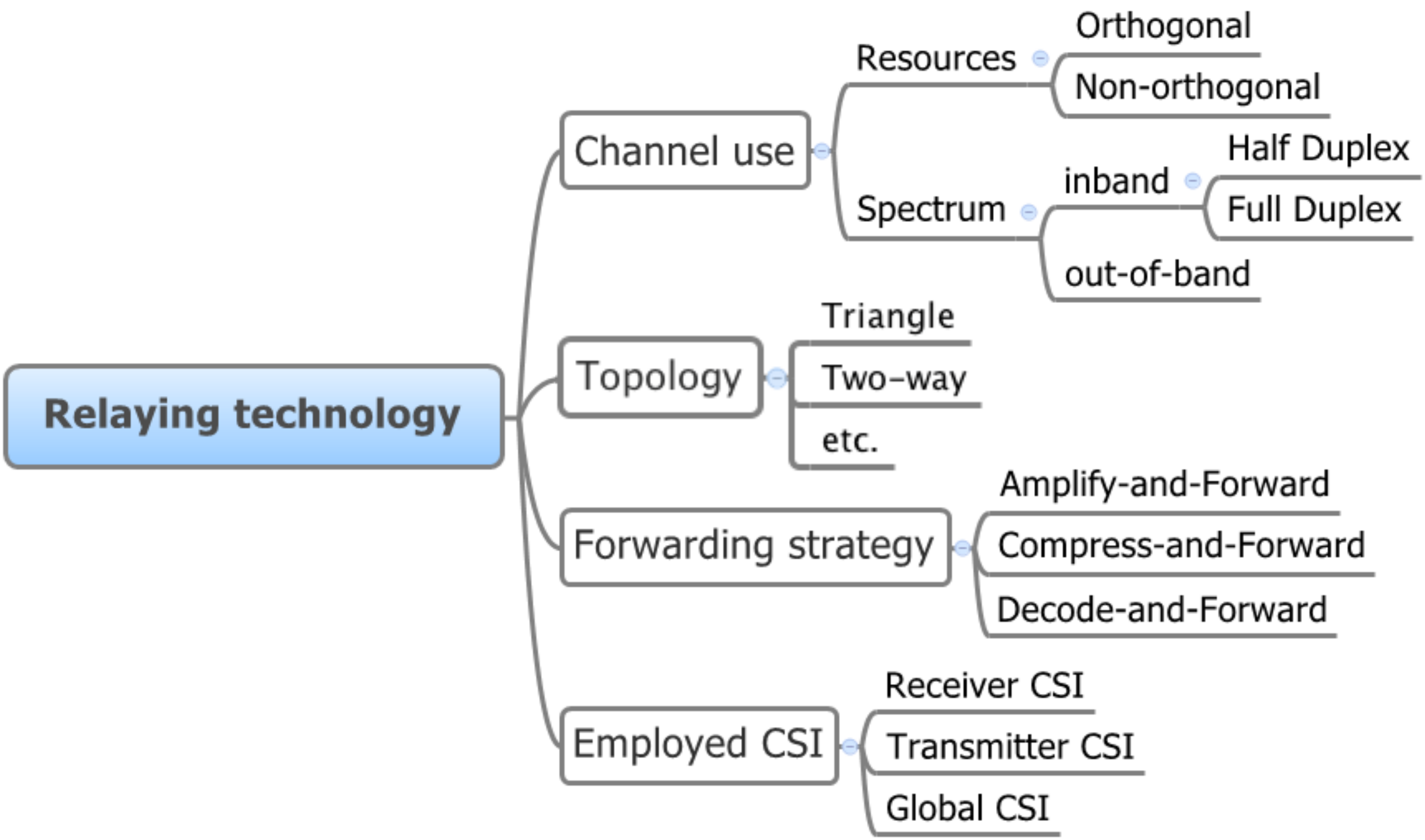
Our objective: Give you the overview (and some tools) to understand how cooperation changes ***your*** network

Outline

- **Technologies**
- Application
- Theory
- Practice
- Conclusion and Discussion

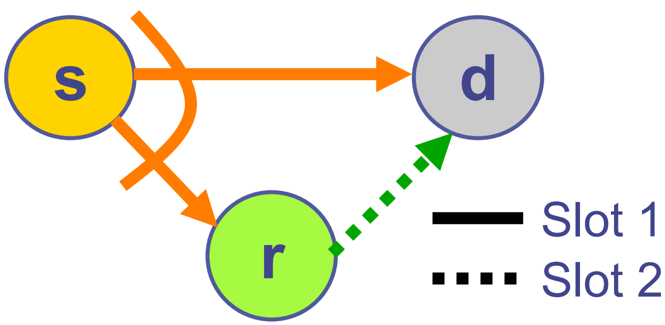


Technologies for Cooperation – A taxonomy



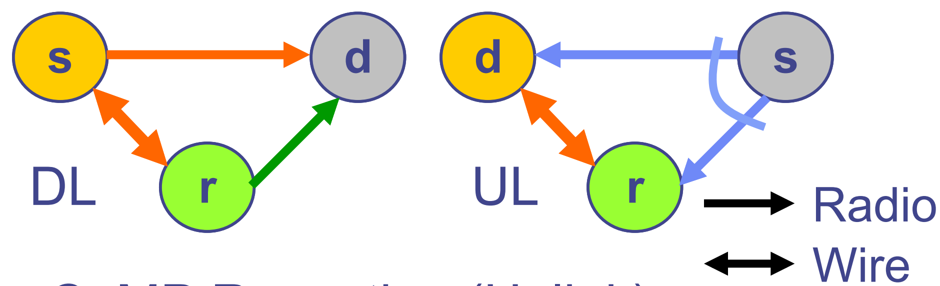
Channel Use: Orthogonal vs. Non-Orthogonal

- Cooperative Relaying:
  All links are wireless
- Typical: Two phases
  1. s transmits to r and d
  2. r forwards to d via orthogonal channel, d combines



- Benefits: Diversity & power gain, Broadcast in phase 1
- Drawbacks: Overhead and delay due to orthogonal forwarding

- Coordinated Multipoint (CoMP):
  Wireless links and wired backhaul
- CoMP Transmission (Downlink):
  1. Backhaul: s and r synchronize
  2. Synchronized transmission to d

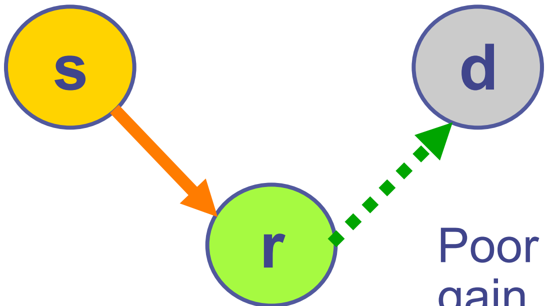


- CoMP Reception (Uplink):
  1. s transmits to r and d
  2. Backhaul: r and d exchange signals and d combines
- Benefits: Diversity and multiplexing gain, low overhead in the air
- Drawbacks: Backhaul highly loaded, tight synchronization required

Duplex Mode and Cooperation

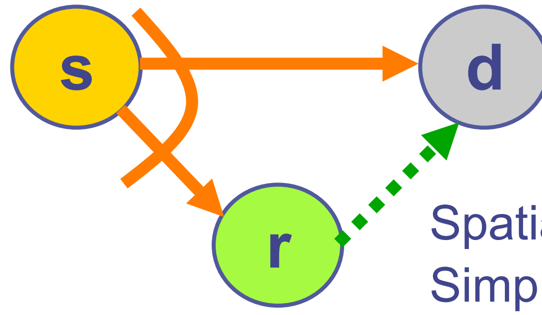
Slot 1 Slot 2

Half duplex, No cooperation



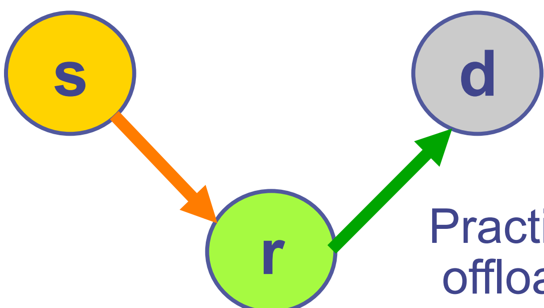
Poor diversity gain, 3GPP Type 1

Half duplex, cooperation



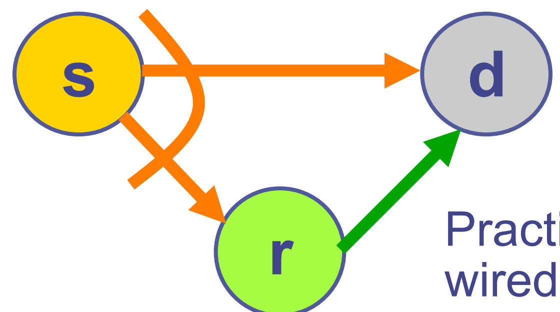
Spatial diversity
Simple 3GPP Type 2

Full duplex, No cooperation



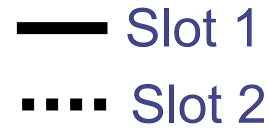
Practical with backhaul offloading in frequency (3GPP Type 1a) or space (3GPP Type 1b)

Full duplex, cooperation

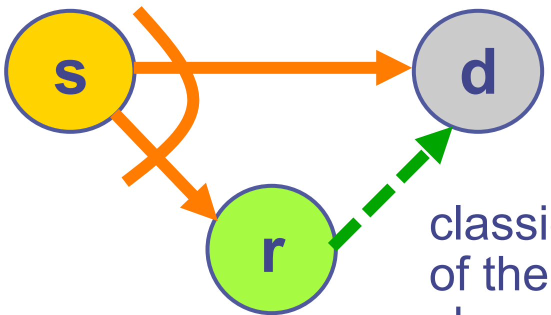


Practical with wired backhaul (e.g., CoMP) or 2nd radio

Common Topologies for Cooperative Relaying

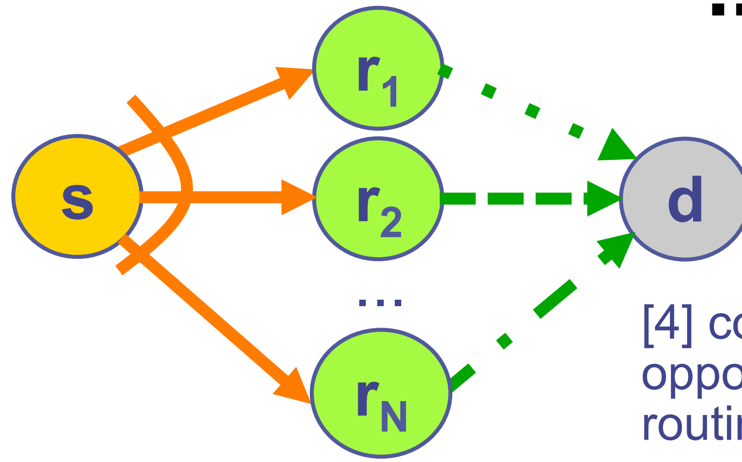


Triangle



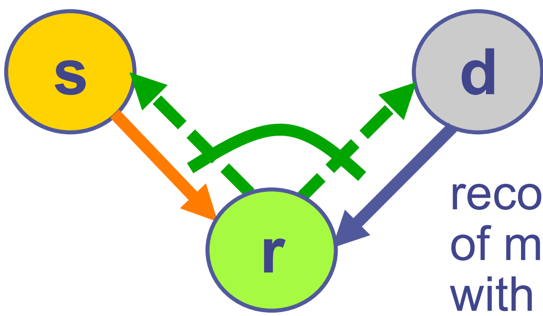
classic topology of the relay channel [1]

Diamond



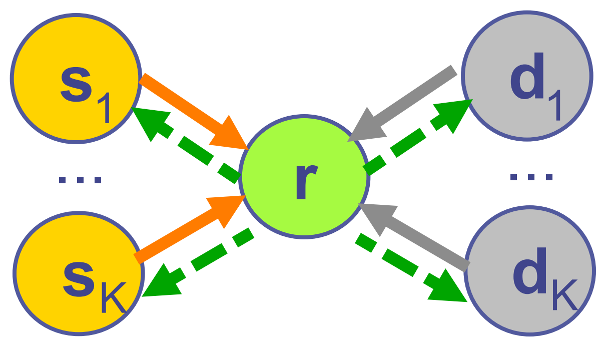
[4] common in opportunistic routing and resource allocation

Two-way



recovers large part of multiplexing loss with perfect CSI tx at s and d [12]

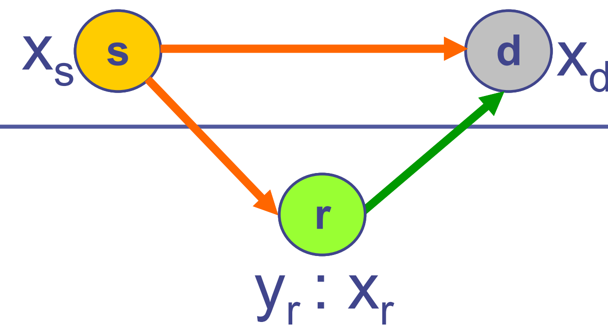
Star



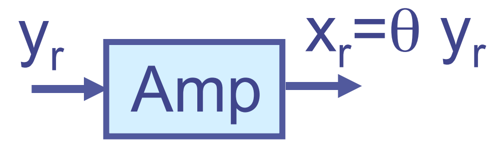
No multiplexing loss with 2K relay antennas [35], interesting with interference

Direct link (s,d): Often ignored for simplicity

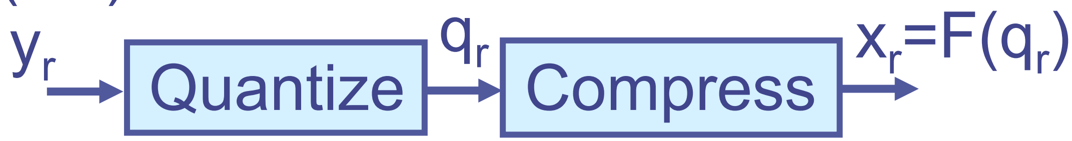
Forwarding Strategy



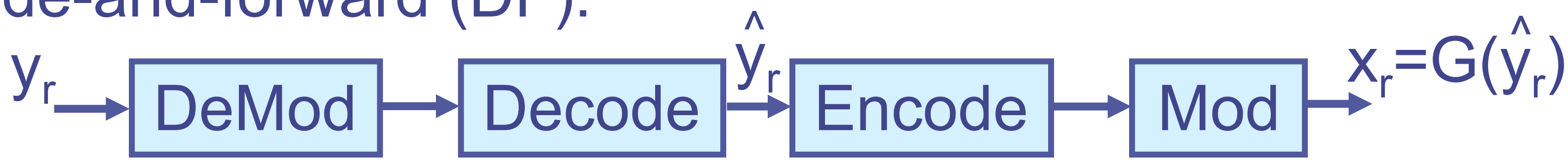
- Amplify-and-forward (AF):
  - Practical in baseband but amplifies noise
    => Poor performance at low SNR
  - Improved by *Bursty AF*: s transmits short peak but HF amps non-trivial to implement



- Compress-and-forward (CF):
  - Special case:
    Quantize-and-forward



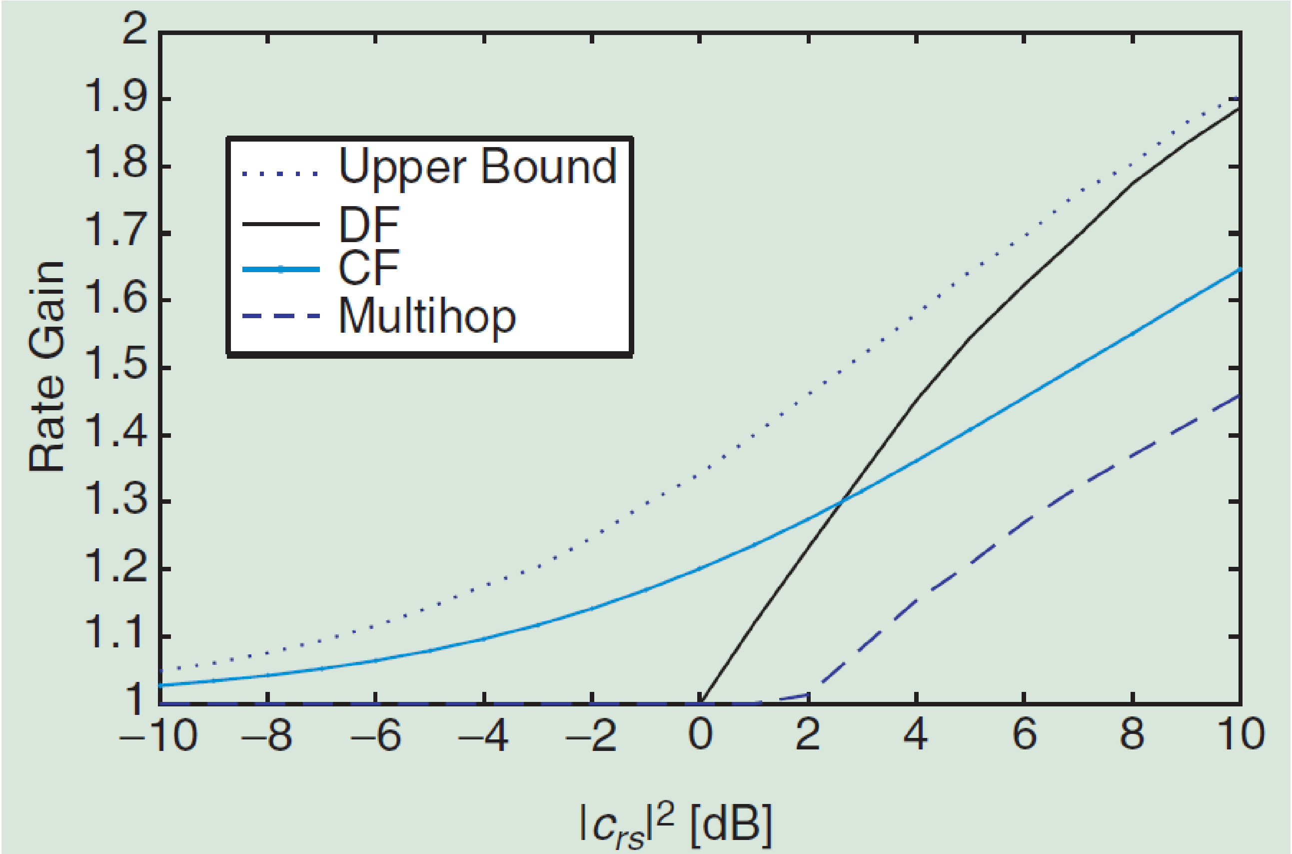
  - r forwards soft-information, costs rate but d decodes with partial CSI
  - r doesn't need to know code of s => Operates independent from s
- Decode-and-forward (DF):



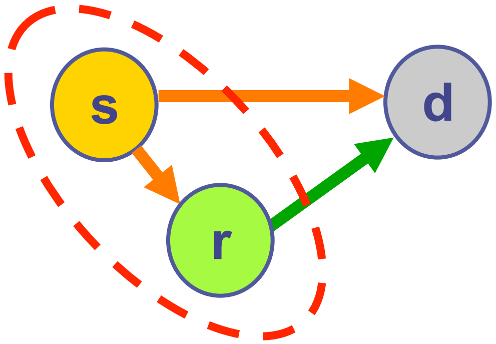
  - Selection DF (SDF): Relay only forwards if correctly decoded
  - r forwards hard-information, efficient but requires hard decision at r
  - r has to know code of s => Need to coordinate s and r

CF and DF first defined in Cover, El Gamal, 1979 [2]

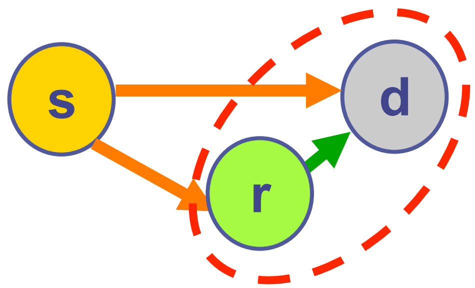
When to Use Which Forwarding Strategy?



DF: "Tx diversity"



CF: "Rx diversity"

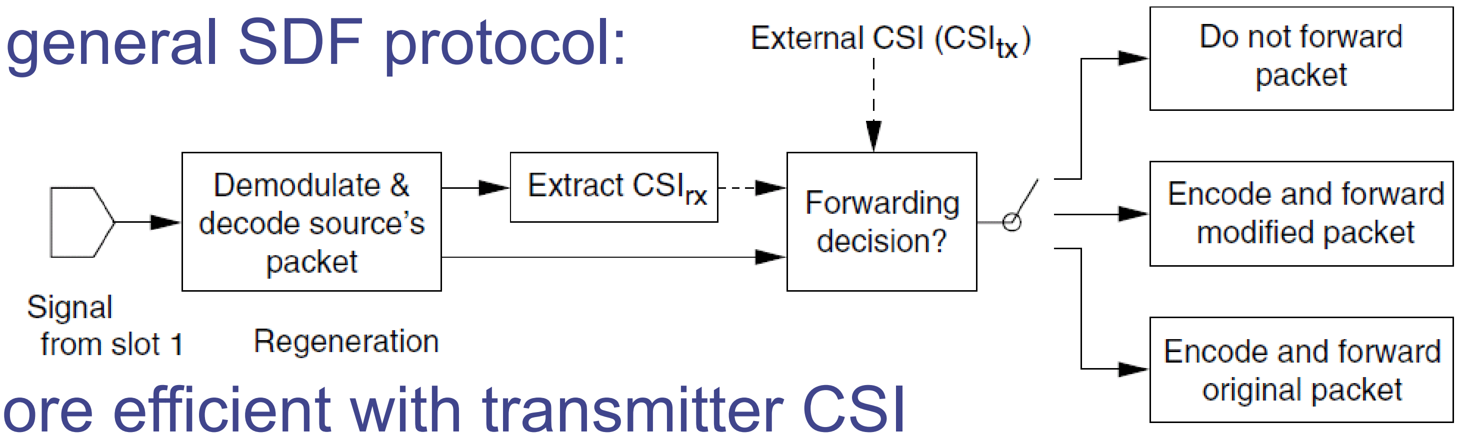


- DF: Prefer when relay close to source
  - Low SNR: Hard decision at r performs poorly
- CF: Prefer when relay close to destination
  - No hard decision at r but forwarding soft-information costs rate

Gastpar, Kramer, and Gupta, 2002 [14]; Plot: Stankovic, Host-Madsen, et al., 2006 [10]

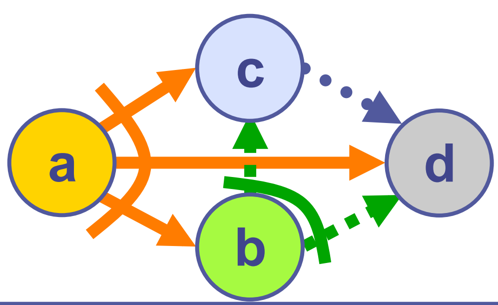
Employed Channel State Information (CSI)

- SDF requires at least receiver CSI
  - At relay: Decoding and error detection
  - At source: Coherent combining (e.g., MRC)
- A general SDF protocol:

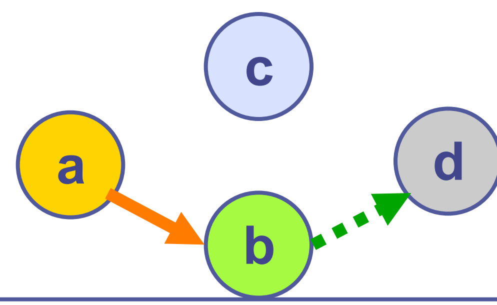


- More efficient with transmitter CSI

- Receiver CSI: K=3 channel uses

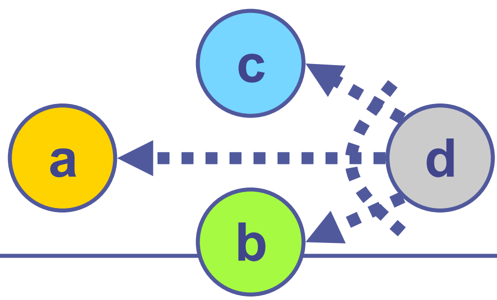


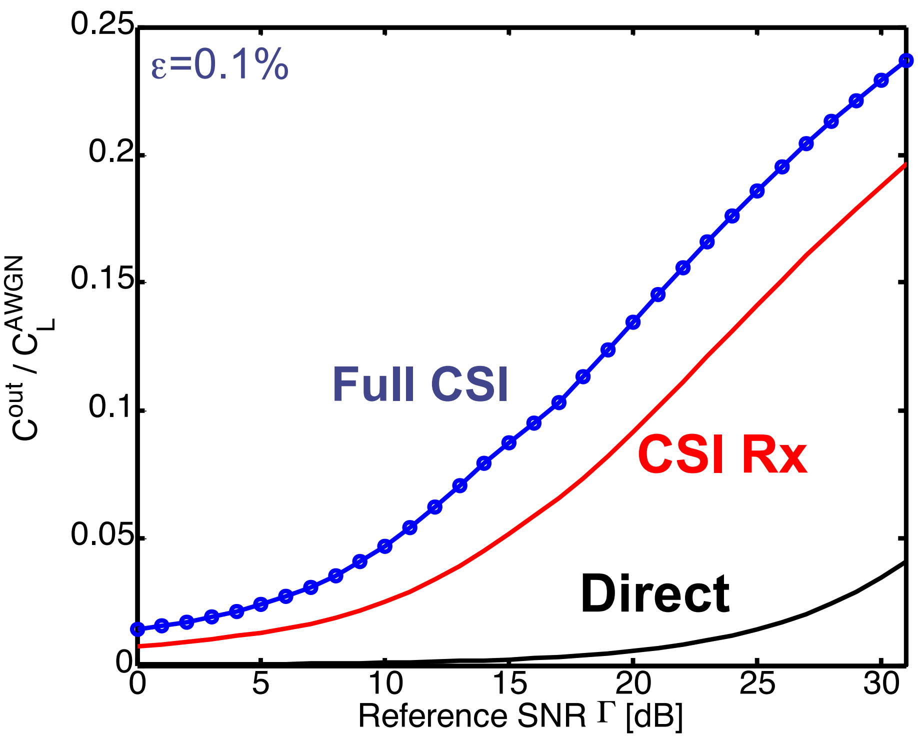
- Transmitter CSI: K=2 channel uses



Benefit of Transmitter CSI

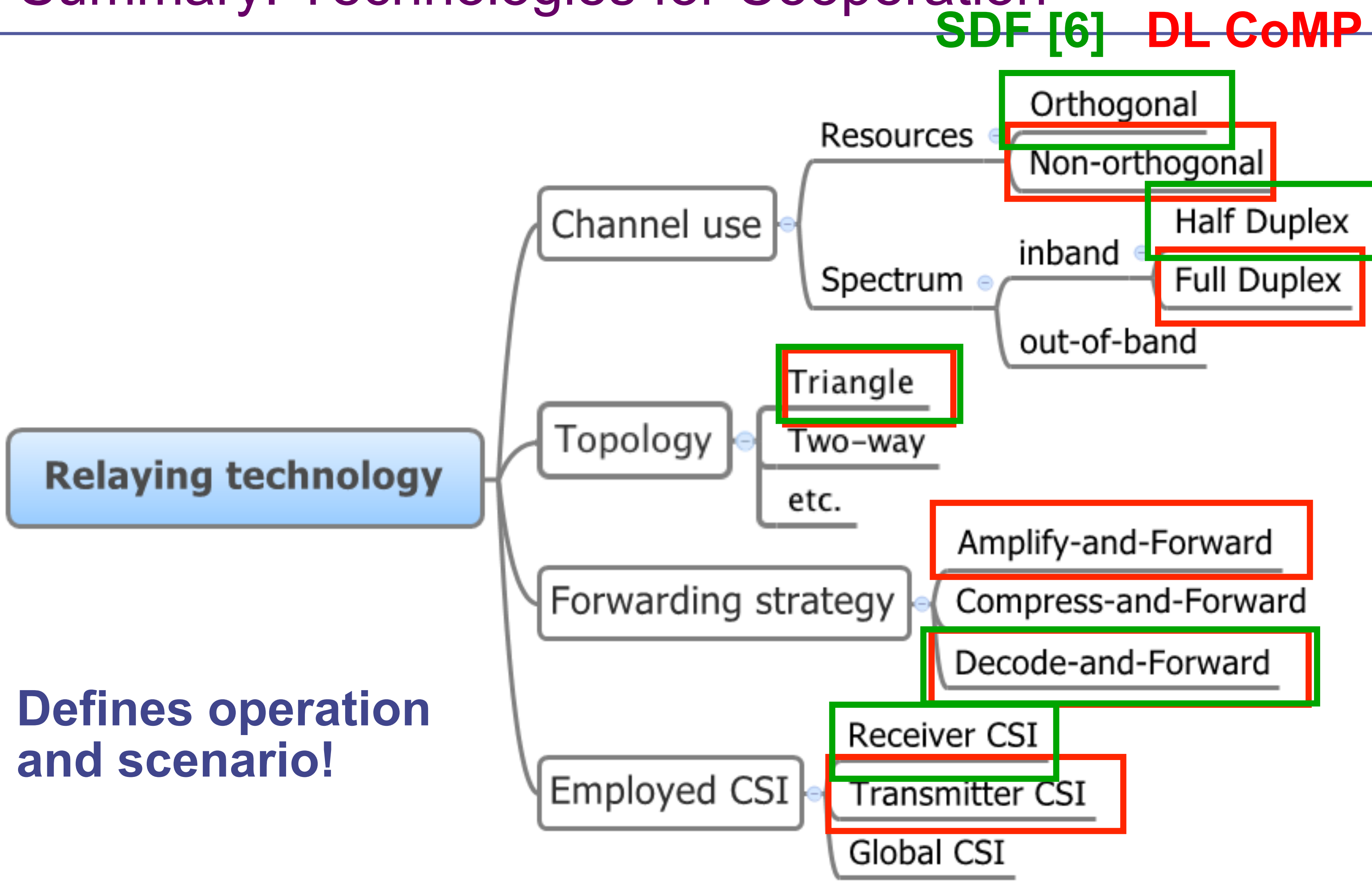
- Transmitter CSI required for adaptation, here:
  1. Pairing: Find "best" relay
  2. Forwarding decision: Forward a message or not?
  3. Scheduling: Coordinate interference through relaying
- With full CSI:
  - Capacity substantially improves
- Non-reciprocal channels:
  - CSI Tx requires feedback
  - Performance with limited CSI feedback?





Valentin, Lichte, et al. [8]

Summary: Technologies for Cooperation



Defines operation and scenario!

Outline

- Technologies
- **Application**
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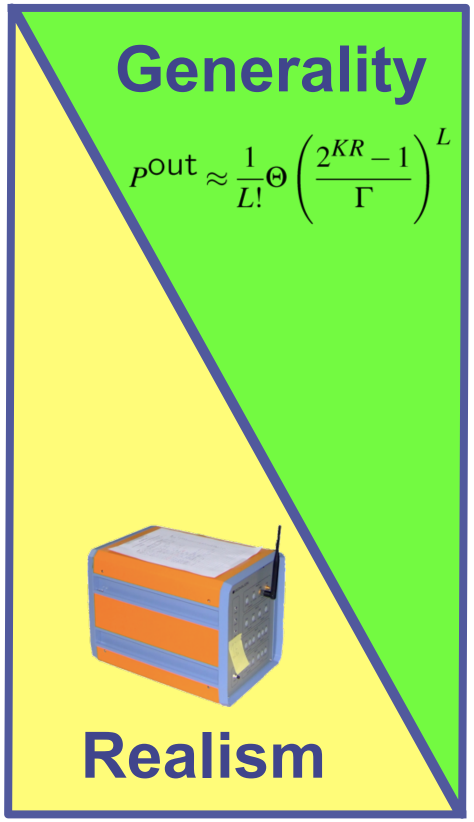
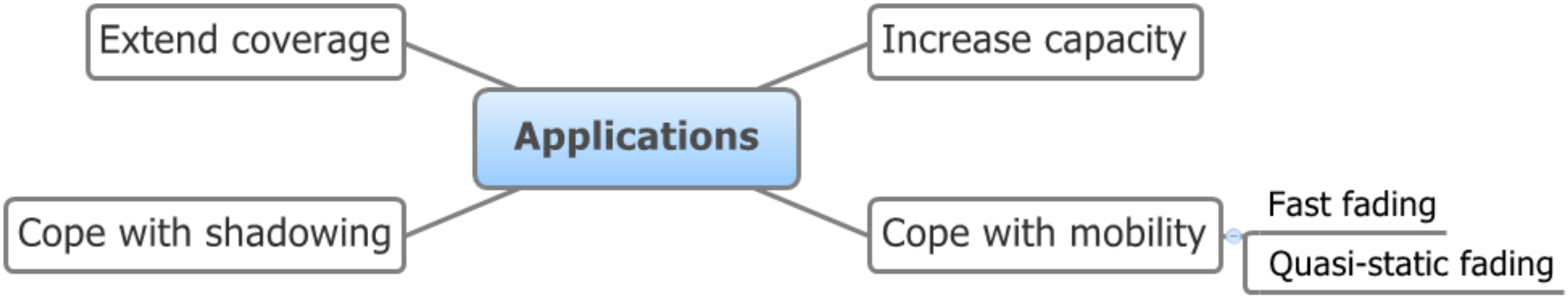
- Practice
- Conclusion and Discussion

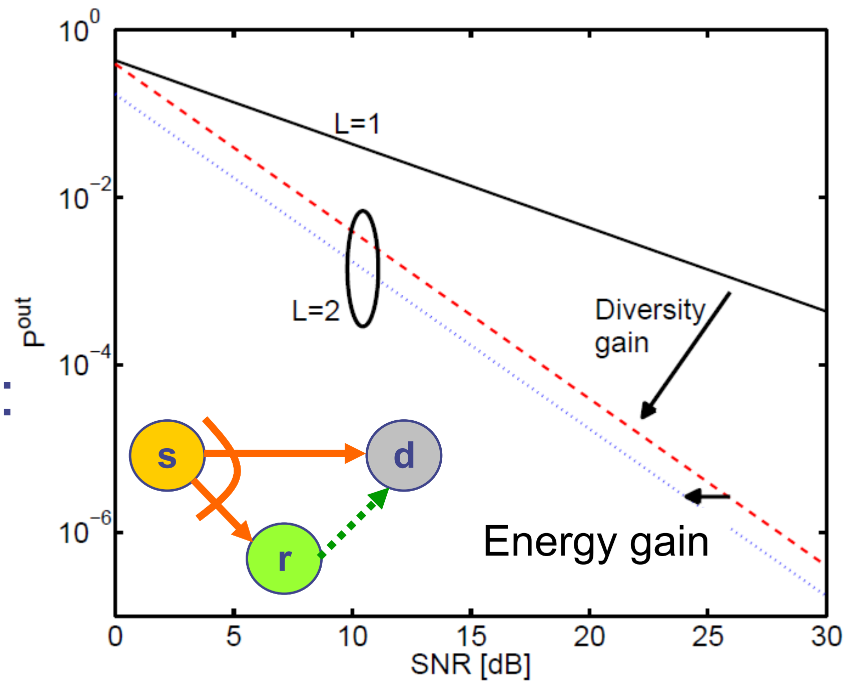


Applications and Scenarios



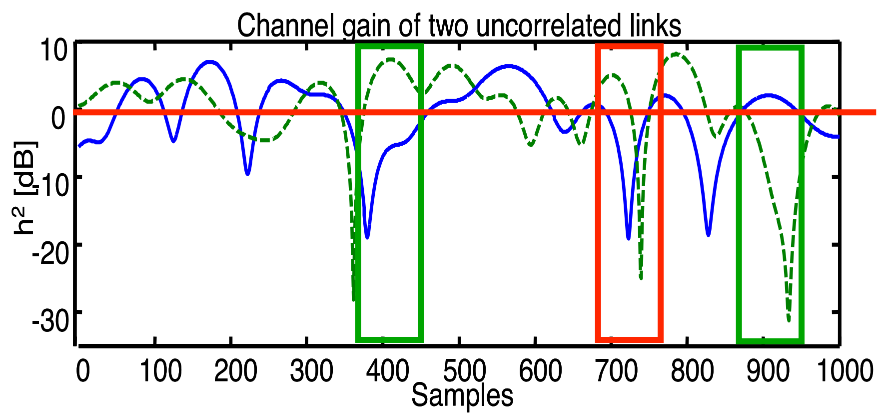
Gains with Cooperation and Competing Techniques

- Energy gain, also achieved by:
  - FEC coding
  - Non-cooperative relaying



- Diversity gain, also achieved by:
  - (H)ARQ in time
  - Interleaving in time
  - Space-time-coding in space

- Spatial multiplexing gain, also achieved by:
  - MIMO precoding
  - Unclear: How to achieve without tight sync of s and r?



Cooperative Technologies and Their Application

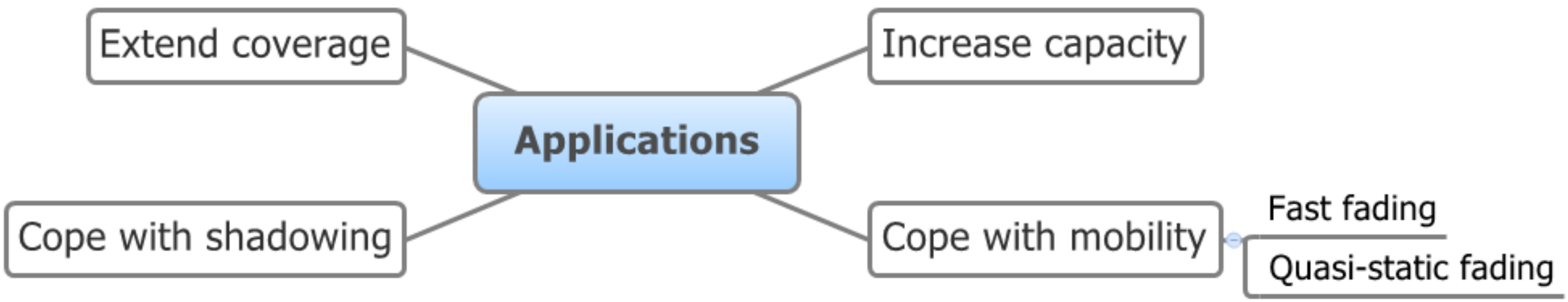
Technology/ Application	***Extend coverage***	***Cope with shadowing***	***Increase capacity***	***Cope with mobility***
Cooperative Relaying	Helps at cell boundary, fills coverage holes, cheap	Spatial Tx diversity	Gains at low SINR and if combined with traffic offloading or classification	Spatial Tx diversity, *Competitors:* HARQ, interleaving, deployment
CoMP	Helps at cell boundary, only in uplink, costly	*Uplink:* Spatial Rx diversity, *Downlink:* Spatial Tx diversity	*Downlink:* Interferes with neighboring cells *Uplink:* Gains but backhaul costs, *Competitor:* MIMO precoding	*Uplink:* Spatial Rx diversity, *Downlink:* Spatial Tx diversity, *Competitors:* as above

Efficient

Insignificant gain w.r.t. established technology

Not applicable

Summary: Applications and Scenarios



- Cooperation is a natural choice to cope with
  - Shadowing: Coverage holes in wireless cells, slow mobility
  - Limited range: Cell boundaries, Mesh or WSNs
- Increasing capacity with cooperation is hard
  - Orthogonal relaying: Multiplexing loss
  - DSTC and CoMP: Strict synchronization via limited backhaul

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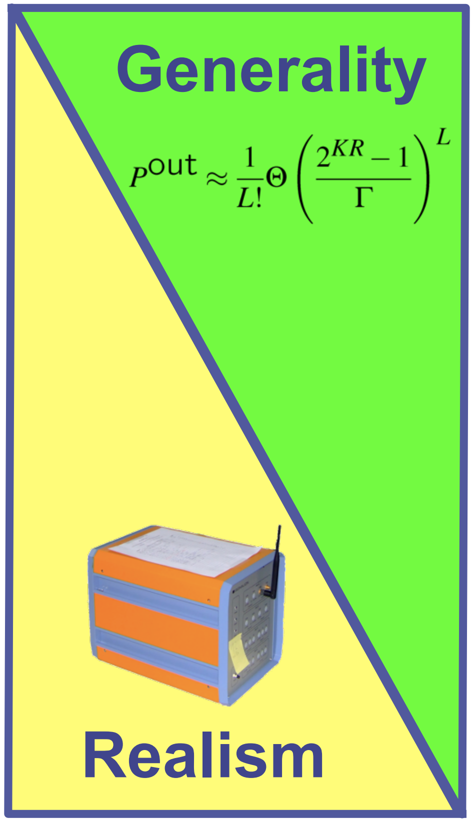
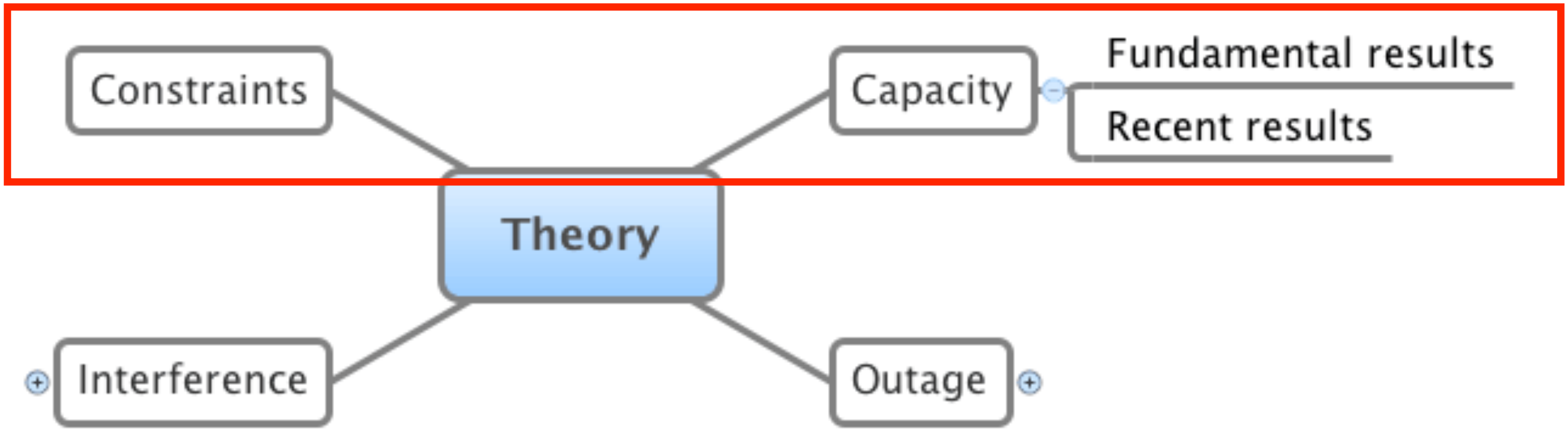


Theory: Analytical Models and Results



Important Constraints

1. Half-duplex constraint: In most wireless systems, transmission and reception are coupled at the antenna.

   => Node cannot receive and transmit in the same time-frequency block

   => Relay requires at least two orthogonal time-frequency blocks to receive and transmit

2. Energy constraint: Overall transmit energy spent in the cooperative system must be less or equal to the energy spent for a direct transmission.

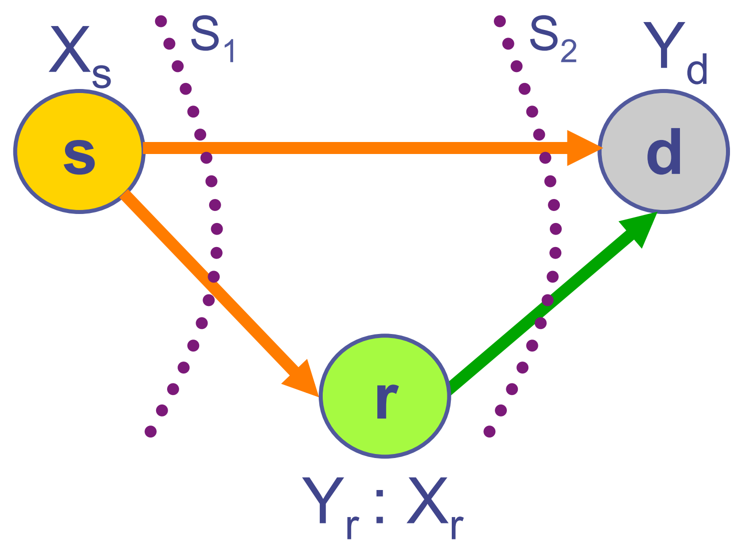
3. Weaker than Constraint 2: Transmit power constraint

   - All transmitters spend no more than P Watts but use additional time

   => Relaying may spend more transmit energy than direct transmission

Capacity: The Relay Channel

- The Relay Channel [2]:
  - X: Set of transmitted codewords x[1],...,x[k]
  - Y: Set of received codewords
  - p(.) probability distribution of codewords selected by encoder
  - S: Cut sets



- Immediate consequence of the cut-set bound: Capacity of the (general) Relay Channel is upper-bounded by

$$C \leq \sup_{p(x_s, x_r)} \min\{I(X_s, X_r; \underbrace{Y_d}_{S_1 \text{ at d}}), I(X_s; \underbrace{Y_d, Y_r | X_r}_{S_2 \text{ at d}})\}$$

Capacity: The Degraded Relay Channel

- Not known: Exact capacity of the (general) Relay Channel

- Known: Capacity of the ***Degraded*** Relay Channel
  - Degraded: y_d depends on x_s only through y_r and x_r
  - Formally: $$p(y_d|\boxed{x_s,}x_r,y_r) = p(y_d|x_r,y_r)$$
  - Implies: X_s −> (X_r, Y_r) −> Y_d forms a Markov chain
  - Thus: $I(X_s; Y_d,Y_r|X_r) = I(X_s; Y_r|X_r)$

is equivalent to the cut-set bound

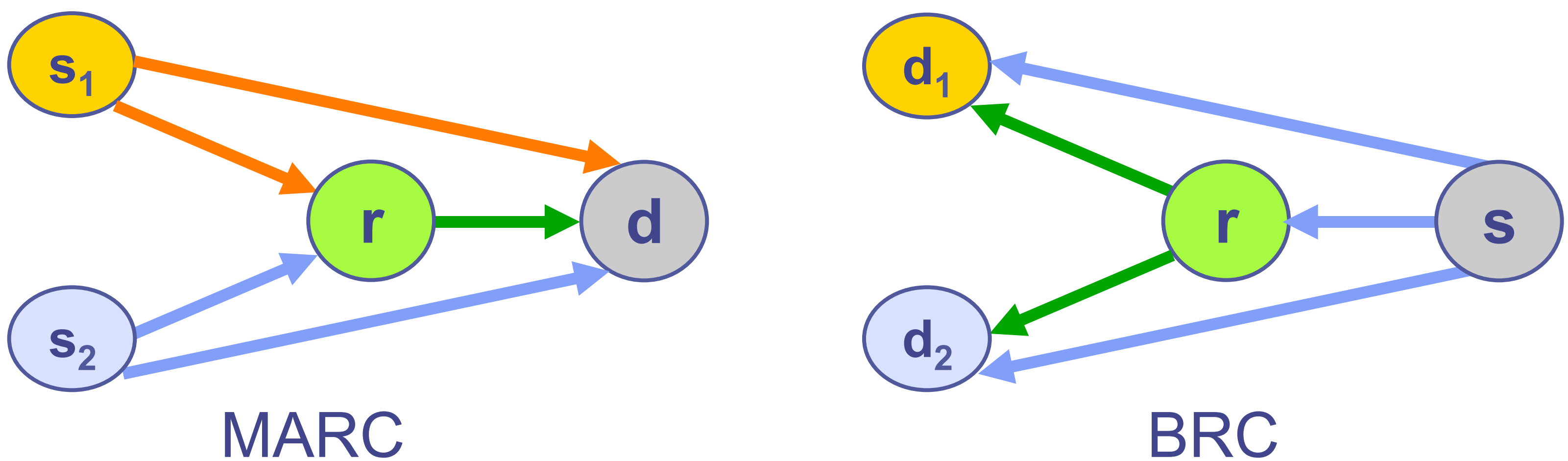
$$C = \sup_{p(x_s,x_r)} \min\{I(X_s,X_r;Y_d), I(X_s;\boxed{Y_r|X_r})\}$$

and is reached by ***Decode-and-Forward***, random binning, and Block-Markov coding

Cover, El Gamal, 1979 [2]

Capacity of Other Relay Configurations

- Capacity of Broadcast Relay Channel (BRC) and Multiple-Access Relay Channel (MARC)
  - Upper bound in [3]



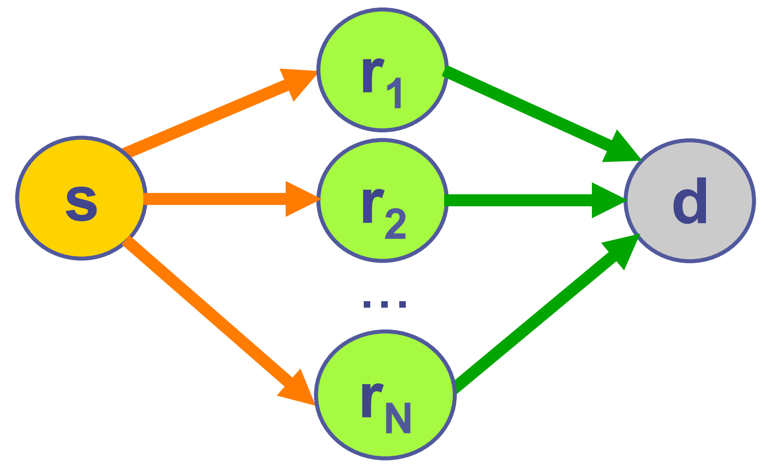
- Ergodic capacity reached by: Decode-and-Forward
  - If phase information available at transmitter and relay close to source
  - MARC and BRC results follow from generalization to multiple relays

Kramer, Gastpar, Gupta, 2005 [3]

Recent Capacity Results

- Diamond configuration: N relays, no direct link
  - Common in resource allocation and opportunistic relaying

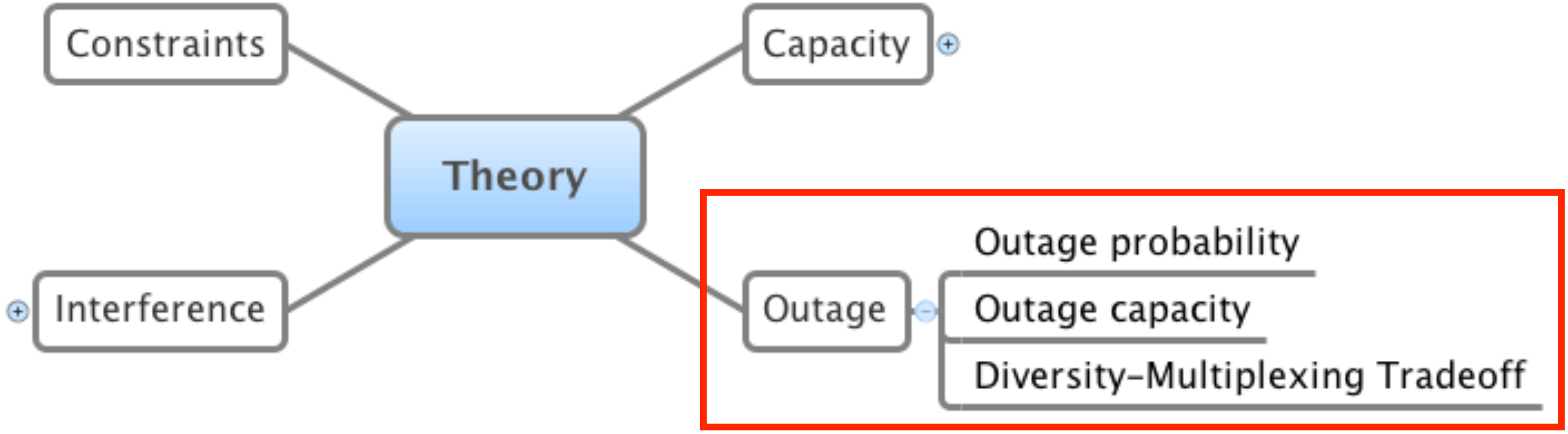
- Exact capacity unknown:
  - Approximation by Gastpar and Vetterli
  - Maximal additive gap of N and maximal multiplicative gap of N^2



- Recent result by Niesen and Diggavi:
  - For N≥4: Approximation more accurate than [4]
    - Achieved by Bursty AF
    - Maximal gaps: Additive 1.8 bits, multiplicative 14
  - That is: Approximation accuracy independent on number of relays

Gastpar and Vetterli, 2005 [4]; Niesen and Diggavi, 2010 [5]

Theory: Analytical Models and Results



Outage Probability: For One Relay

- Outage: Transmitter rate R higher than channel capacity C
  - Equivalent: Instantaneous SNR γ does not meet SNR threshold needed for correct decoding
- Outage probability: Error rate of block fading channels

$$P^{\mathrm{out}} := \mathbb{P}\{C < R\} = \mathbb{P}\{\gamma < \hat{\gamma}\} = \int_0^{\hat{\gamma}} p_\gamma(\gamma)d\gamma$$

  - Finite codewords: Coding sufficient to compensate for noise but cannot cope with fading => Deep fade is only error event
- For single relay with Selection DF or AF:
  - Laneman, Wornell, Tse derived for high SNR [6]

Diversity order

Multiplexing loss

Spectral efficiency

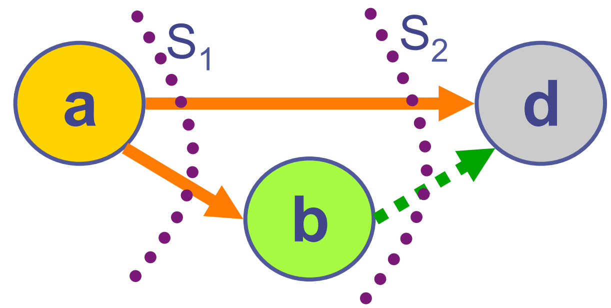
$$P^{\mathrm{out}}_{\mathrm{CTR}} = \frac{1}{2}\frac{1}{\Gamma_{a,d}\Gamma_{a,b}} + \frac{1}{\Gamma_{a,d}\Gamma_{b,d}}\left(\frac{2^{2R}-1}{\Gamma}\right)^2$$

  - Equal result obtained by cut set analysis

$SNR_{i,j} = \Gamma_{i,j}\,\Gamma$

Cut Set Analysis: From 1 to N Relays

- Example for one relay:



$$P^{\text{out}}_{\text{CTR}} = \frac{1}{2} \underbrace{\frac{1}{\Gamma_{a,d}\Gamma_{a,b}} + \frac{1}{\Gamma_{a,d}\Gamma_{b,d}}}_{\Theta} \left(\frac{2^{2R}-1}{\Gamma} \right)^2$$

- Generalizes to N relays: Cut set method Boyer [7]
  - Based on flow networks, i.i.d. Rayleigh fading, and high SNR
- Proven [7]: It suffices to study the “diversity bottleneck”
  - Obtain L and Θ from M cut sets S_M of minimum rank

$$\mathbb{S}_M := \{ S \in \mathbb{S} \mid |S| = L \}$$

$$\Theta = \sum_{\forall S_m \in \mathbb{S}_M} \left(\prod_{\forall L \text{ links } (i,j) \in S} \frac{1}{\Gamma_{i,j}} \right)$$

insert in

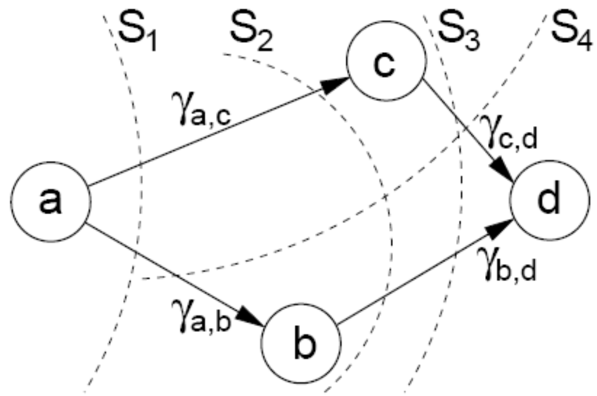
No. subchannels

$$P^{\text{out}} \approx \frac{1}{L!} \Theta \left(\frac{2^{KR}-1}{\Gamma} \right)^L$$

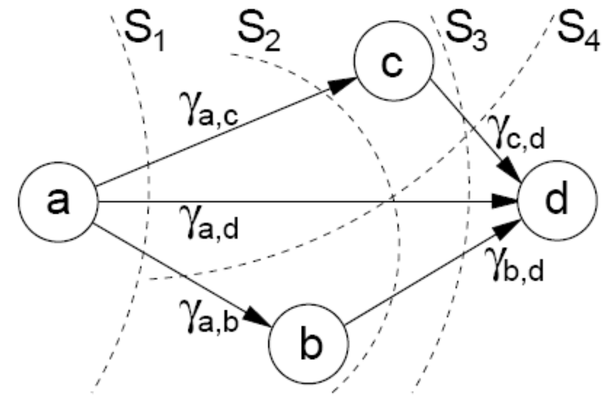
Network graph

Boyer, Falconer, et al. 2007 [7]

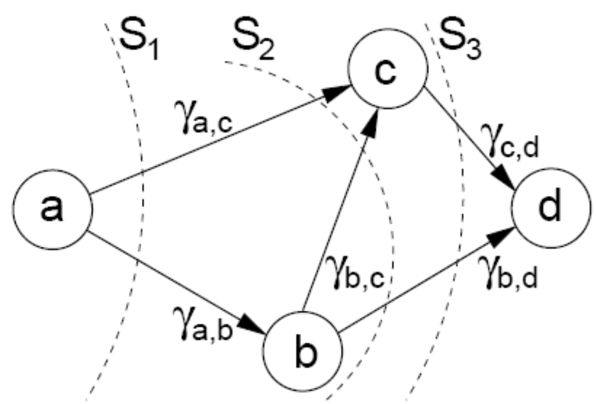
Examples for N=2 Relays: Diamond Configurations



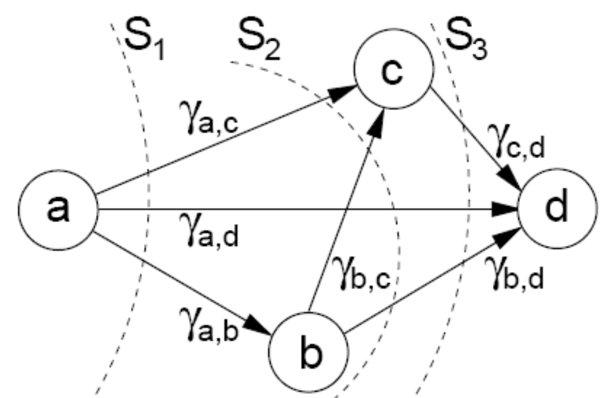
(a) Weak Sparse Diamond (WSD)



(b) Strong Sparse Diamond (SSD)



(c) Weak Full Diamond (WFD)



(d) Strong Full Diamond (SFD)

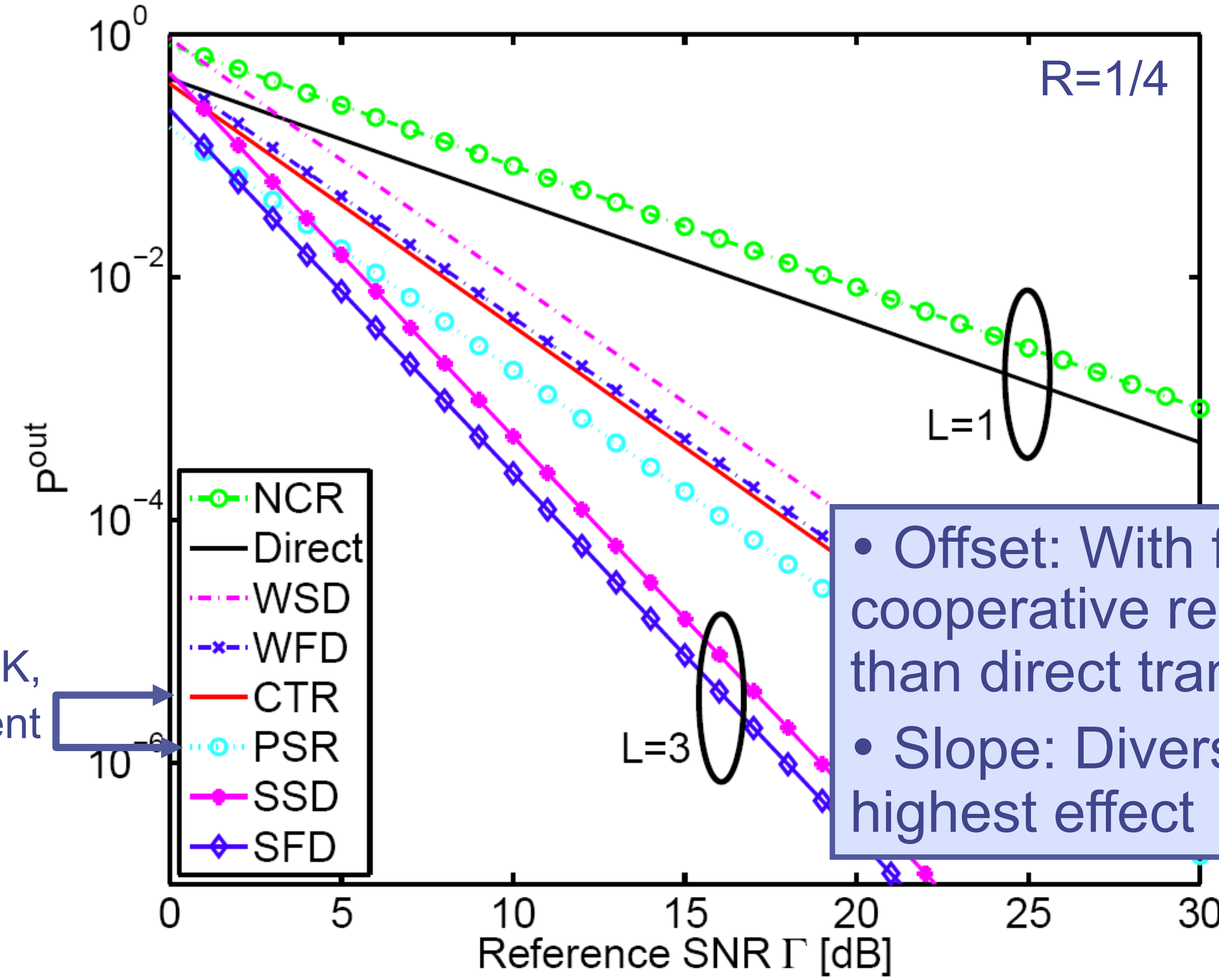
Examples for N=2 Relays: Outage Probability

Flow network	Outage probability at high SNR, $P^{\mathrm{out}} \approx$	Div. order, L	Div. order at c, L_c	# subchan. K	
Direct	$\frac{1}{\Gamma_{a,d}} \frac{2^R-1}{\Gamma}$	1	–	1	0 relays
NCR	$\Theta_T \left(\frac{2^{2R}-1}{\Gamma}\right)$	1	1	2	N=1 relay
CTR	$\frac{1}{2\Gamma_{a,d}} \Theta_T \left(\frac{2^{2R}-1}{\Gamma}\right)^2$	2	1	2	
WSD	$\frac{1}{2} \Theta_S \left(\frac{2^{3R}-1}{\Gamma}\right)^2$	2	1	3	N=2 relays
WFD	$\frac{1}{2} \Theta_F \left(\frac{2^{3R}-1}{\Gamma}\right)^2$	2	2	3	
SSD	$\frac{1}{6\Gamma_{a,d}} \Theta_S \left(\frac{2^{3R}-1}{\Gamma}\right)^3$	3	1	3	
SFD	$\frac{1}{6\Gamma_{a,d}} \Theta_F \left(\frac{2^{3R}-1}{\Gamma}\right)^3$	3	2	3	
Any	$\frac{1}{L!} \Theta \left(\frac{2^{KR}-1}{\Gamma}\right)^L$	$\lvert S_m \rvert$	$\lvert S_m^c \rvert$	$N+1$	N relays

$$\Theta_S = \frac{\Gamma_{a,b}\Gamma_{a,c} + \Gamma_{a,b}\Gamma_{c,d} + \Gamma_{a,c}\Gamma_{b,d} + \Gamma_{b,d}\Gamma_{c,d}}{\Gamma_{a,b}\Gamma_{a,c}\Gamma_{b,d}\Gamma_{c,d}} \quad \Theta_F = \frac{\Gamma_{a,b}\Gamma_{a,c} + \Gamma_{b,d}\Gamma_{c,d}}{\Gamma_{a,b}\Gamma_{a,c}\Gamma_{b,d}\Gamma_{c,d}} \quad \Theta_T = \frac{\Gamma_{a,b} + \Gamma_{b,d}}{\Gamma_{a,b}\Gamma_{b,d}}$$

Valentin, Lichte, et al., 2008 [8]

Examples for N=2 Relays: Numerical Results



Equal K, Different Graph

- Offset: With fading, non-cooperative relaying worse than direct transmission
- Slope: Diversity order highest effect

Unified Analysis: Outage Capacity for Arbitrary Networks

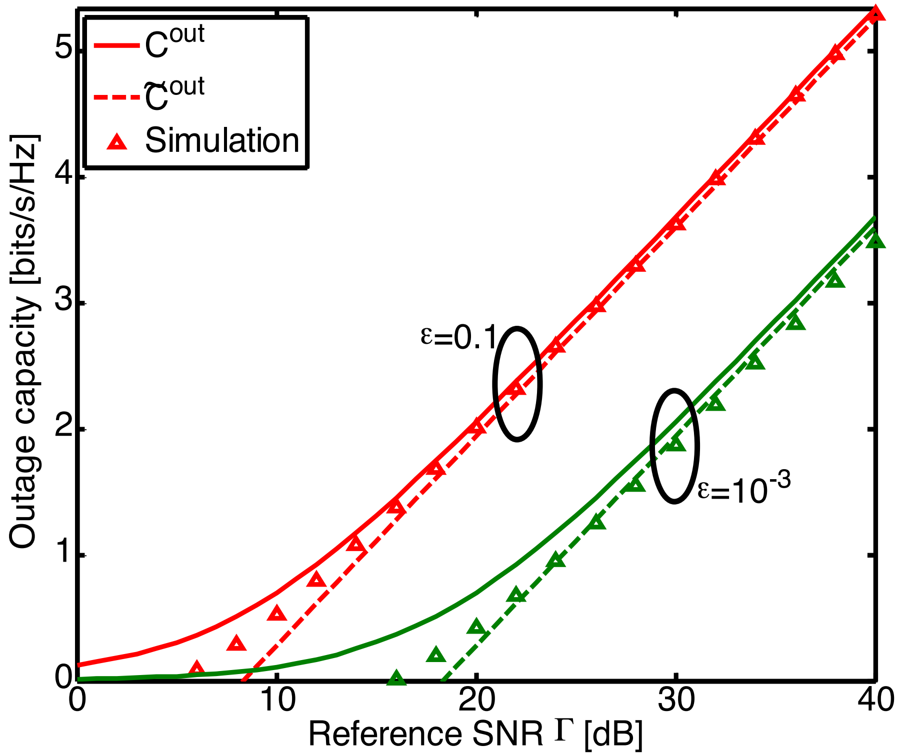
- Outage capacity: Maximize R such that error rate constraint ε is not exceeded
  - Intuition: Throughput under at a given maximum error rate
  - Formally: $C^{\text{out}} := \sup \{R : P^{\text{out}}(R) \leq \epsilon\}$
  - Obtained by solving $P^{out}(R)=\varepsilon$ in R

$$C^{\text{out}} := R = \frac{1}{K} \log_2 \left(\sqrt[L]{\frac{L!\epsilon}{\Theta}} \cdot \Gamma + 1 \right)$$

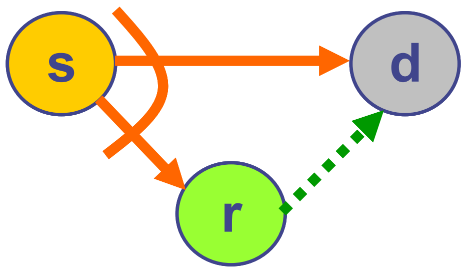
- Shown in [8]: At high SNR and L, C^{out} simplifies to

$$\tilde{C}^{\text{out}} \approx \underbrace{\frac{1}{K}}_{\text{Multiplexing loss}} \Big(\underbrace{\log_2(L \cdot \text{SNR})}_{= C_L^{AWGN}} + \underbrace{\frac{1}{L} \log_2 \epsilon}_{\text{Fading}} - \underbrace{\frac{1}{L} \log_2 \Theta - 1}_{\text{Relaying}} \Big)$$

Outage Capacity: Close Approximation?



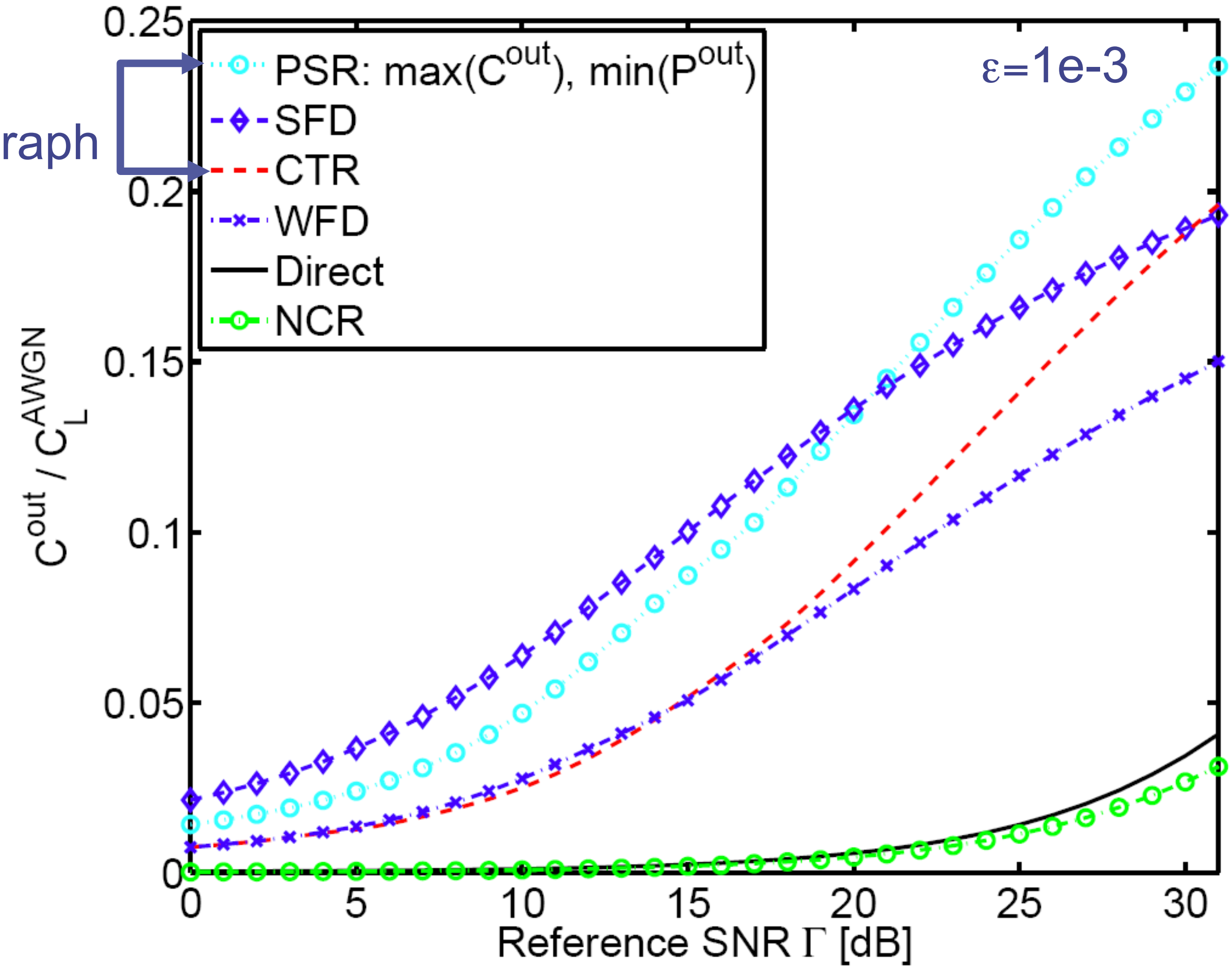
Triangle configuration:
L=2, K=2



- High SNR: Close match to simulation results
- Low SNR: Second approximation [7] is closer
  - Even for low *L*

Numerical Results: Outage capacity/AWGN Capacity

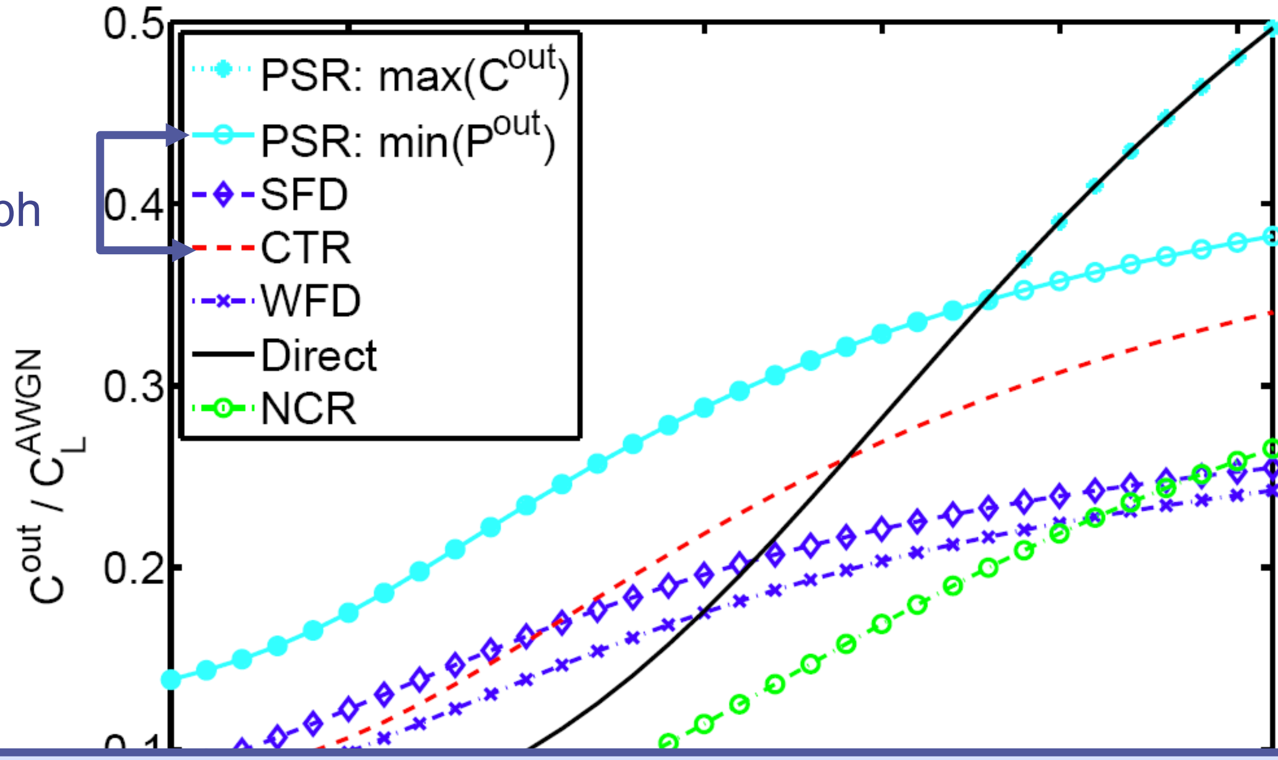
Equal K,
Different Graph



Valentin, Lichte, et al., 2008 [8]

Numerical Results: Outage capacity/AWGN Capacity

Equal K,
Different Graph



- Expect data rate gain at: Low SNR, low ε
- With ideal CSI: Opportunistic relaying outperforms SDF
- Opportunistic relaying: Not no. of used relays defines diversity order but no. of available relays [11]

Valentin, Lichte, et al., 2008 [8]

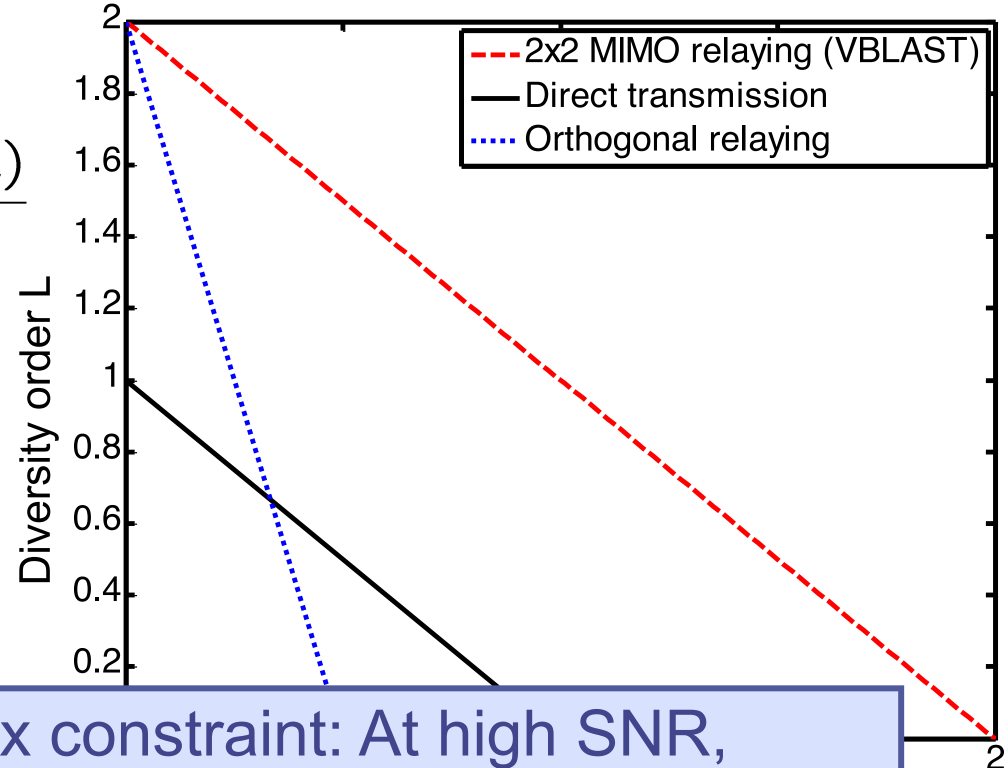
Diversity-Multiplexing Tradeoff

- How fast does P^{out} decrease and data rate increase for increasing SNR?
  - Intuition: Robustness vs. data rate
- Diversity order:

$$L = -\lim_{\mathrm{SNR}\to\infty} \frac{\log P^{\mathrm{out}}(R, SNR)}{\log \mathrm{SNR}}$$

- Multiplexing gain:

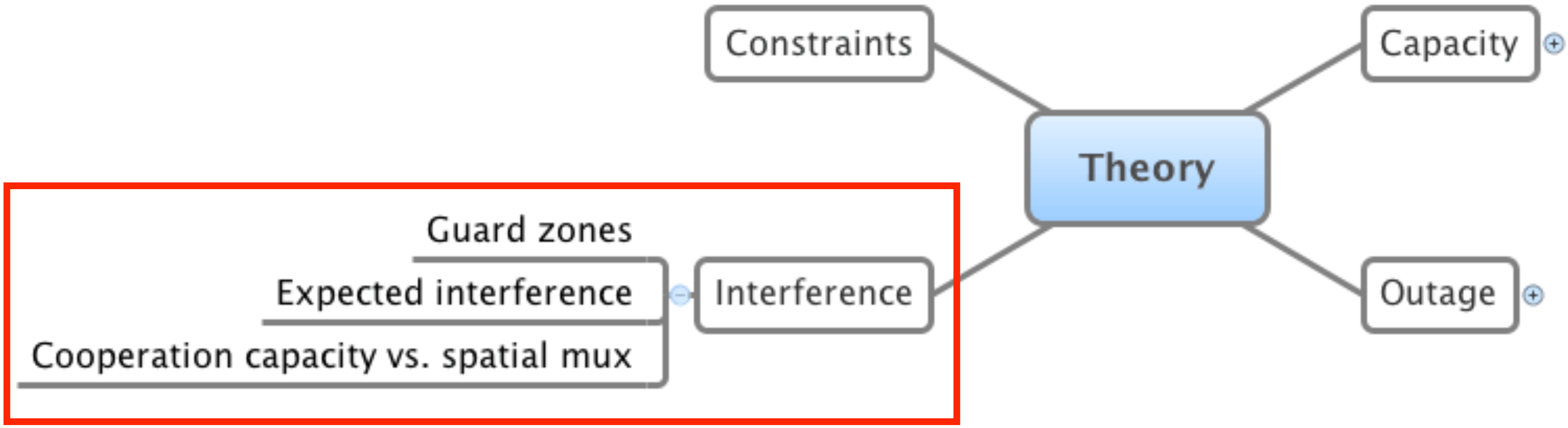
$$r = \lim_{\mathrm{SNR}\to\infty} \frac{R(SNR)}{\log_2 SNR}$$



Consequence of half-duplex constraint: At high SNR, orthogonal relaying improves error rate but not throughput

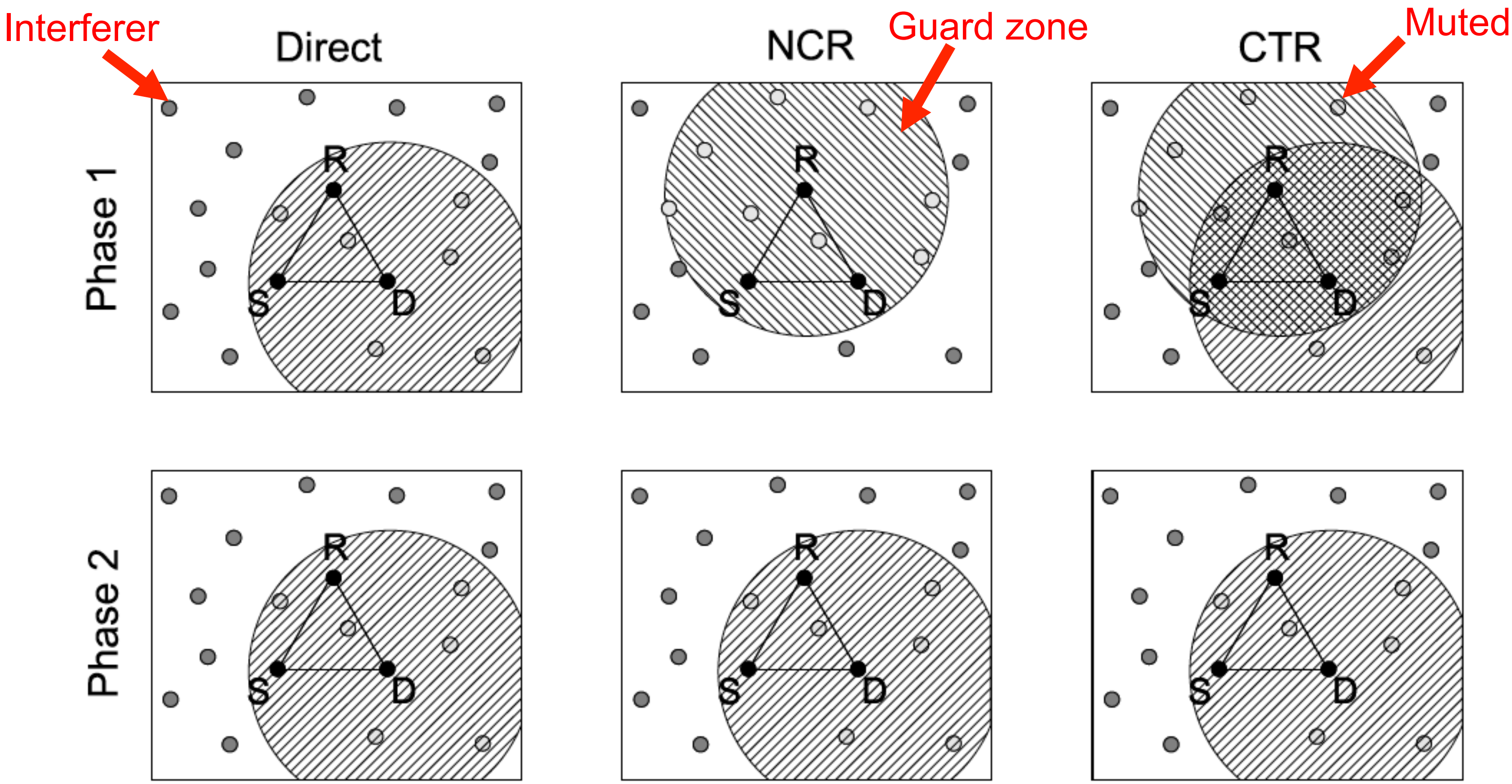
Zheng and Tse, 2003 [9]

Theory: Analytical Models and Results



Interference: Guard Zones

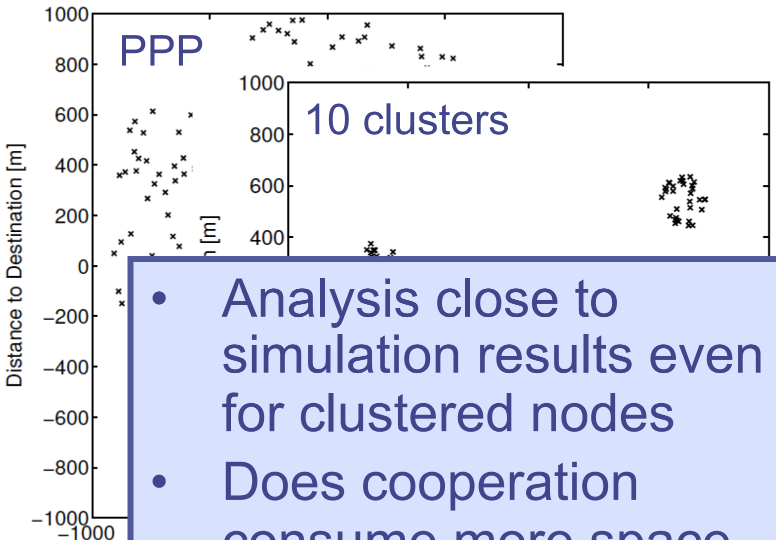
- Relaying consumes space: Model by guard zones [16]
  - Reflects IEEE 802.11 CSMA/CA MAC and cognitive radios with isotropic propagation



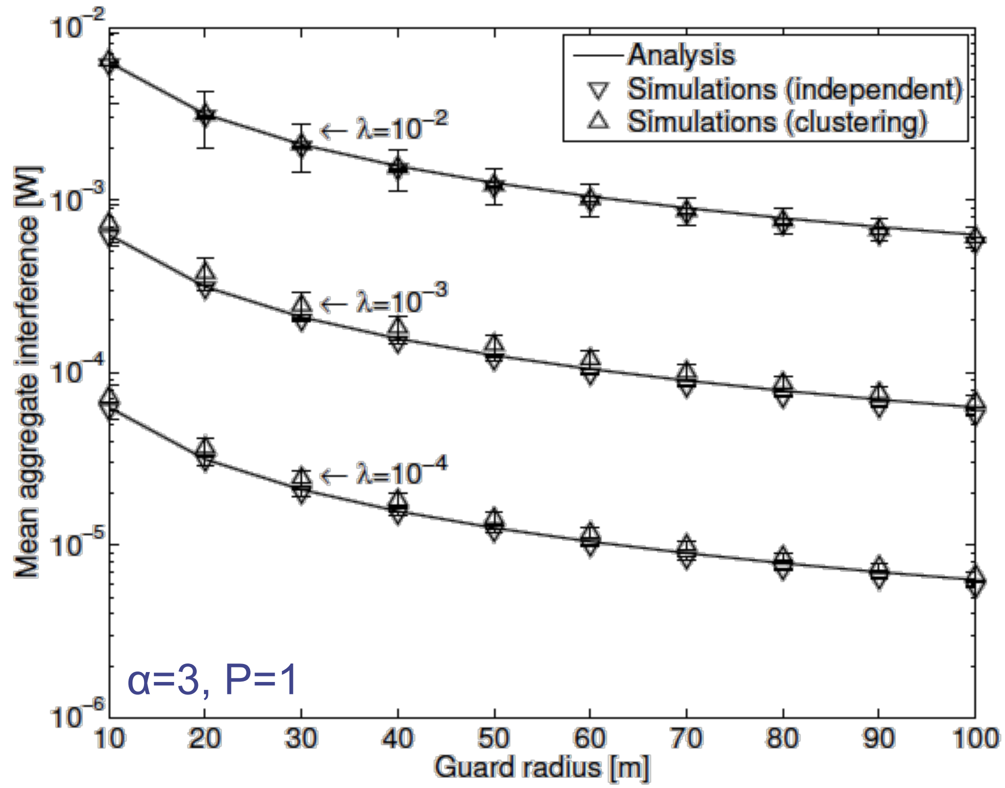
Lichte, Valentin, et al., 2009 [16]

Expected Interference in Randomly Placed Networks

- Aggregate expected interference [15]:
  $$\mathbb{E}[I] = \frac{2\lambda\pi P}{(\alpha-2)g^{\alpha-2}}$$
  - Node density λ, guard radius g, and transmit power per node P, Path loss exponent α
  - Holds for: Spatial Point Poisson Processes (PPP), i.i.d. Rayleigh fading, and α>2
  - For α=2, cp. [16]

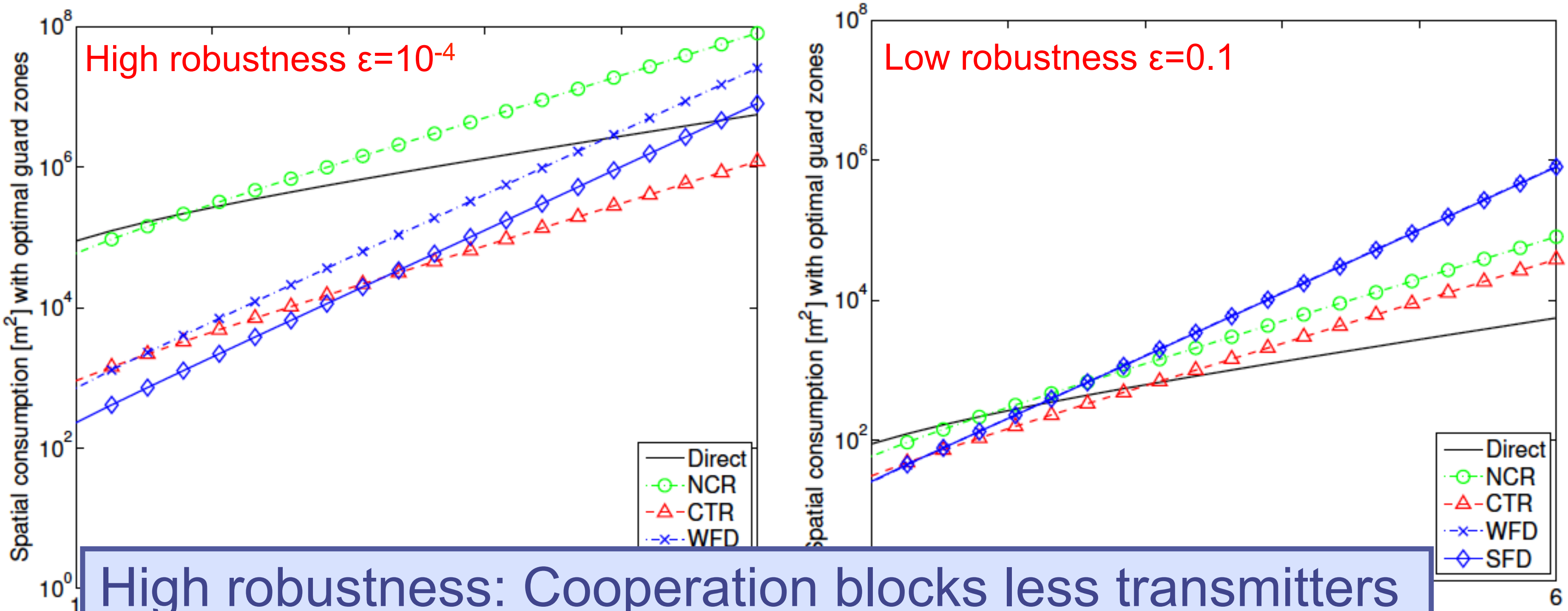


- Analysis close to simulation results even for clustered nodes
- Does cooperation consume more space than direct?



Cooperation Capacity vs. Spatial Multiplexing

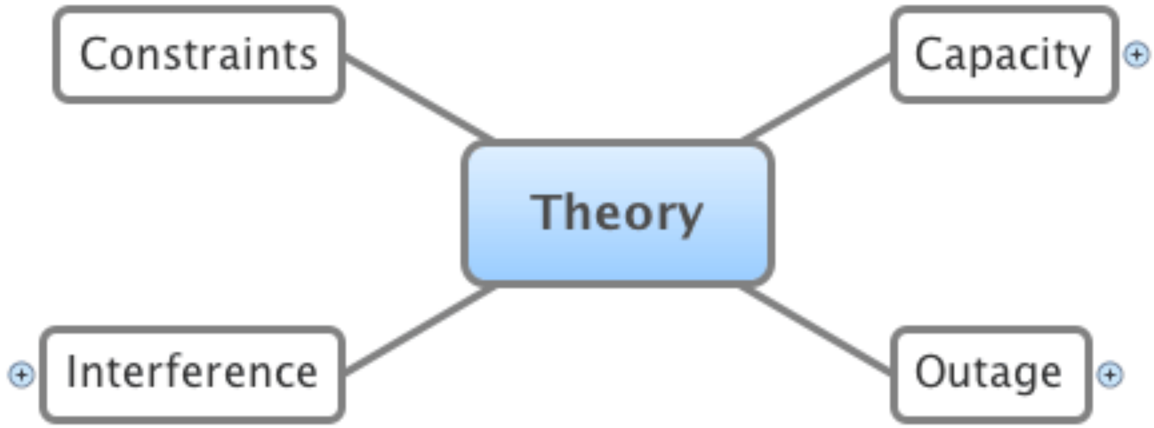
- Increasing guard radius: Decreases E[I] and increases C^{out}
  - Improve capacity per cooperative link at the cost of spatial mux
- Shown: Reserved space versus target C^{out}
  - Half-duplex SDF, λ=0.1 s.t. SIR=25 dB, α=4, i.i.d. Rayleigh fading



High robustness: Cooperation blocks less transmitters than direct; reverses at low robustness

Lichte, 2011, to appear.

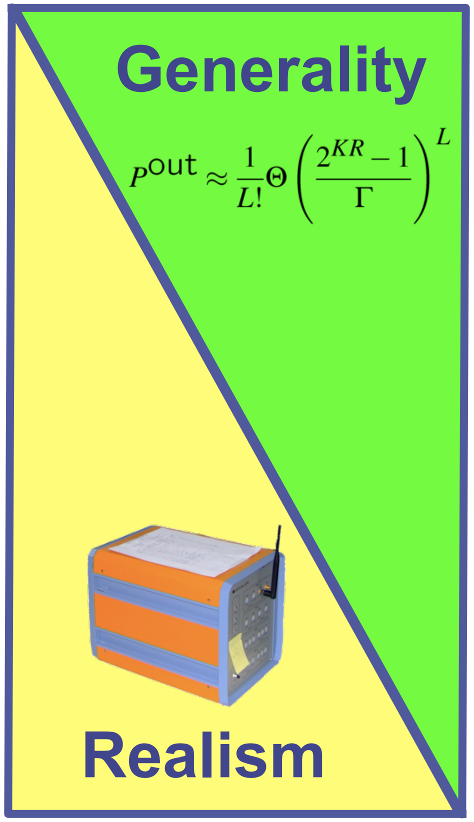
Summary: Analytical Models and Results



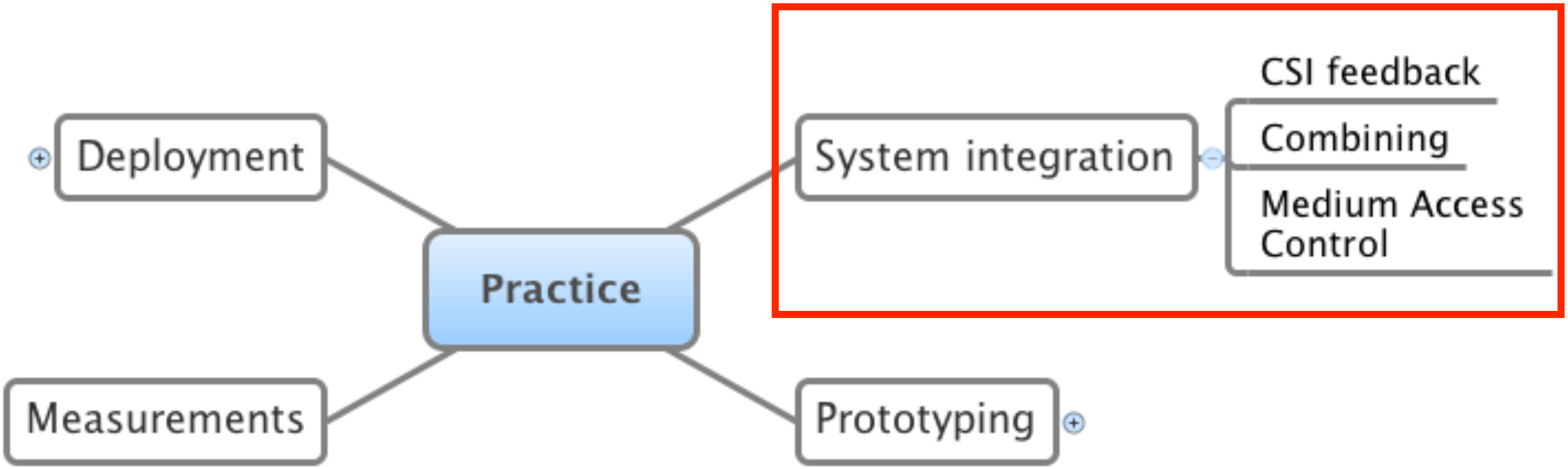
- Unified analytical framework: Not available for capacity but for outage probability and outage capacity
  - Holds for any network with single source/destination at high SNR
- Theoretical results:
  - DF achieves capacity and full diversity order in many setups
  - Half-duplex constraint => Improves throughput or spatial multiplexing only at low SNR or low target error rate
    - Well suited for robust communication, e.g., wireless sensors
    - But improves WLAN or LTE capacity only at the cell edge

Outline

- Technologies
- Application
- Theory
- **Practice**
- Conclusion and Discussion

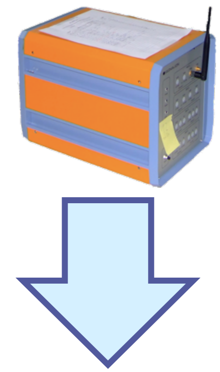


Practice: System Integration, Prototypes, and Measurements



Integrating Cooperation into Current Systems Requires to

1. Extend models to capture:
    - Performance gains of cooperation
    - Degradation of these gains by practical limitations



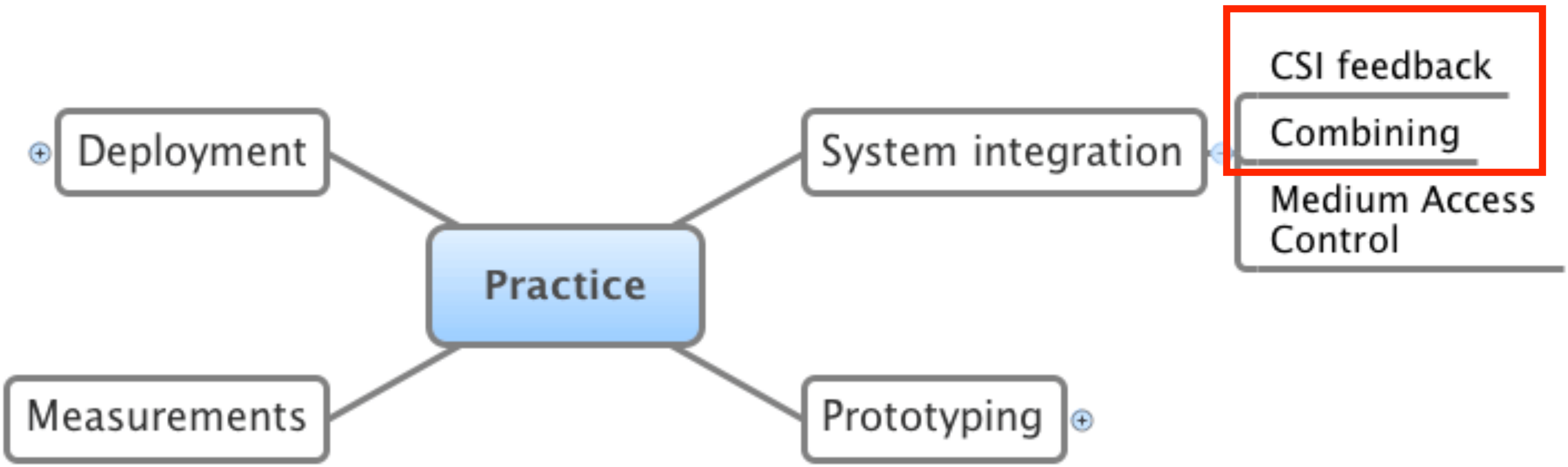
$$P^{\text{out}} \approx \frac{1}{L!}\Theta\left(\frac{2^{KR}-1}{\Gamma}\right)^{L}$$

2. Design new functions to support cooperation

3. Integrate main and support functions into transceiver

4. Carefully study this new system by simulation, prototyping, and experiment

Practice: System Integration, Prototypes, and Measurements



Relaying with Limited CSI Feedback: Outage Model

- How to incorporate limited CSI feedback?
- Idea: Condition C^{out} on outage capacity of feedback channel

- Formally [28]: $$C_f^{\text{out}} := R_{\text{FB}}(C_{\text{FB}}^{\text{out}}, b_{\text{FB}}, \tau) \cdot C^{\text{out}}$$

  where $0 \leq R_{\text{FB}} \leq 1$ is the unused portion of the feedback channel's outage capacity $C_{\text{FB}}^{\text{out}}$. With $x^+=\max(0,x)$

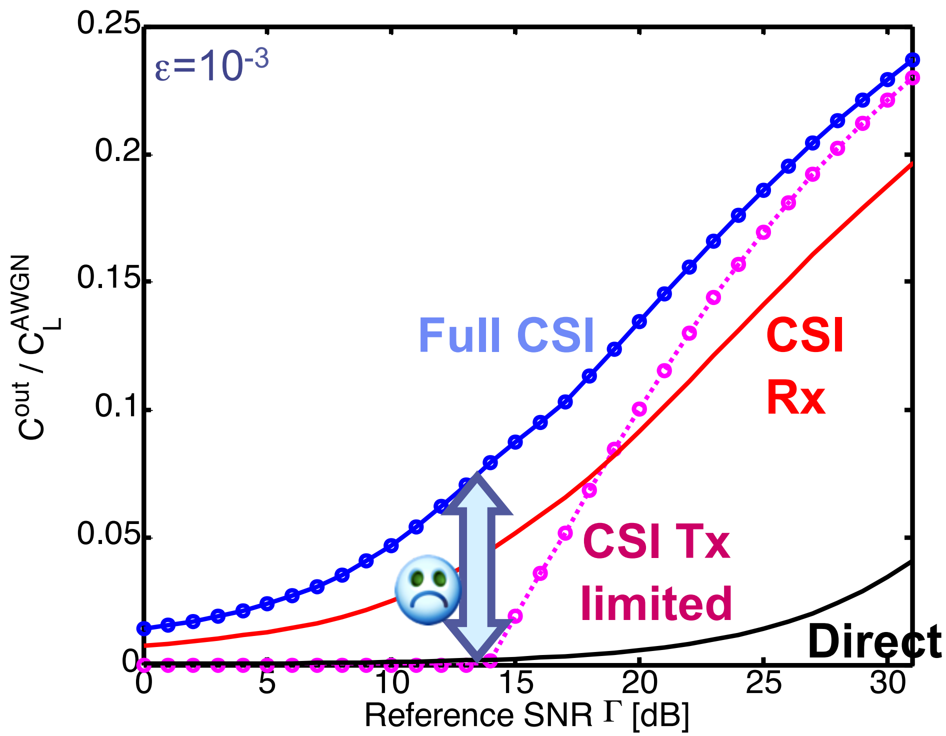
$$R_{\text{FB}} := \left(\frac{C_{\text{FB}}^{\text{out}} - b_{\text{FB}}/\tau}{C_{\text{FB}}^{\text{out}}} \right)^+$$

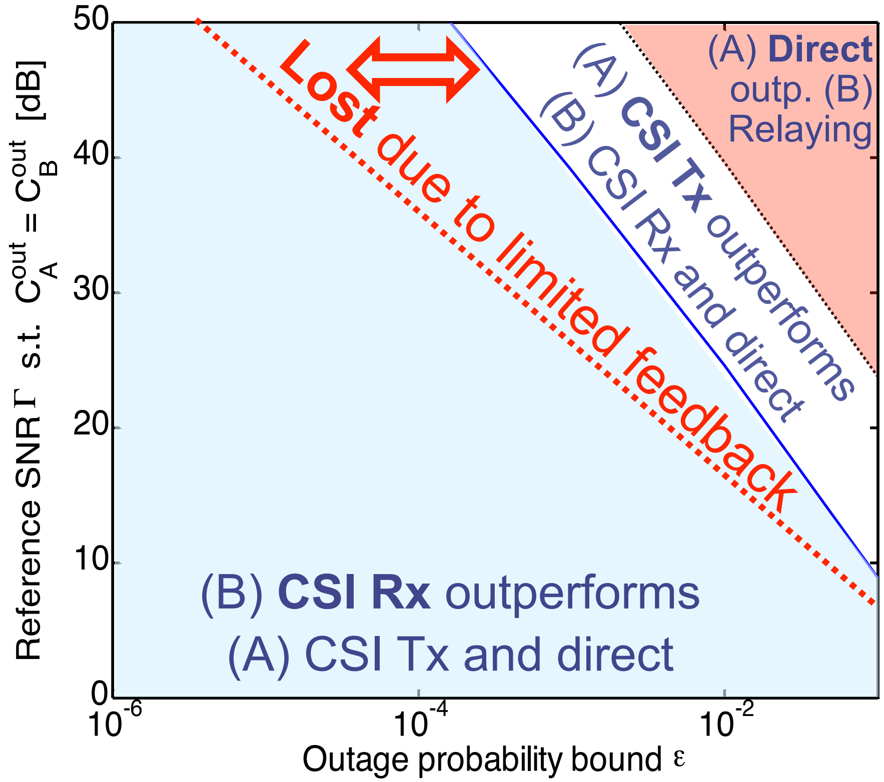
b_{FB} bits feedback/cycle
$1/\tau$ update frequency

- **Consequence:** Feedback channel ‘s capacity **bounds** end-to-end outage capacity

Relaying with Limited CSI Feedback: Results

- Outage capacity for i.i.d. Rayleigh fading, 3 bits feedback via a single broadcast every τ=26 cycles, 2 relays



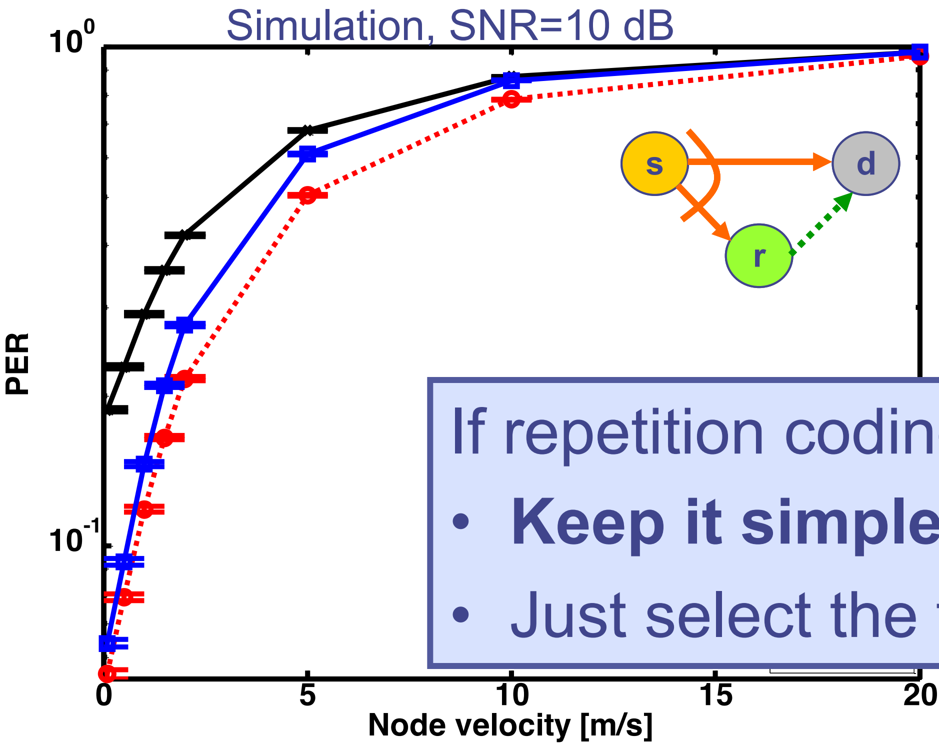


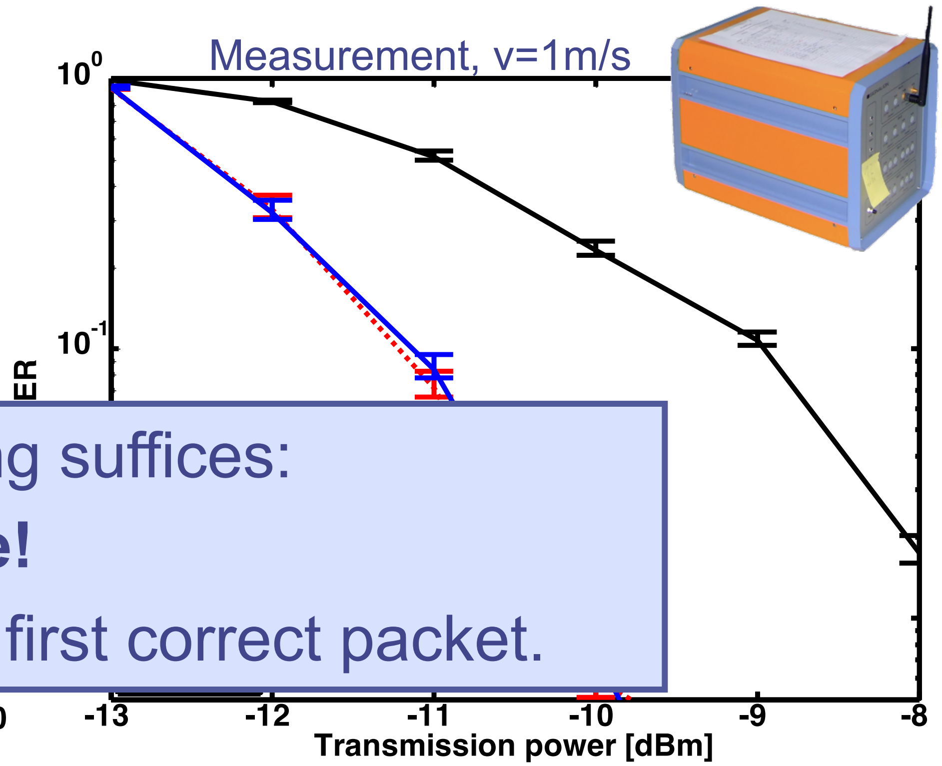
With limited feedback: Loose more C^{out} when target error rate decreases

Valentin, Lichte, et al. 2008 [8]

Combining with Slow Fading and Repetition Coding

- Observation at ***low*** mobility: No large gain with MRC; Packet Selection Combining (PSC) sufficient
- Cooperative WLAN transceivers: Implement PSC not MRC
  - Multi-rate combining straightforward, Only change MAC processor

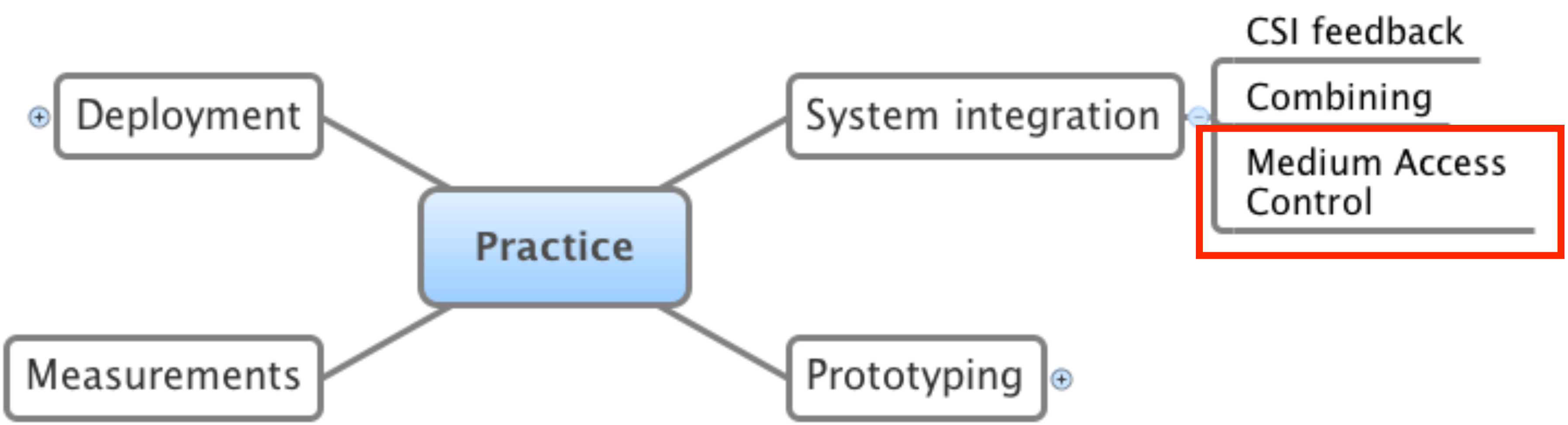




If repetition coding suffices:
- **Keep it simple!**
- Just select the first correct packet.

Valentin, Woldegebreal, et al. 2009 [29]

Practice: System Integration, Prototypes, and Measurements



Challenges of Cooperative MAC Protocols

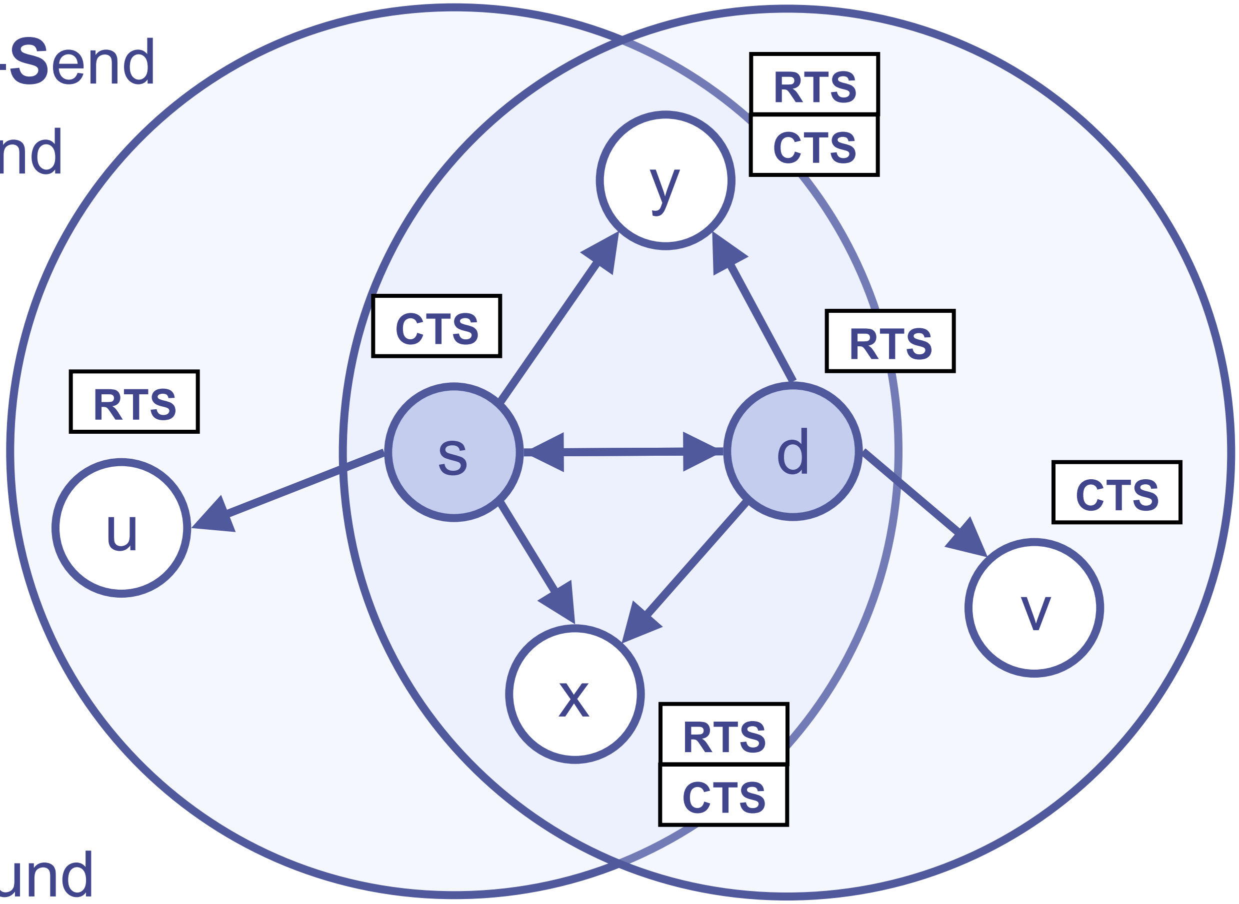
- When to cooperate?
  - Determine at run-time whether cooperation boosts performance
- Whom to cooperate with?
  - Which of my neighbors are hidden to the destination?
  - If they are not hidden, how good are their uplinks?
  - Are they willing to cooperate at all?
- Who decides?
  - Source/relay/destination-initiated cooperation

Basically: Three-step approach

1. Find the set of potential relays
2. Determine whether cooperation is beneficial
3. Choose a particular (hopefully the best) relay

1. Find the set of potential relays

- Use **R**equest-**T**o-**S**end
- and **C**lear-**T**o-**S**end
- Potential relays: Users that receive *both,* here x and y
- Further selection necessary when more than one potential relay found
- Not restricted to unit disk graphs



2. Determine whether cooperation is beneficial

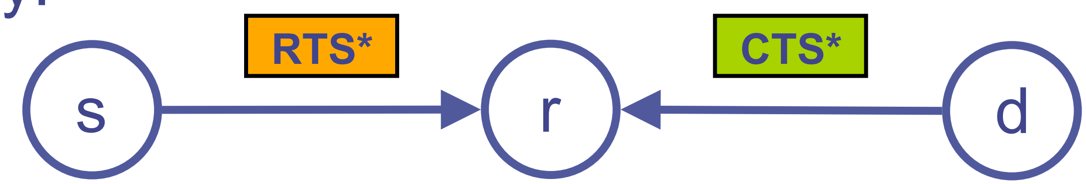
- Theoretically:
  - Direct transmission does not support desired rate (at bandwidth W)

    $$W \log_2\left(1 + \mathsf{SNR}_{s,d}\right) < R_d$$

  - Cooperative transmission does

    $$\frac{W}{2} \min\left\{\log_2\left(1 + \mathsf{SNR}_{s,r}\right), \log_2\left(1 + \mathsf{SNR}_{s,d} + \mathsf{SNR}_{r,d}\right)\right\} \geq R_d$$

- Practically:



  - Modified RTS*: Add desired data rate
    - Relay estimates $SNR_{s,r}$ and destination estimates $SNR_{s,d}$
  - Modified CTS*: Add estimate of $SNR_{s,d}$
    - Relay estimates $SNR_{r,d}$ from $SNR_{d,r}$ (Assumption: channel reciprocity)

3. Further selection necessary

- Distinguish three approaches:
  - **Source-initiated cooperation**
  - Relay-initiated cooperation
  - Destination-initiated cooperation

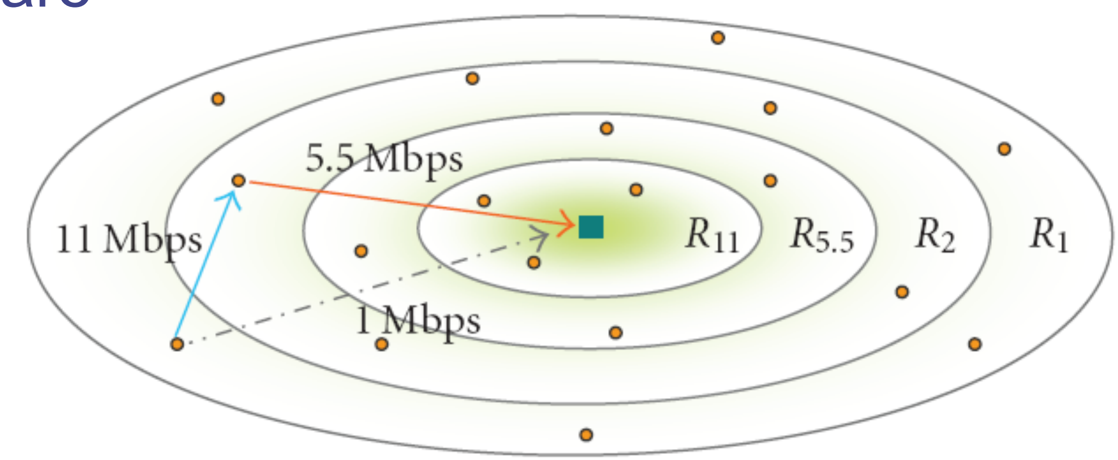
- Problems?

Source initiates: Infrastructure networks

- Sender far away from access point (AP): low rate
  - Limited mobility, slow fading => low rate persists for long time
  - Direct transmission in IEEE 802.11b: as low as 1 Mbps
- Users closer to AP: higher rates
  - Provide alternative paths with higher rates
  - Cooperation: path diversity
- Gain exists if rates R are

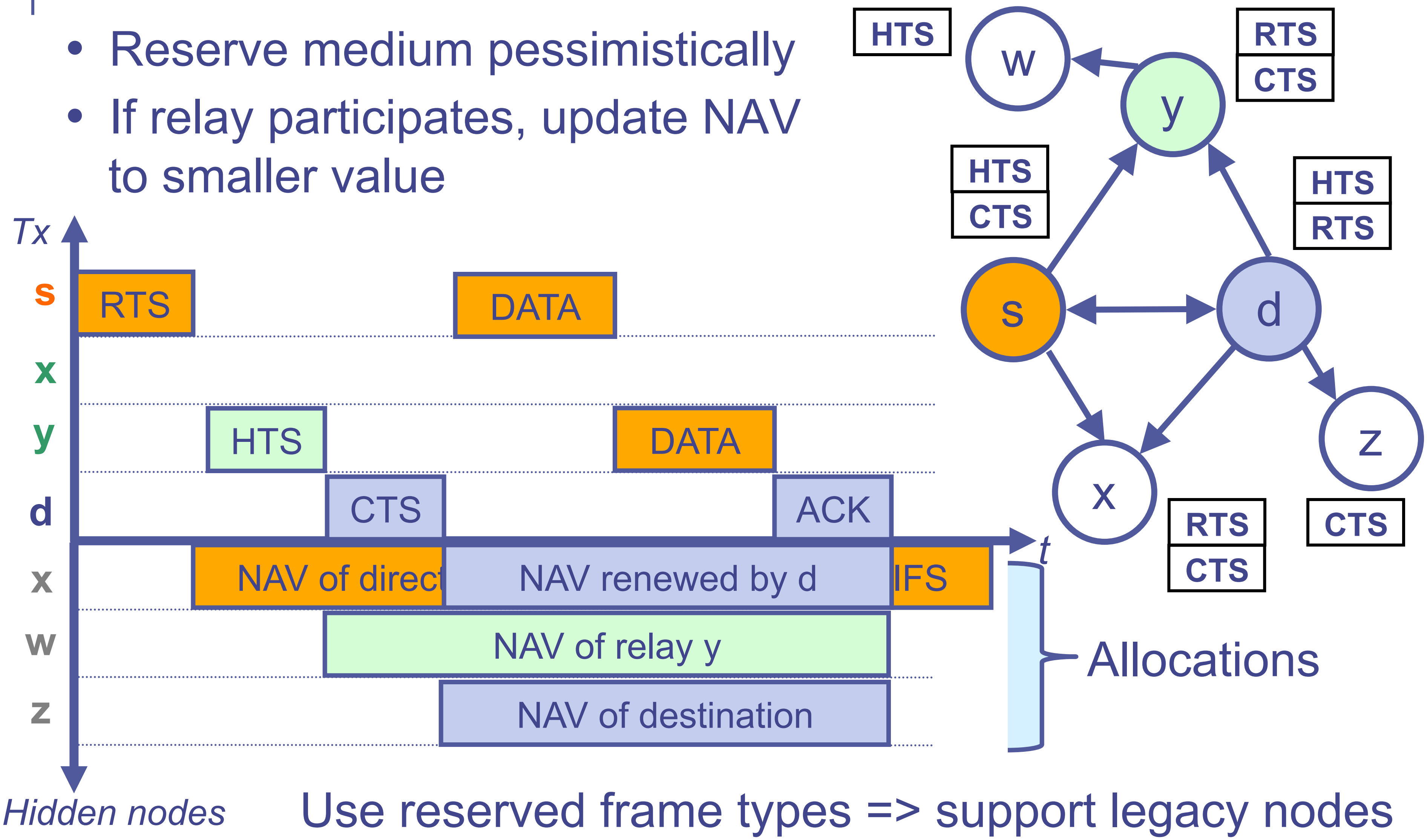
$$\frac{1}{R_{\mathrm{sr}}} + \frac{1}{R_{\mathrm{rd}}} > \frac{1}{R_{\mathrm{sd}}}$$

- **Source-initiated** cooperation: How to obtain the rates?



CoopMAC: A protocol for path diversity

- Reserve medium pessimistically
- If relay participates, update NAV to smaller value

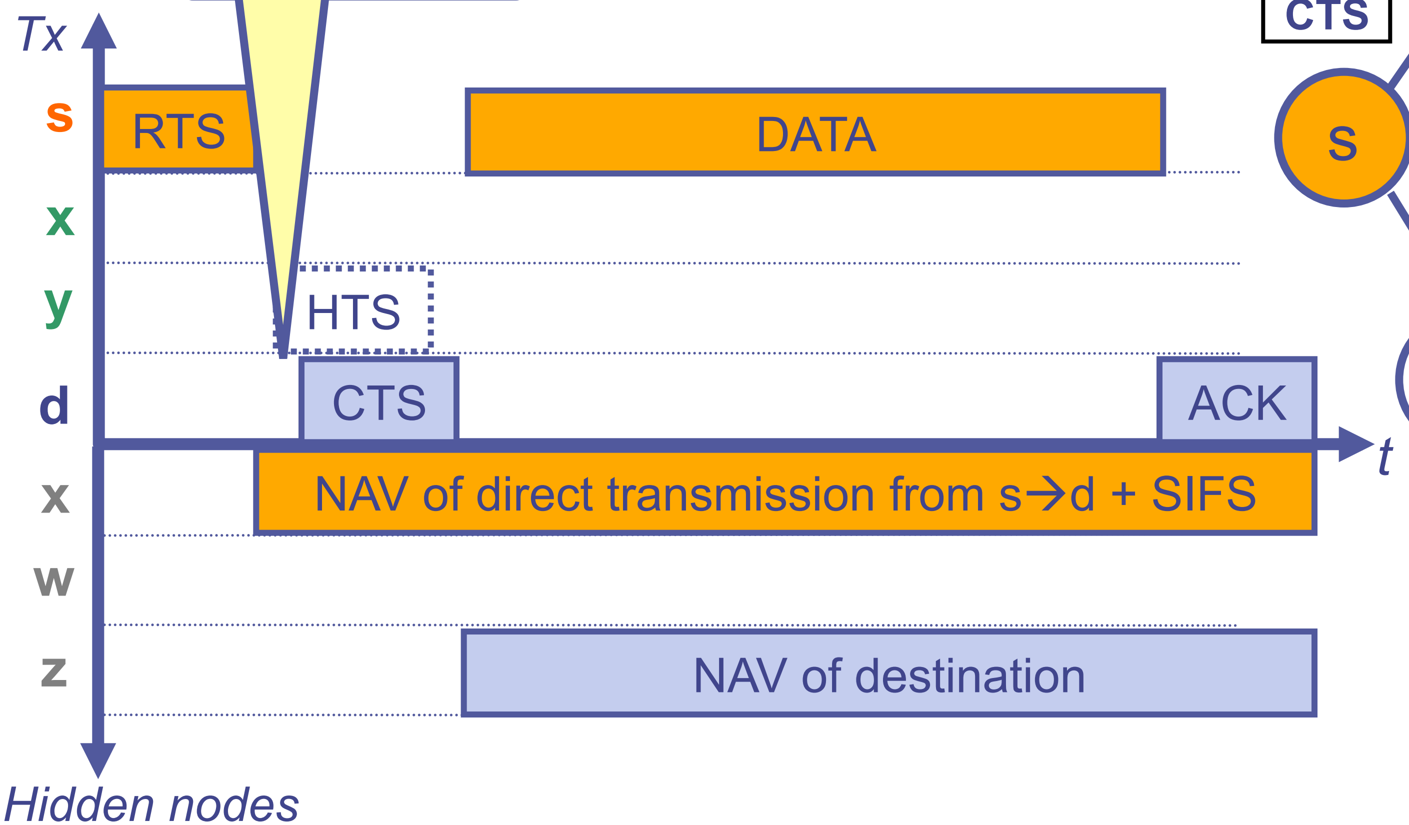


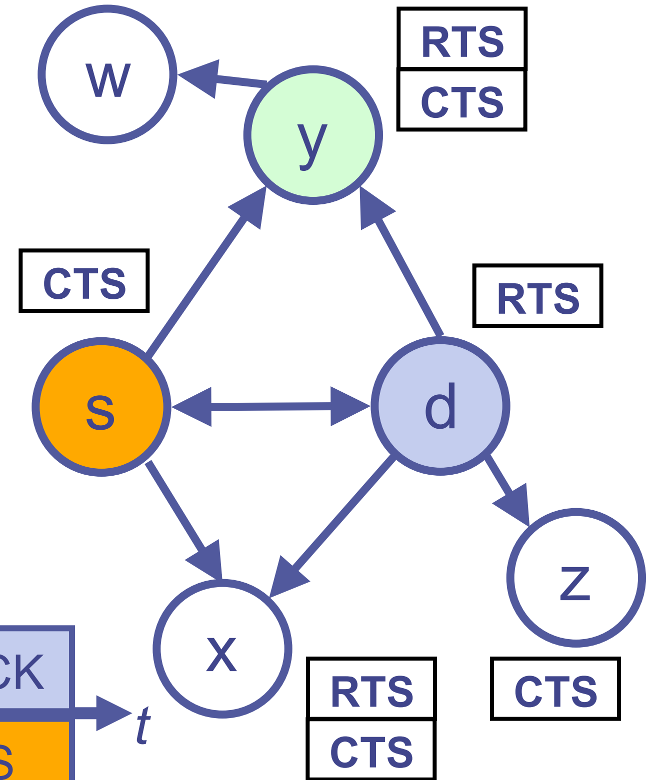
Use reserved frame types => support legacy nodes

Korakis et al., 2009 [20]

CoopMAC: A protocol for path diversity

- Reserve medium pessimistically
- If relay does not participate, only a single SIFS is wasted





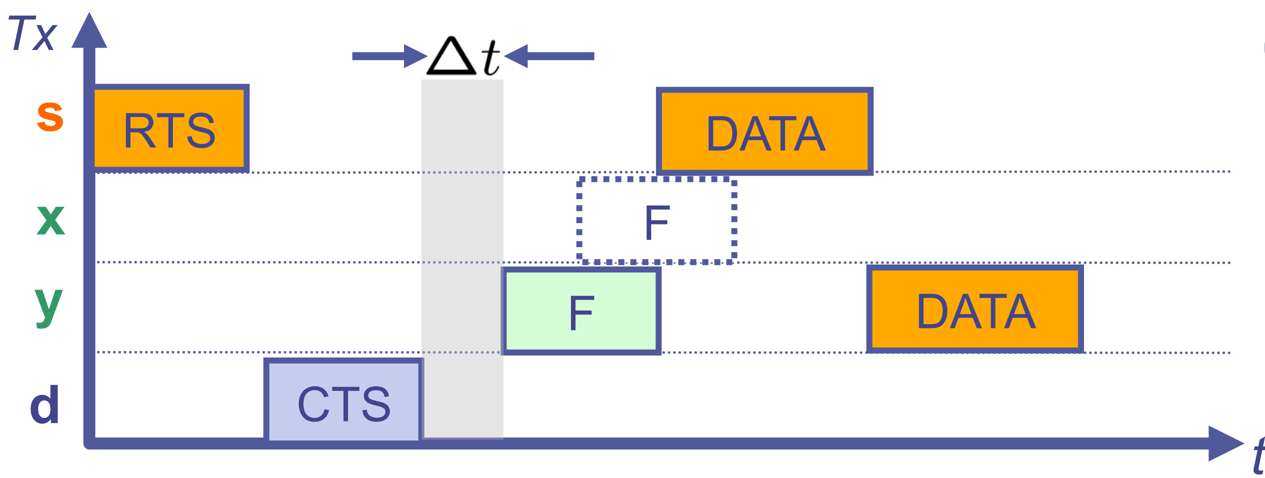
3. Further selection necessary

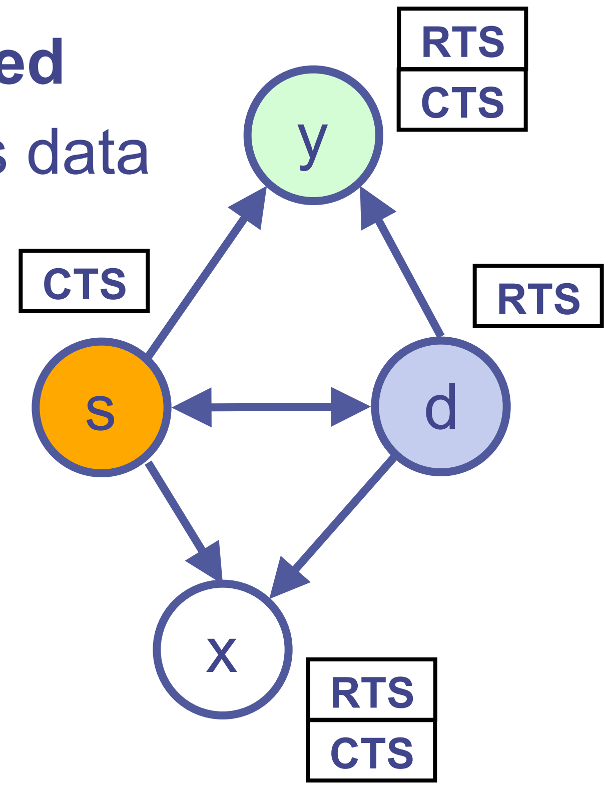
- Distinguish three approaches:
  - Source-initiated cooperation
  - **Relay-initiated cooperation**
  - Destination-initiated cooperation

- Problems?

Relay initiates: Opportunistic relaying

- Idea: Relay contention => **relay-initiated**
- **Proactive**: *Before* the source transmits data
- Contention: inversely proportional to received signal strength





- Determine start of flag (F) packet $\Delta t \sim 1/\mathrm{SNR}$
  - $\mathrm{SNR} = \min\{\mathrm{SNR}_{s,r}, \mathrm{SNR}_{r,d}\}$

Only one “best” relay retransmits; relays at least need to detect the other relays to avoid collisions

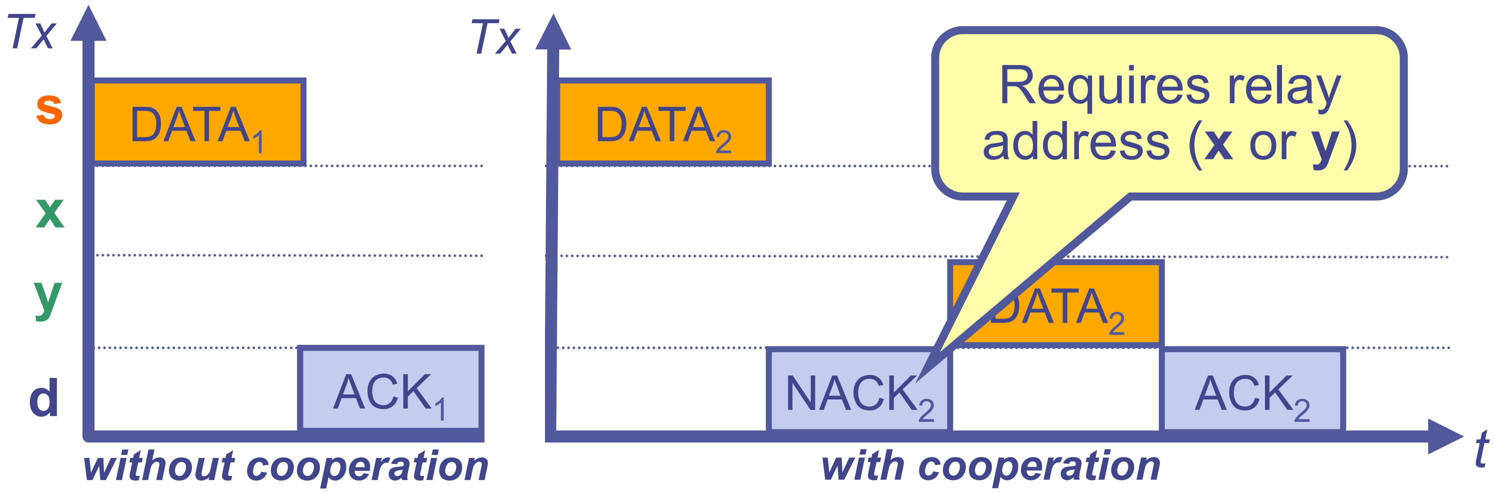
3. Further selection necessary

- Distinguish three approaches:
  - Source-initiated cooperation
  - Relay-initiated cooperation
  - **Destination-initiated cooperation**

- Problems?

Destination initiates: Distributed on-demand cooperation

- Idea: Only cooperate when needed *and* select a relay
- Feedback using ACK/NACK => **destination-initiated**



- As in source-initiated protocols: needs to learn about potential relays
- This protocol relies on feedback => needs cooperative signaling

Taxonomy: (s|r|d)-initiated cooperation protocols

<table>
<tr><th></th><th colspan="2">Advantage</th><th colspan="2">Disadvantage</th></tr>
<tr><td>s-initiated</td><td colspan="2">Address relay directly, duration of transmission known beforehand</td><td colspan="2">Two-hop neighborhood information</td></tr>
<tr><td>r-initiated
proactive</td><td rowspan="2">Channel state estimates for (s,r) and (r,d) readily available (e.g., RTS/CTS), local CSI</td><td>Only those relays listen to data that will transmit</td><td rowspan="2">Relays must coordinate themselves,
s and d cannot announce duration</td><td>All relays listen to signaling information</td></tr>
<tr><td>reactive</td><td>Better CSI estimate during data transmission</td><td>All relays listen to data, needs more energy</td></tr>
<tr><td>d-initiated</td><td colspan="2">Throughput-efficient by adaptive cooperation</td><td colspan="2">Requires reliable feedback to the relays or source: not trivial to realize efficiently</td></tr>
</table>

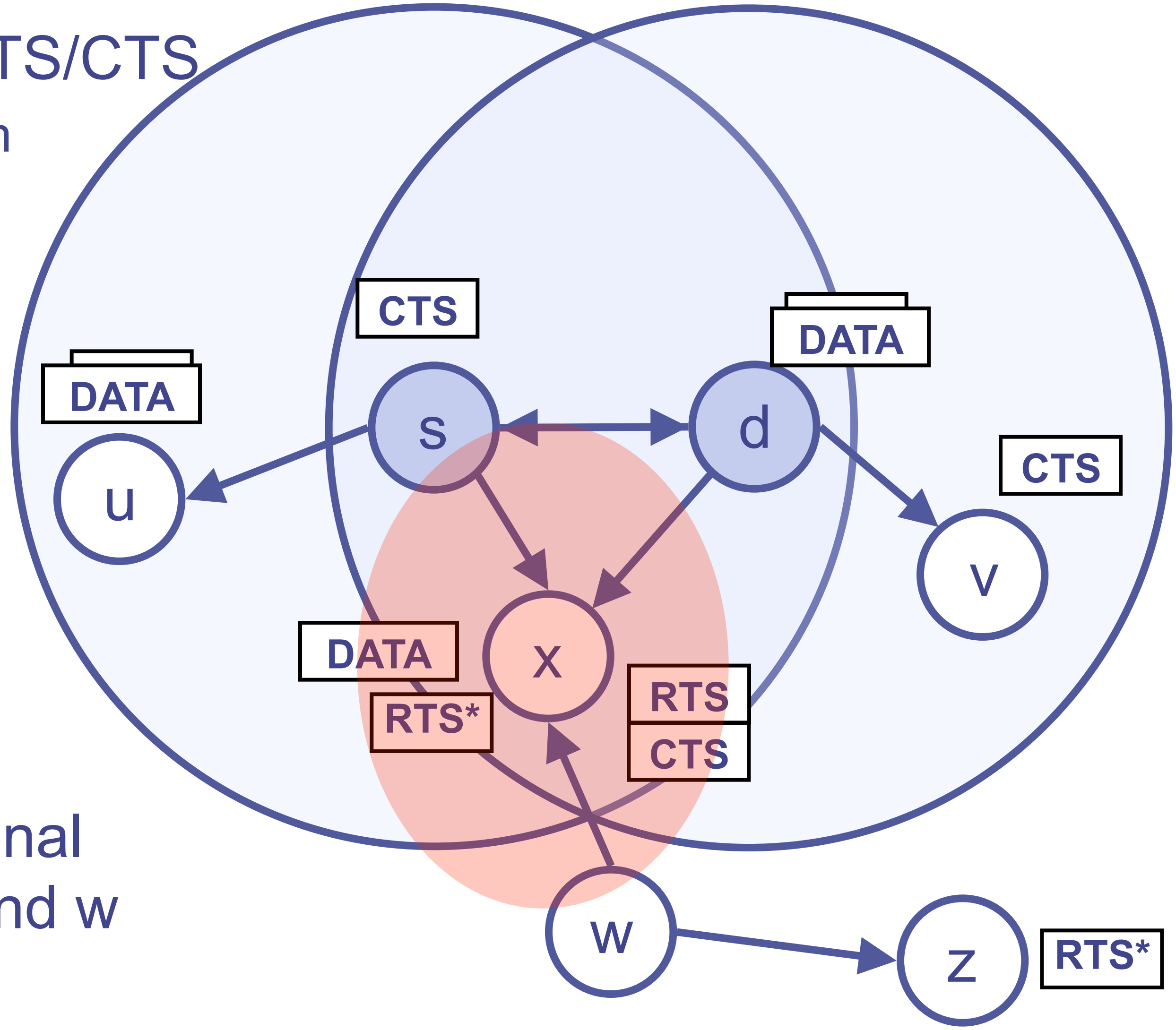
3. Further selection necessary

- Distinguish three approaches:
  - Source-initiated cooperation
  - Relay-initiated cooperation
    - Proactive
    - Reactive
  - Destination-initiated cooperation

- **Problems?**
  - **Relay blocking**
  - **Direct signaling**

Problem: Relay blocking

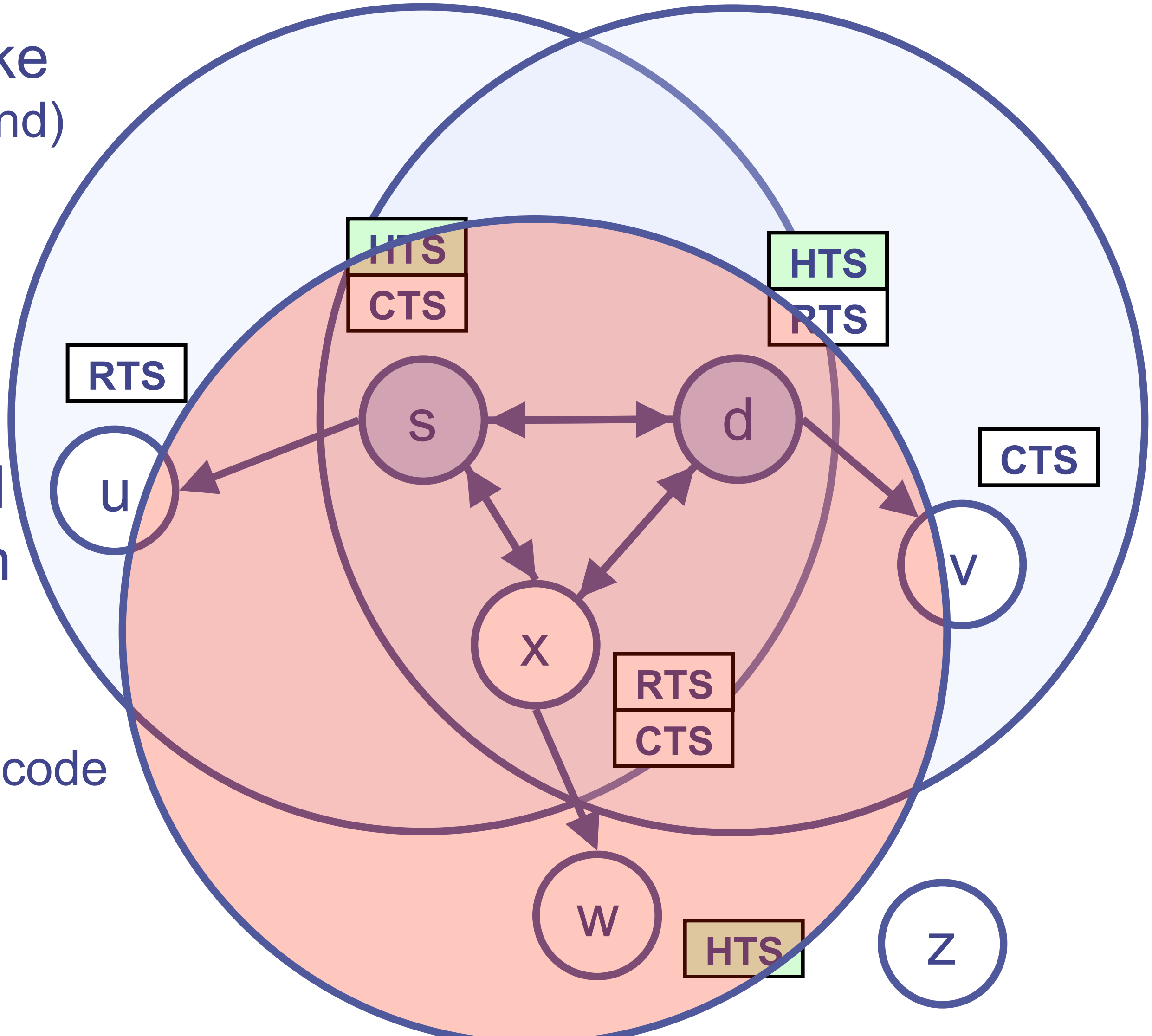
- Signaling with RTS/CTS
  - Mitigates hidden node problem
  - Relay selection
- Relay x affects spatial multi-plexing:
  - Node w must not transmit while relay x is overhearing
- Solve by: Additional guard zone around w



Islam and Hamouda, 2008 [25]

Solution: Cooperative handshake RTS/CTS/HTS

- Extend handshake (**H**elper-clear-**T**o-**S**end)
- Relay x spans a **guard zone**
  - Avoiding interference
- Size of the guard zone depends on
  - Transmission power of HTS
  - Modulation and code rate of HTS



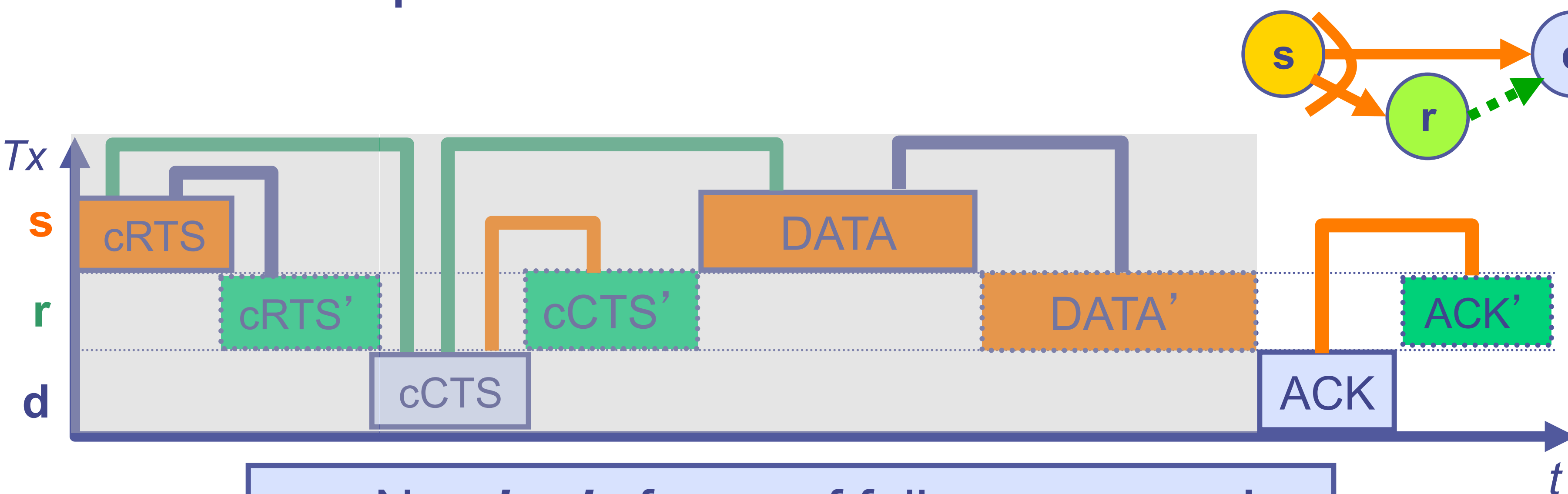
Problem: Direct signaling

- Common assumption: Robust signaling channel
  - Use high modulations/code rates for DATA
  - Use low modulations/code rates for RTS/CTS/HTS/ACK
- Contradiction [19-23,25]:
  - With shadowing or fading, decreasing transmit rate is not enough
  - If cooperation diversity is required for DATA, it is also required for control channels
- Approach: Cooperative signaling [26]
  - Use cooperation diversity even for signaling: Subsequent signaling frames “rescue each other”
    - Provides equal diversity order for DATA and control channels
  - Exploit redundant fields within different frames
    - Adds only 4% overhead to other cooperative MAC protocols [34]

Solution: Apply Cooperation to IEEE 802.11 Signaling

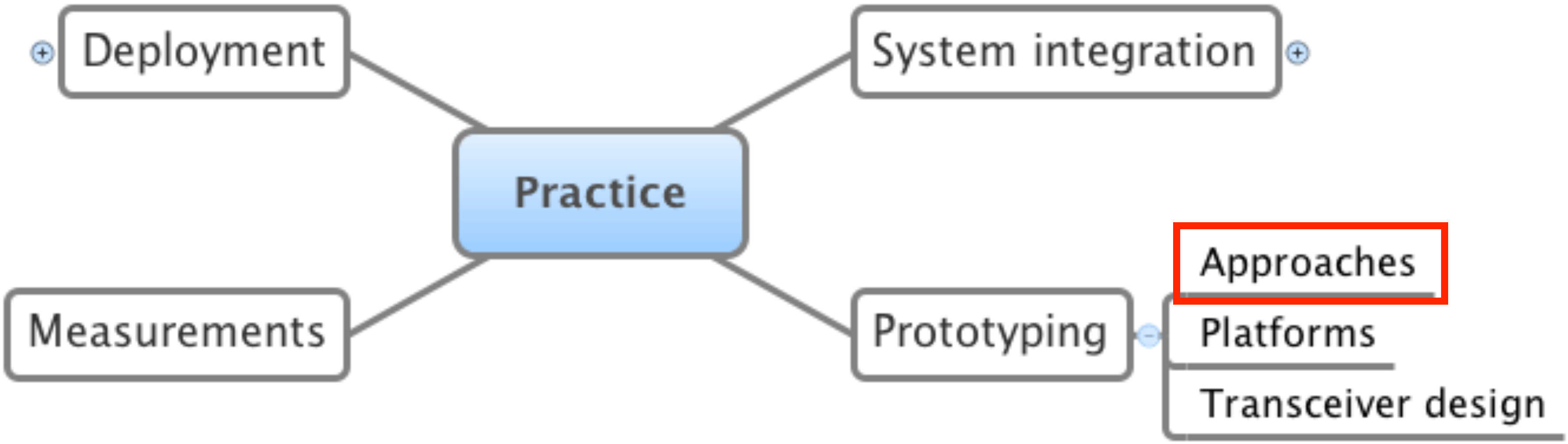
- Cooperative signaling: Protocol operation
  - At *s* and *d*: Combine, At *r*: Subsequent packets ***rescue each other***

1. **Init coop. *s−>r,d*:** *d* combines 2 cRTS; *r* receives cRTS ***or*** cCTS
2. **Confirm coop. *d−>s,r; r−>s*:** *s* combines 2 cCTS; *r* receives cCTS ***or*** DATA
3. **Cooperative DATA transfer *s−>d*:** *d* combines 2 DATA
4. **ACK cooperative transfer *d−>s*:** *s* combines 2 ACK



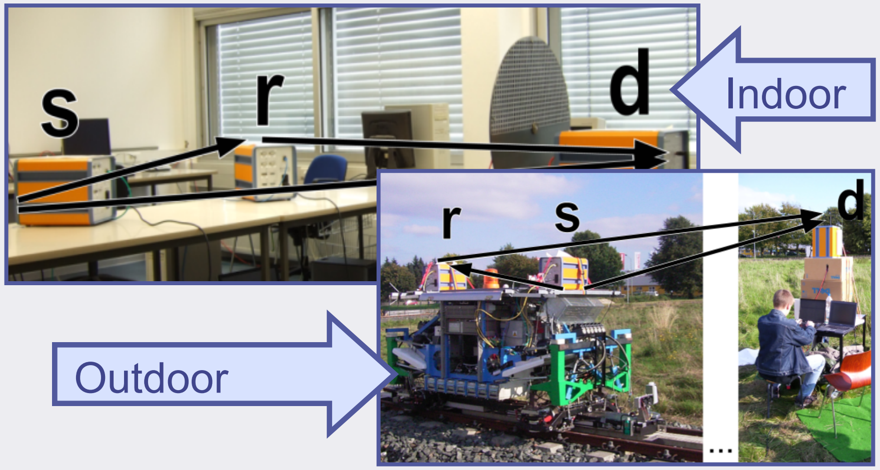
No ***single*** frame of failure anymore!

Practice: System Integration, Prototypes, and Measurements

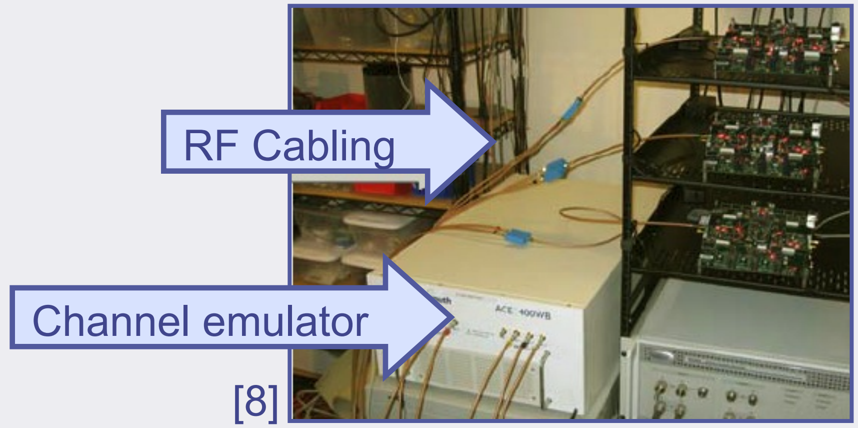


Prototyping Approaches

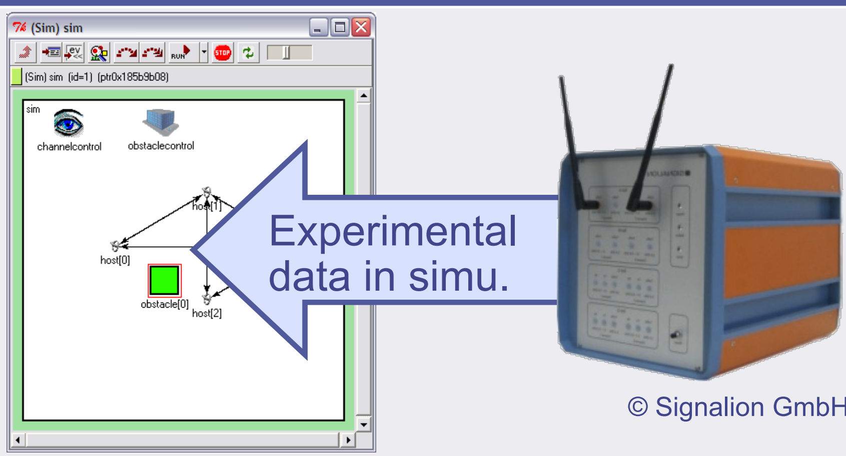
Field measurements



Emulation



Hybrid



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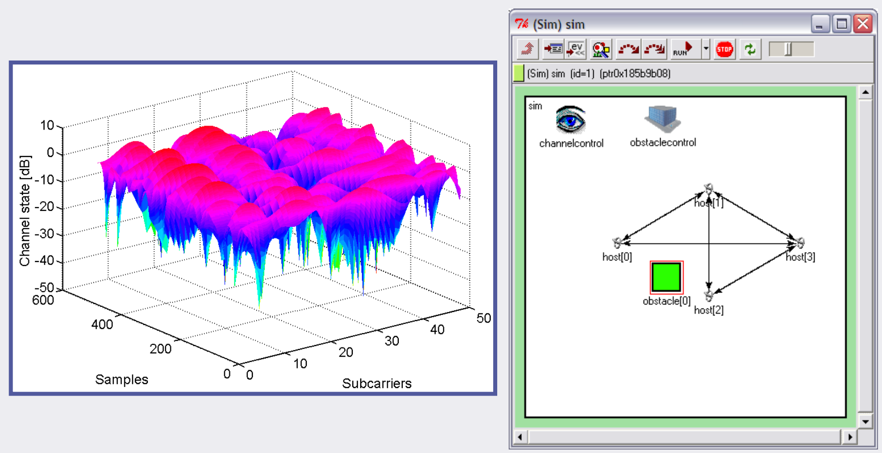
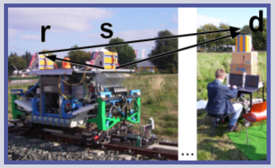
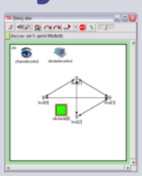
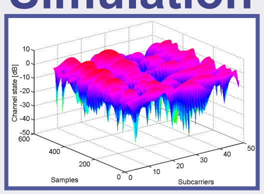
Simulation



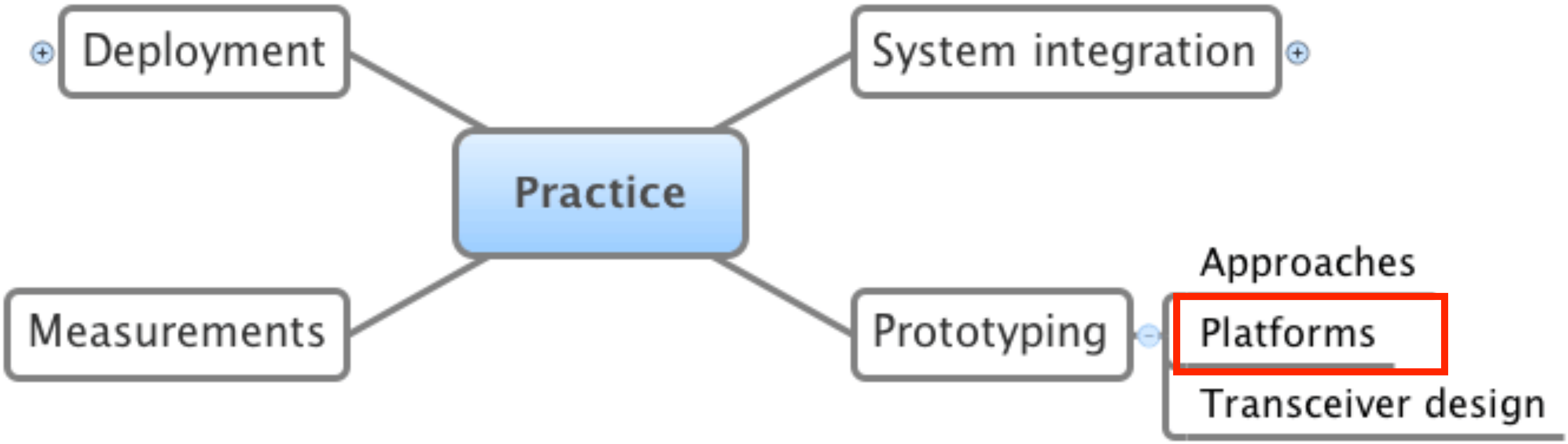
Comparing Prototyping Approaches

Approach	Advantages	Disadvantages
Field 	The real thing	Involved, time-consuming, costly, can be hard to repeat (for others and even for oneself)
Emulation  © Azimuth	Use of the real hardware and implementation in a reproducible environment (e.g., hardware-in-the-loop)	Impractical for many nodes
Hybrid  	Replaces part of the model by reality, yet quick modifications of implementation possible	Restricted to previously measured sample space
Simulation 	Easy to replicate, large networks, large parameter studies possible (e.g., factorial design)	Results strongly depend on the quality of the model, mismatch between reality and model might lead to wrong conclusions

Realism, complexity, cost

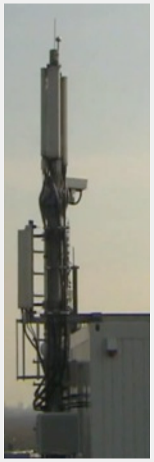
Debugging, setup

Practice: System Integration, Prototypes, and Measurements



Prototyping Platforms

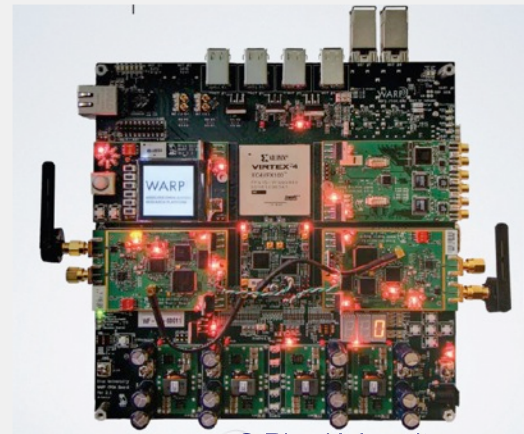
LTE-Advanced Testbed



© Heinrich Hertz Institute

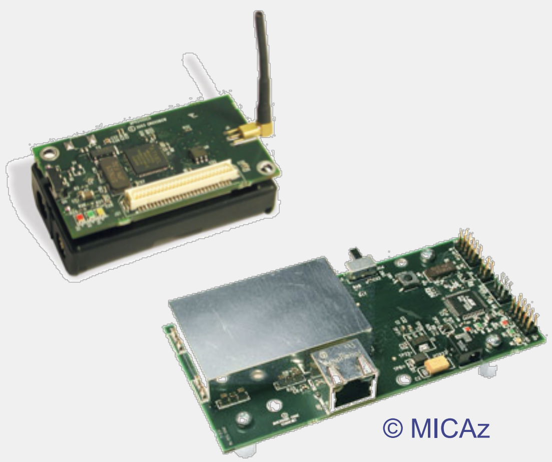
Software-defined radios (e.g., SORBAS, WARP)

© Signalion GmbH

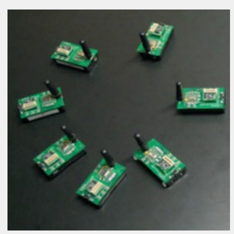


© Rice University

Sensor nodes (e.g., Poor Man's SIMO, Pushpin)



© MICAz



[22]

© tMote Sky

Off-the-shelf WLAN

Comparing Prototyping Platforms

Platform	Possibilities	Development environment
	Whatever you need, if you can afford it (in terms of human resources and money)	Custom solutions, anything is possible
	Modify 802.11 PHY, time-critical parts in hardware (e.g., Viterbi), (de)modulation in software ➔ flexible combining	Pipelined architecture comprising several DSPs and FPGAs; VHDL, C/C++, additionally SDL
	Fixed 802.15.4 PHY, limited processing power, implement own (de)coding on external machine	TinyOS, nesC, external processing on workstation using e.g., MATLAB
	Fixed 802.11 PHY with fixed coding scheme, MAC protocol implemented as Linux driver	Linux kernel, C/C++, Firmware (closed-source vs. reverse-engineered open-source)

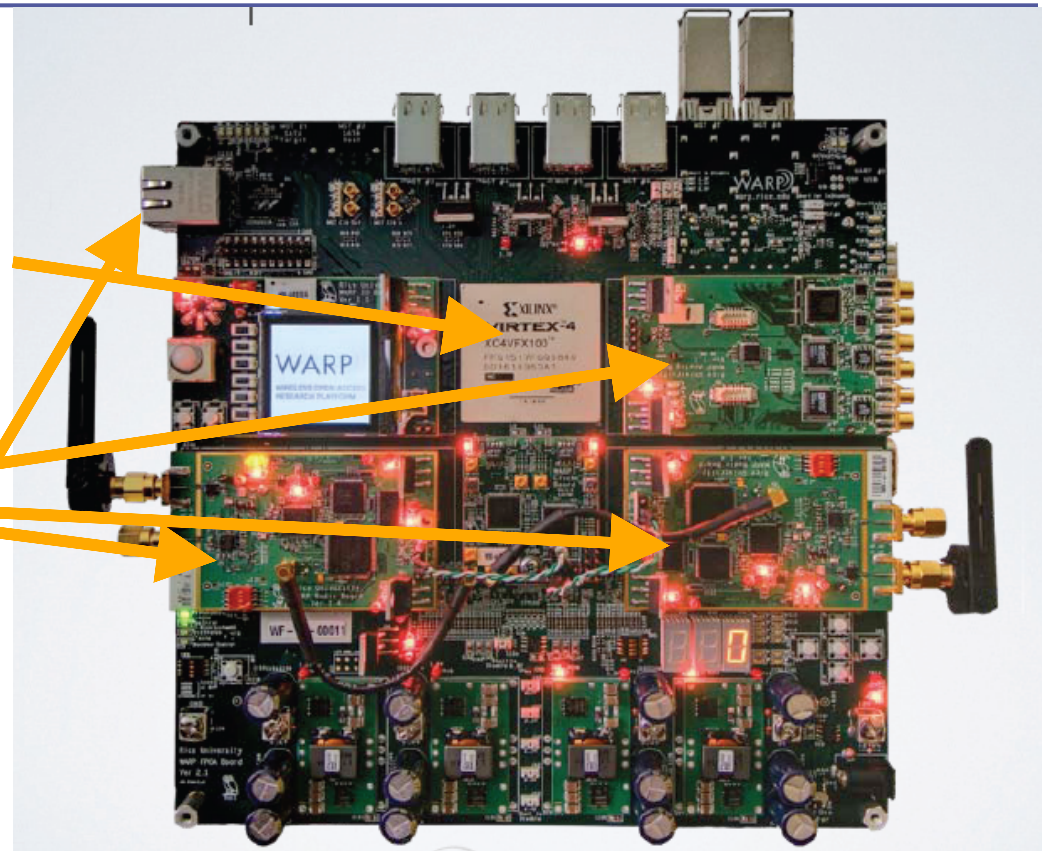
SORBAS WLAN Prototyping System

- SDR with IEEE 802.11a implementation
  - Dual-band: 2.4 GHz and 5 GHz
  - Physical layer and MAC completely programmable
  - Hybrid design, pipelined architecture
  - JTAG, Ethernet, USB, RS-232 interfaces
  - Linux driver for integration as an ordinary wireless network device
  - Development tools: Xilinx ISE, Analog Devices VisualDSP++, and Telelogic SDL Suite

Dual-band RF transceiver	↔	Virtex II FPGA	↔	TigerSHARC DSP	↔	TigerSHARC DSP	↔	Virtex II FPGA	↔	BlackFin DSP
Radio frontend		Physical layer (slave)				Physical layer (master)				MAC
Analog		Digital, fully programmable (VHDL, C, Assembler, SDL)								

WARP FPGA Board and Radios

- Cooperative OFDM transceiver
- Xilinx Virtex-II Pro FPGA
  - 2 PowerPC 405 cores
  - Real-time functions
- Up to 4 radios
  - Maxim MAX2829 wideband chipset
  - 2.4 GHz and 5 GHz
- 10/100 Ethernet
  - Traffic source/sink
  - Download statistics



Large cost Single SISO unit: USD $9500.00

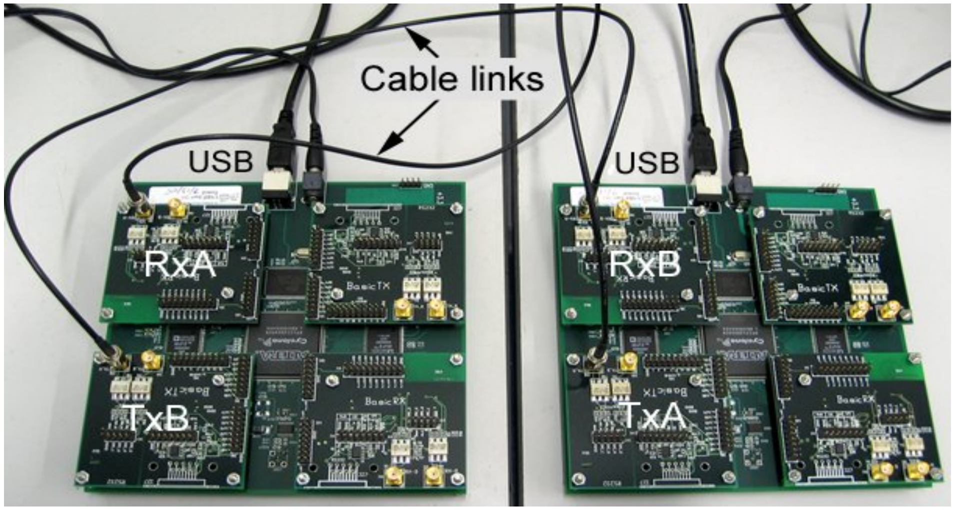
Single MIMO unit: USD $11500.00

- Open source: http://warp.rice.edu/trac/wiki

Hunter, Murphy, and Sabharwal, 2010 [24]

GNU Radio and USRP

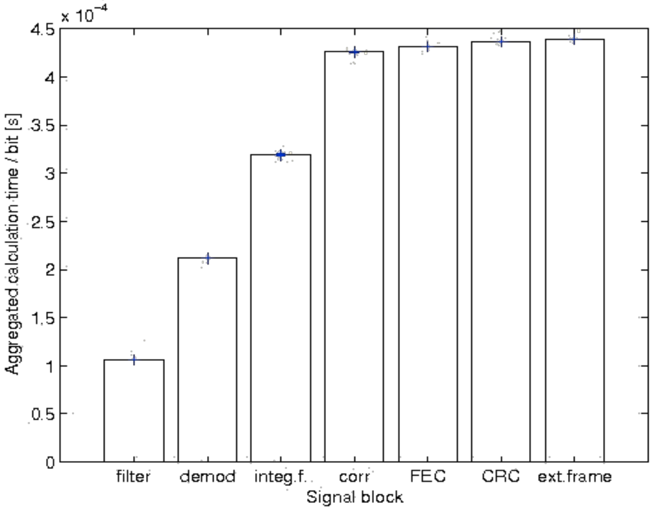
- GNU Radio: Open source software radio
  - Runs on PC, easy to learn
  - Hardware support by USRP
  - Multiple transceiver frontends



- Measured: Latency of .11-like transceiver chain

- Main result [30]:
  - Average delay: 3.14 ms/bit
  - Time is mostly spent for GNU Radio signal graphs
  - Maximum data rate 636 bit/s

  => GNU Radio is too slow for real time measurements

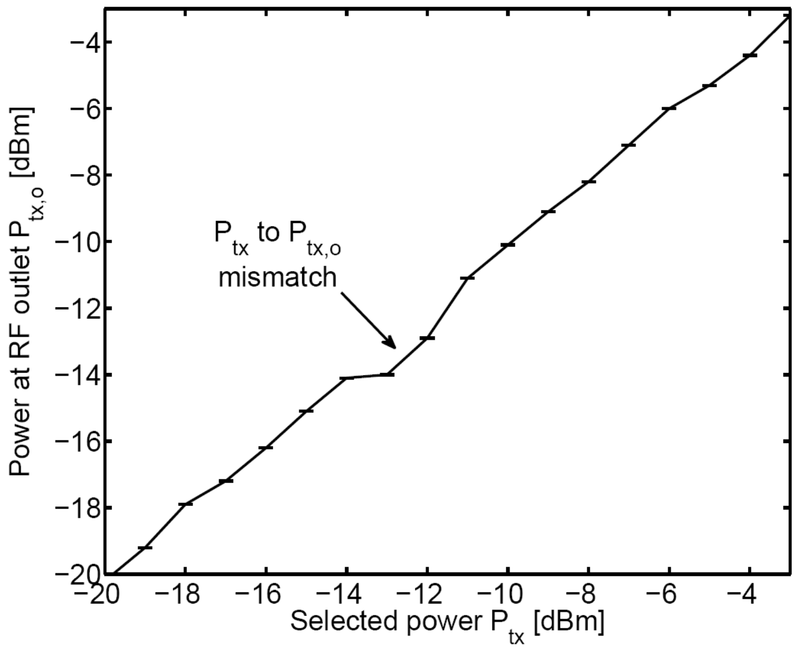


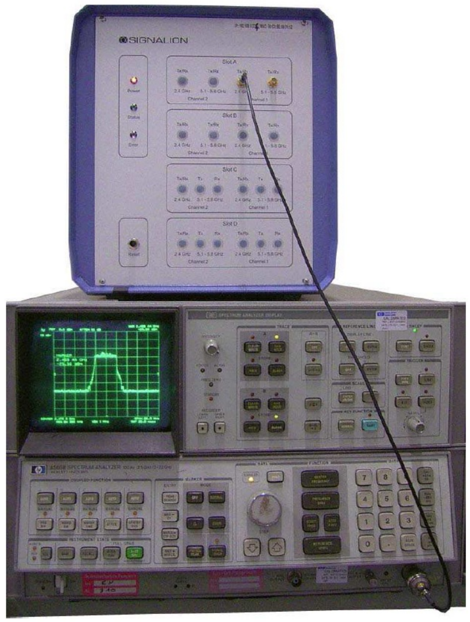
Open-Source Drivers

- Open-source drivers available, e.g.:
  - MadWifi/ath5k/ath9k (Atheros .11a/g)
  - ar9170/carl9170 (Atheros USB .11a/g)
  - OpenFWWF + b43 (Broadcom/AirForce .11b/g)
  - HostAP (Prism .11b)
- Physical layer inaccessible
  - Possibilities
    - Promiscuous mode: access to any received packet
    - Disable CRC: access to corrupt packets after decoding
    - Prioritization of transmissions by modifying contention windows
  - Constraints
    - No hard real-time: e.g. FlexMAC ≈ 70 μs vs. 802.11 SIFS = 10 μs
    - Fixed (de)coding and (de)modulation) e.g., no PHY combining
    - ACKs cannot be separately deactivated

Prototyping Wireless systems – Three Simple Rules

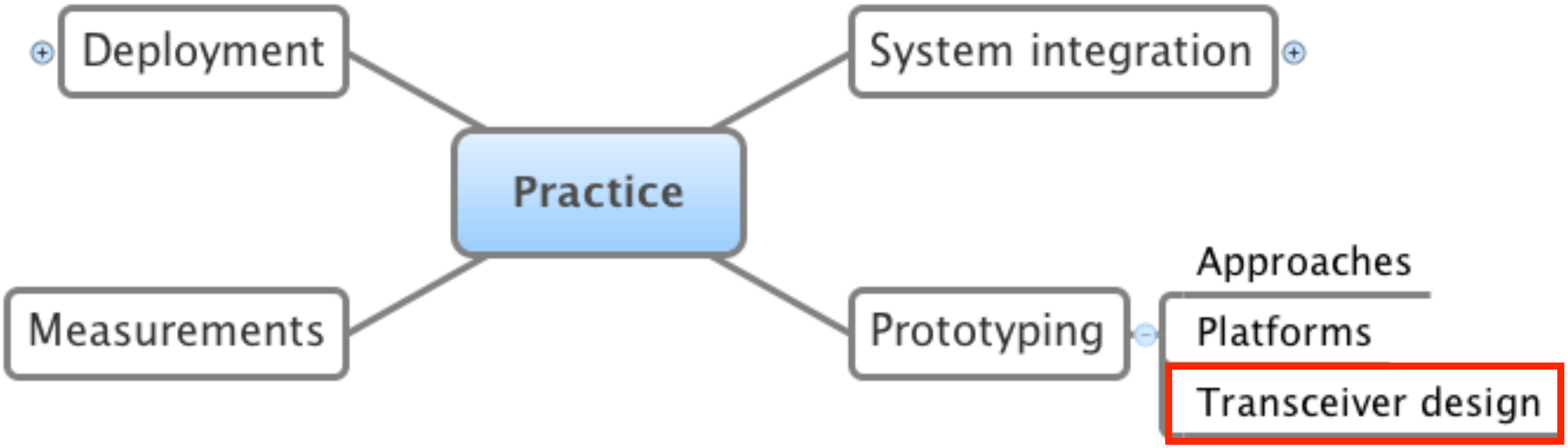
- Whichever platform you choose: Watch out!





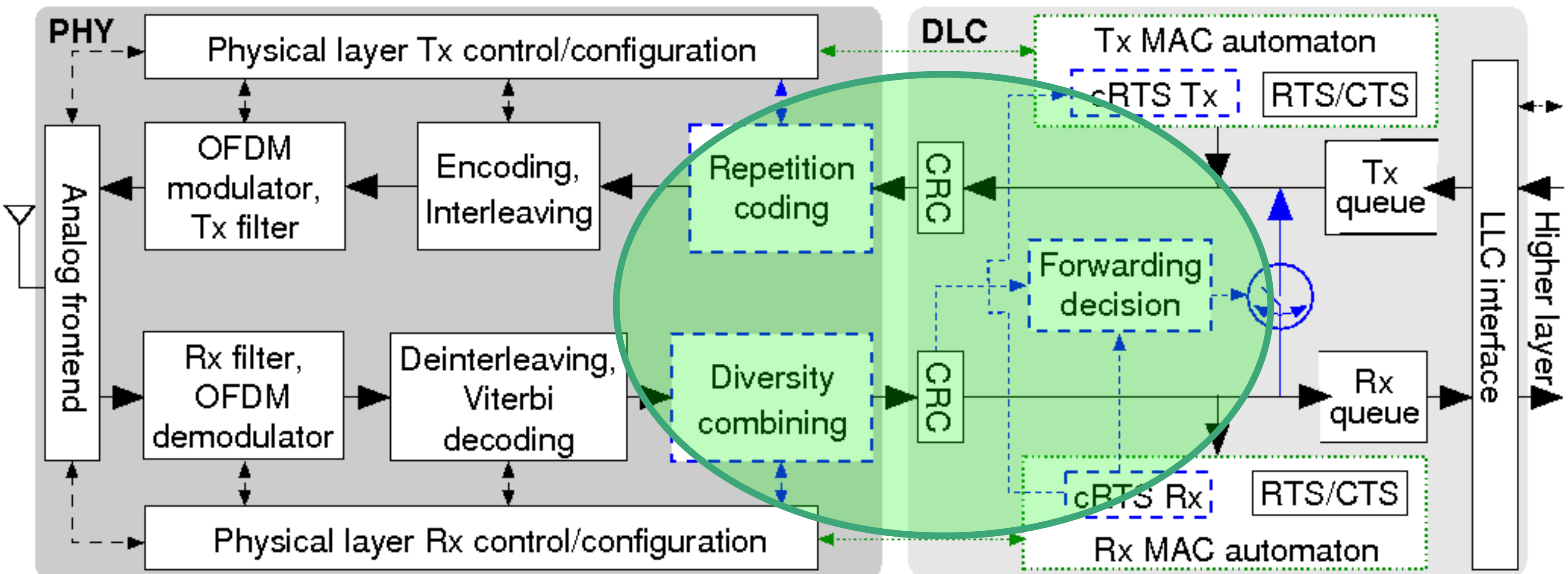
- Understand:
  1. Physical parameters of your device: Time, power, frequency
  2. How adding functions changes its operation and performance
  3. How environment (interfaces, driver, compiler, lab,...) affects your measurements

Practice: System Integration, Prototypes, and Measurements



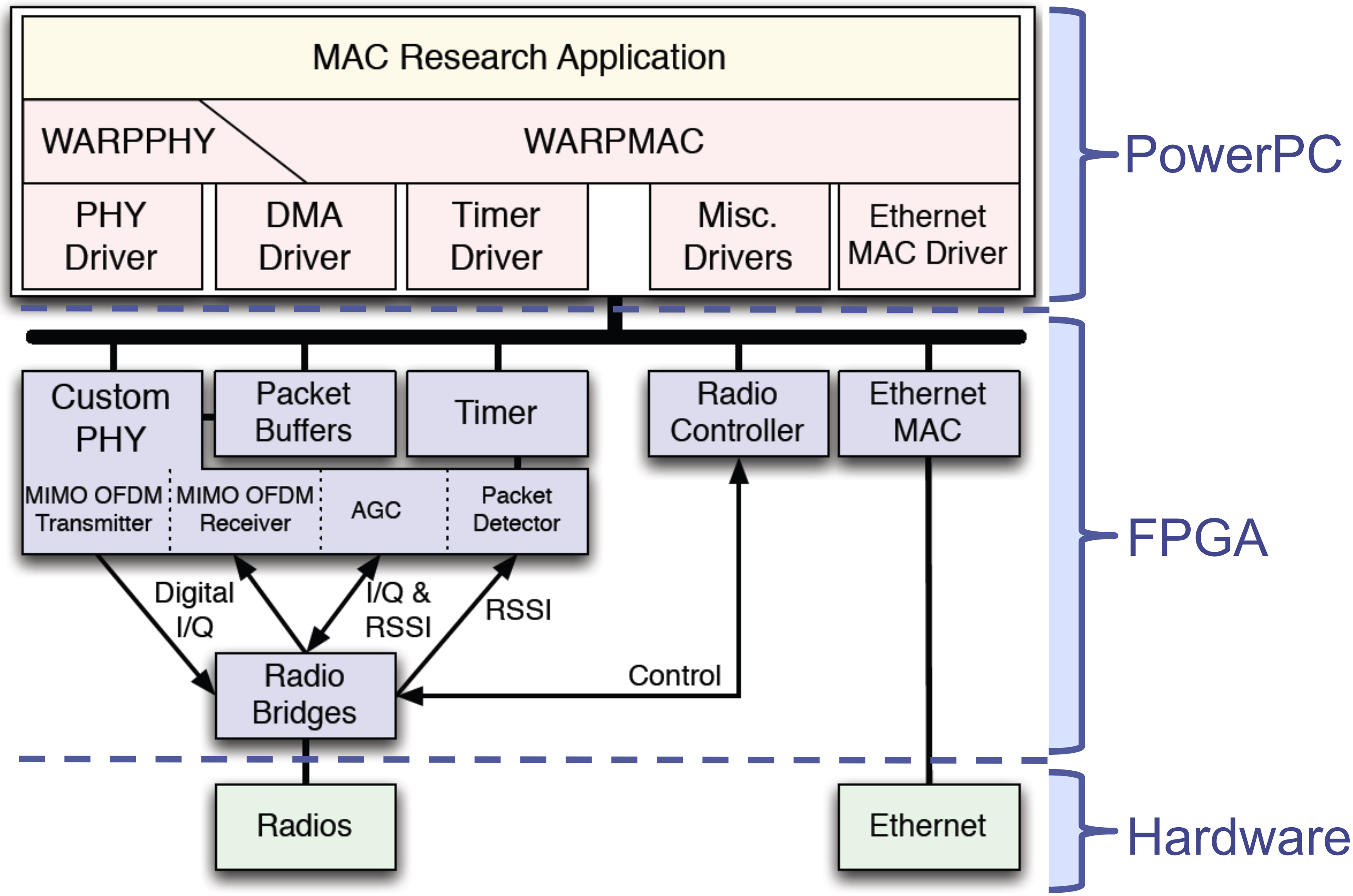
Transceiver Design for Cooperative WLANs

- DLC: Cooperative MAC, fallback mode to direct (legacy)
  - CRC-based forwarding decision, Tx queue bypass
- 802.11a/g PHY: Repetition codes, MRC or packet selection
  - Indoor measurements: Both combining schemes perform equally => Just select the first correct packet



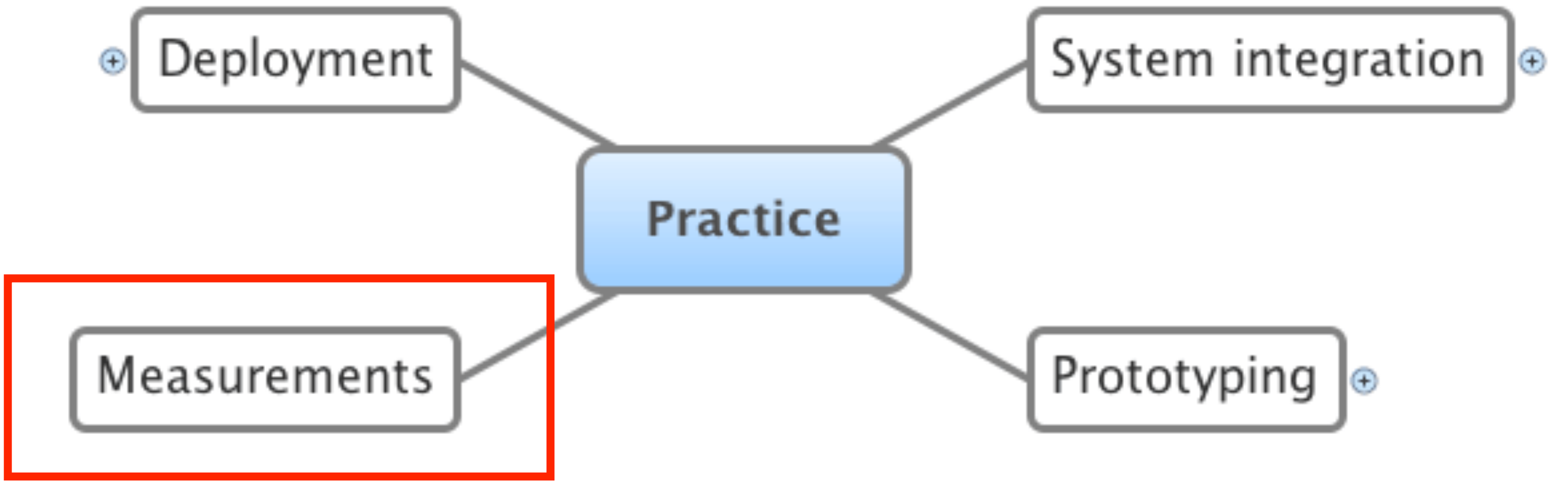
Valentin, Lichte, et al., 2008 [26]

WARP Node Block Diagram

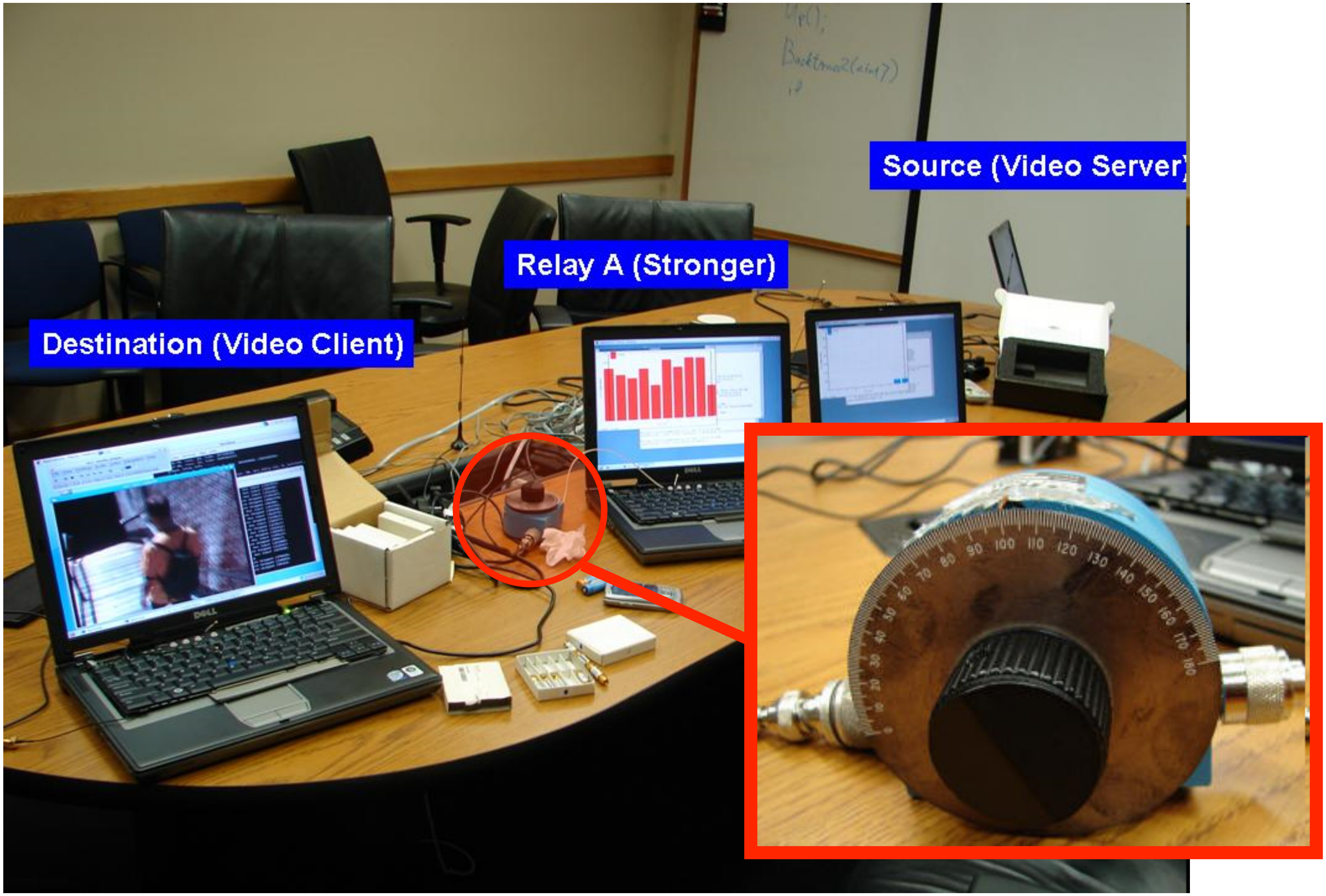


Hunter, Murphy, and Sabharwal, 2010 [24]

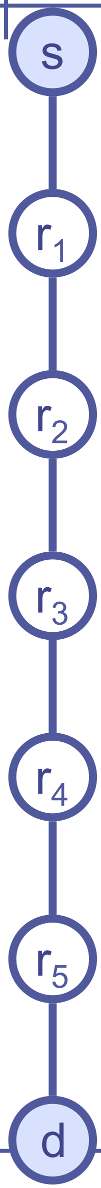
Practice: System Integration, Prototypes, and Measurements

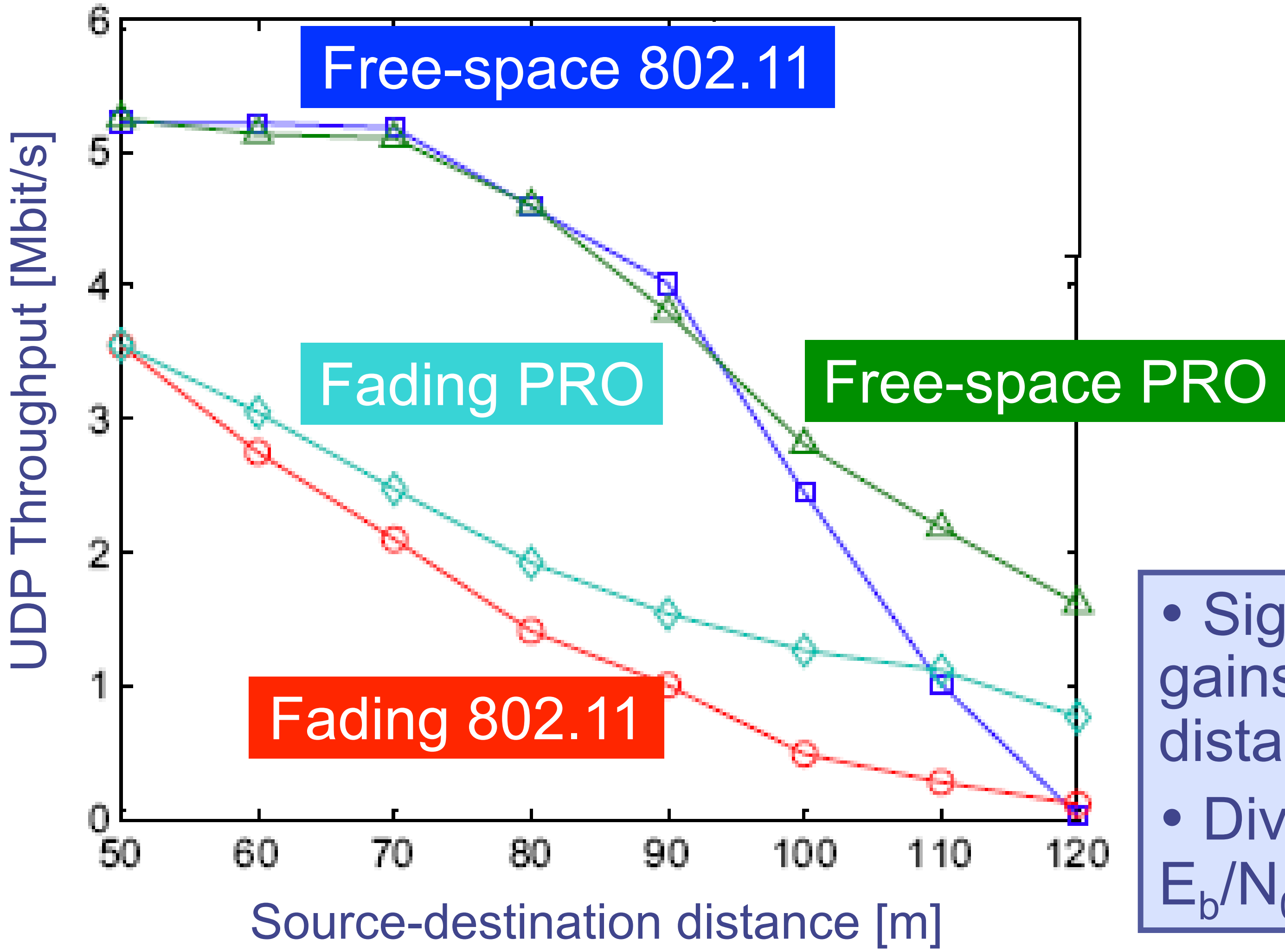


Opportunistic Relaying Using FlexMAC



Results in Equidistant Chain Scenario





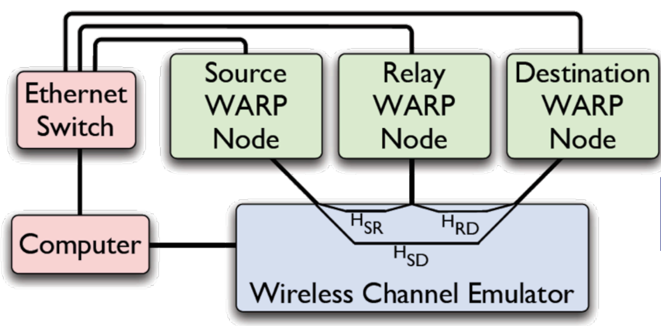
- Significant gains at high distance
- Diversity or E_b/N_0 gains?

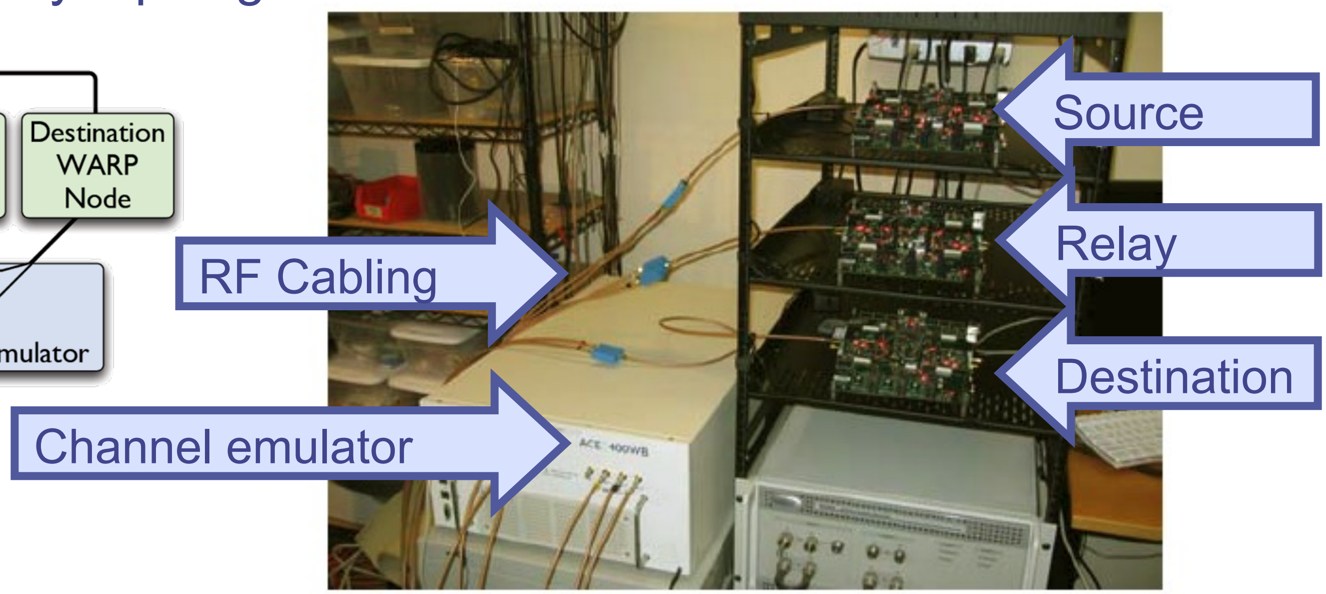
Lu, Steenkiste, and Sten, 2009 [27]

WARP-Based Measurements

- Wireless channel emulator
  - Reproducible propagation environment
  - Example: TGn model B [802.11n standard]
    - Delay spread 80 ns, Doppler spread 2.6 Hz
    - Very slow channel: T_{coh}=87ms @ 2.4 GHz
  - Arbitrary average SNRs between nodes
    => test arbitrary topologies

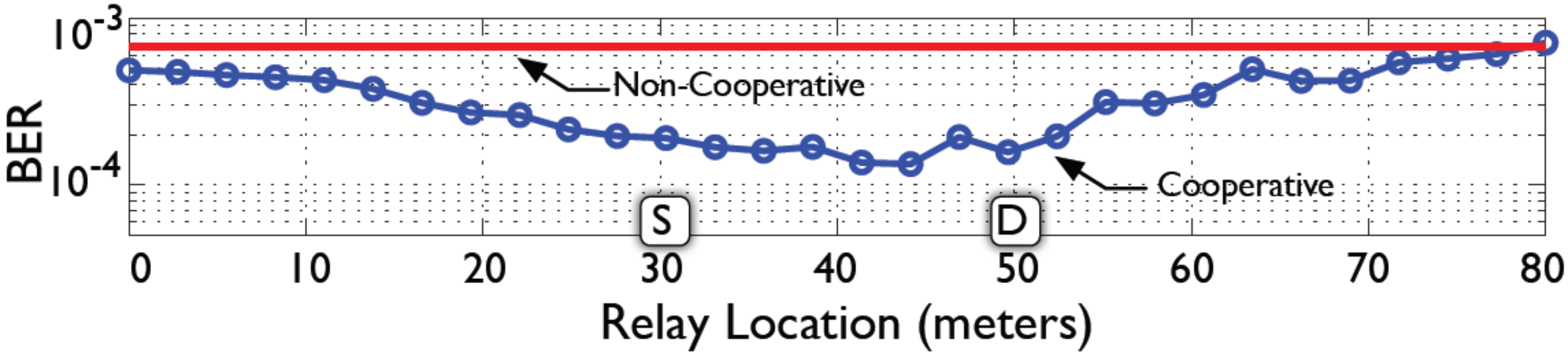
© Azimuth



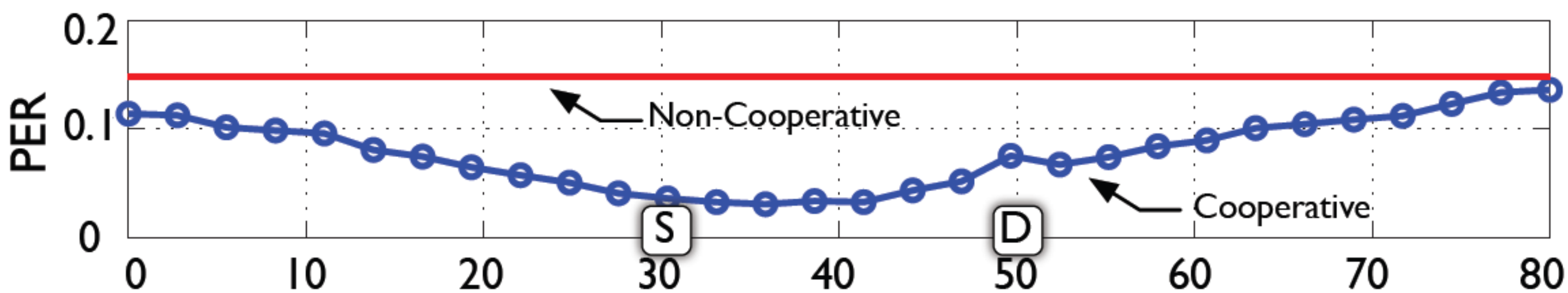


Bit and Packet Error Rates vs. Relay Location

- Bit error rate (BER) vs. relay location



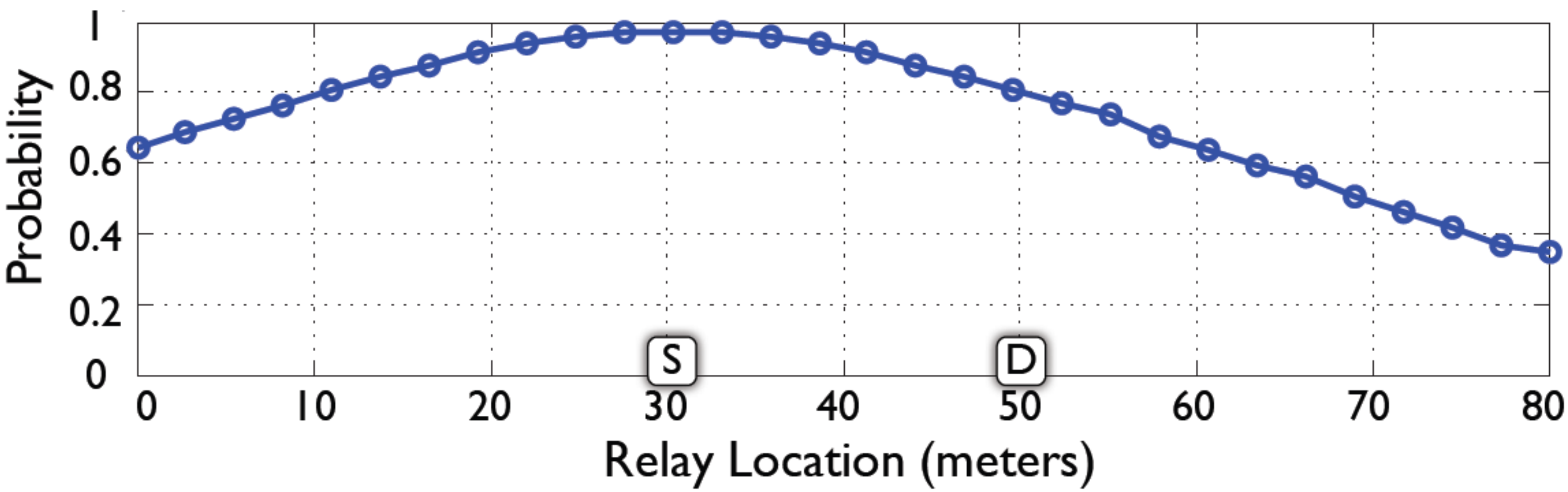
- Packet error rate (PER) vs. relay location



Relay location that minimizes error rate:
Within first half of S-D distance

Probability of Relay Cooperation

- Probability of cooperation vs. relay position



Probability of relay cooperation increases when relay closer to source

SORBAS-Based Prototype for Cooperative WLANs

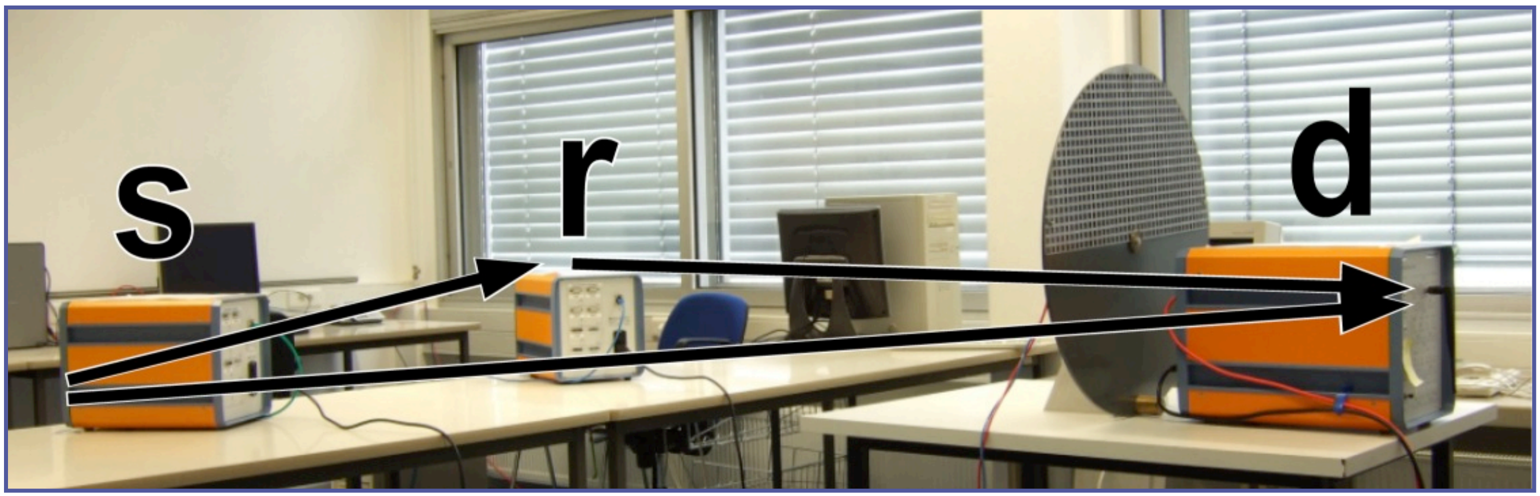
- Platform
  - SORBAS software defined radio:
    Fully programmable IEEE 802.11a/g
    MAC and PHY

- Implemented
  - MAC: CSR with cooperative signaling
  - PHY: Combining schemes (MRC, SC, ...)
- First prototype that
  - Integrates cooperative relaying into IEEE 802.11a/g MAC ***and*** PHY
  - Cooperates at ***full*** IEEE 802.11a/g rate
  - Measurement results in [26] reproduce cooperation ***diversity gains*** known from theory

Field Measurements: Indoor Scenario

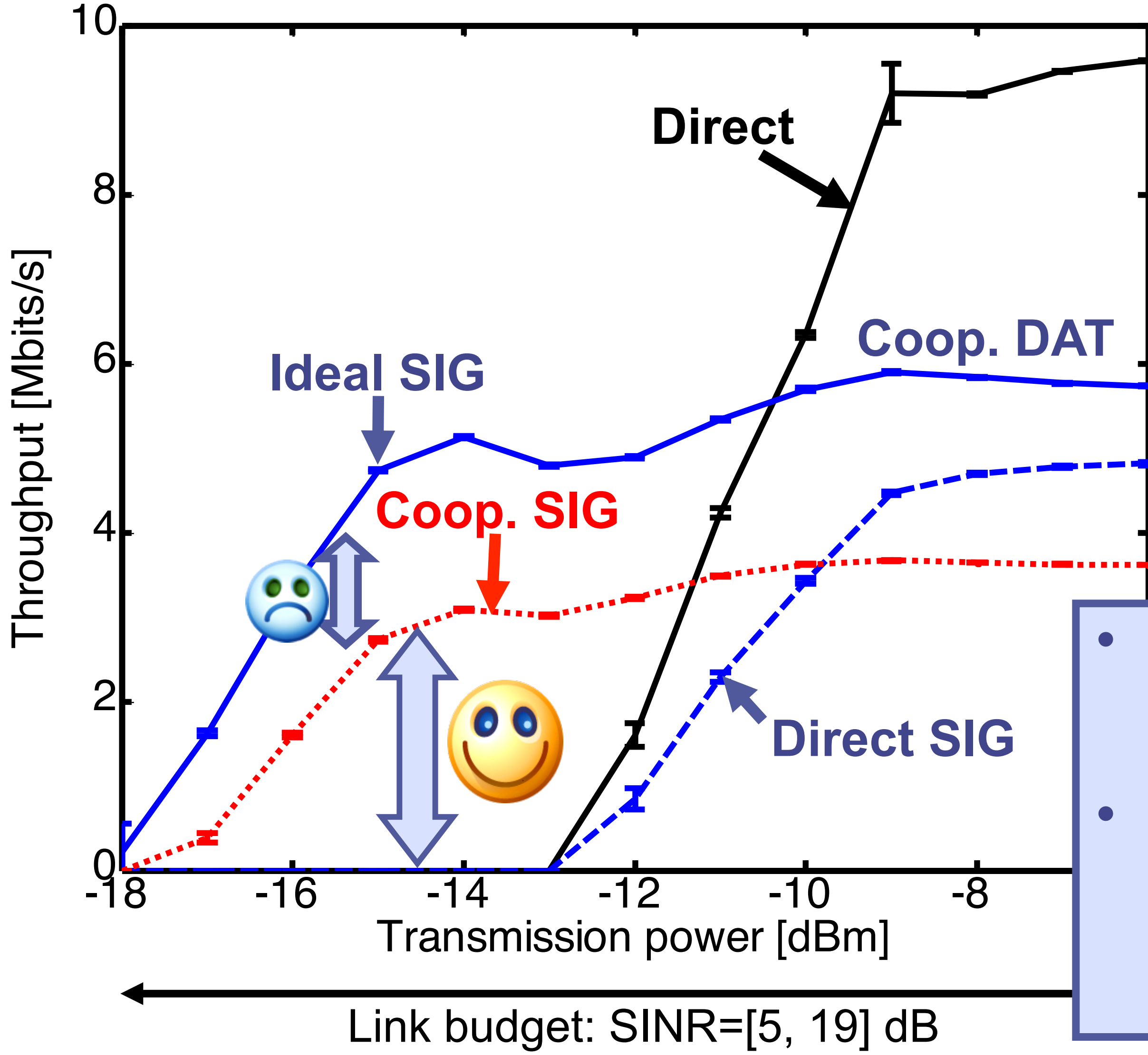
- Intention: Office situation with slow mobility
  - Environment: Computer lab with rotating disc (v=1 m/s), NLOS, constant distances
  - Fixed PHY rates: Data 18 Mbit/s, control packets 6 Mbit/s (robust)
  - Traffic: 1024 Byte UDP packets, constant bit rate (saturated)

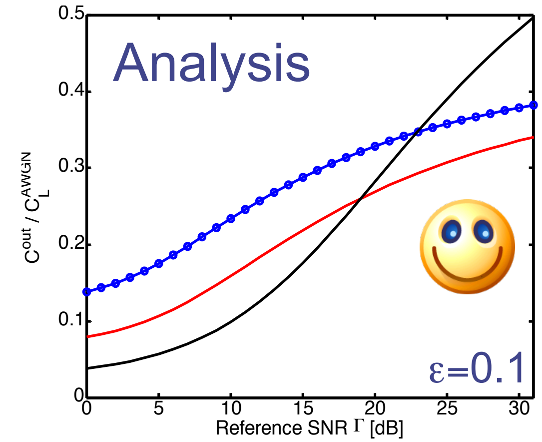
  - Measured: PER and **throughput** at UDP layer



Valentin, Lichte, et al., 2008 [26]

Results: Indoor Scenario – UDP Throughput

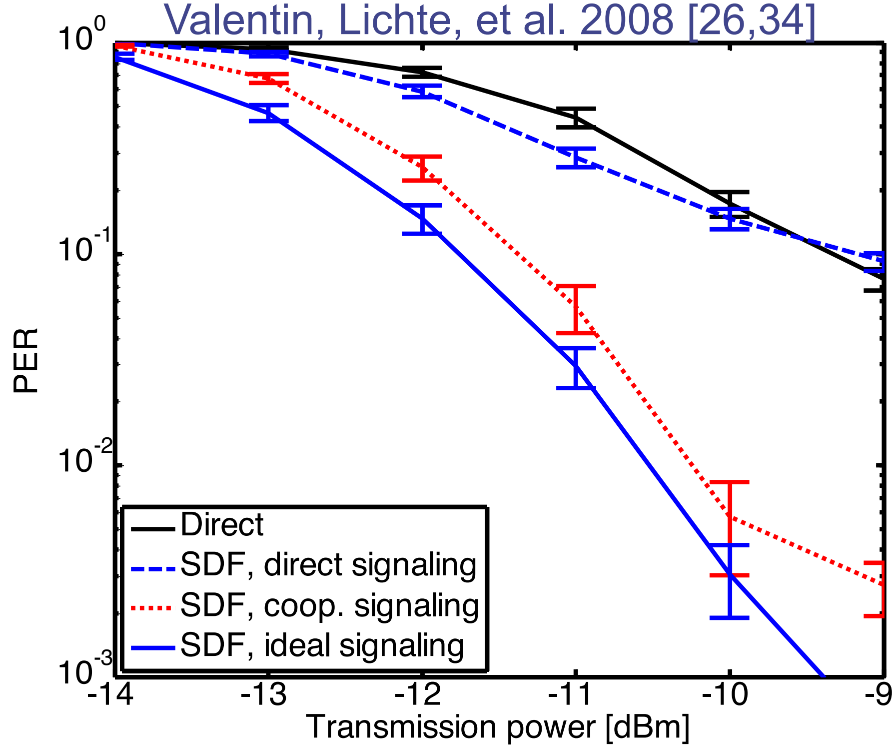




- Cooperation vs. Direct: Throughput gain in low power regime
- ***Only* with cooperative signaling**
  - But: Significant costs

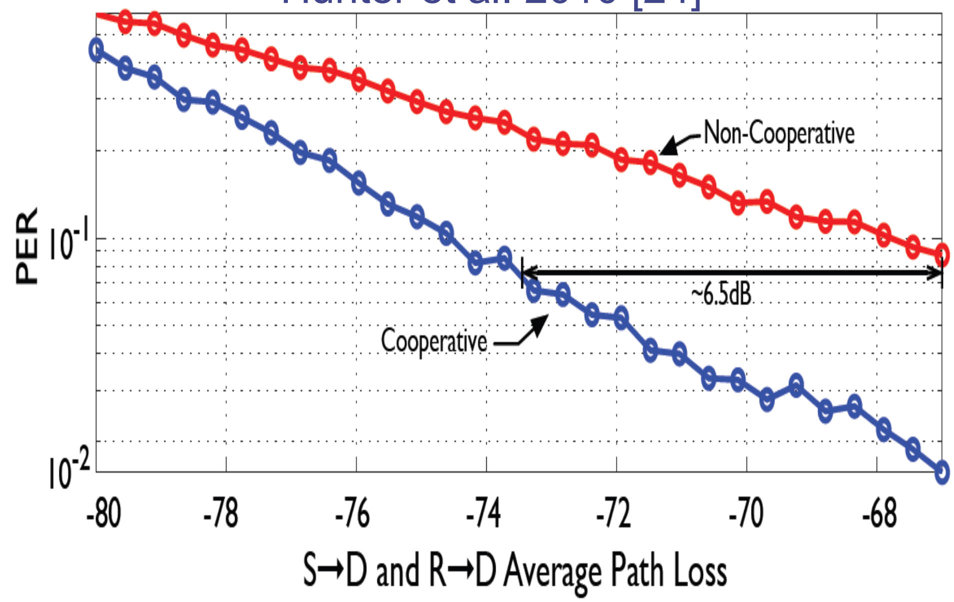
Results: Indoor Scenario – UDP PER

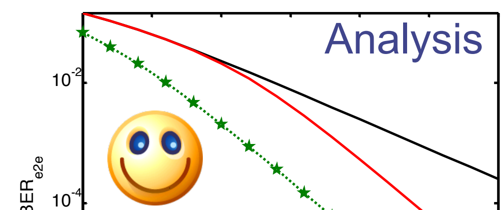
Valentin, Lichte, et al. 2008 [26,34]



Link budget: SINR=[9, 22] dB

Hunter et al. 2010 [24]



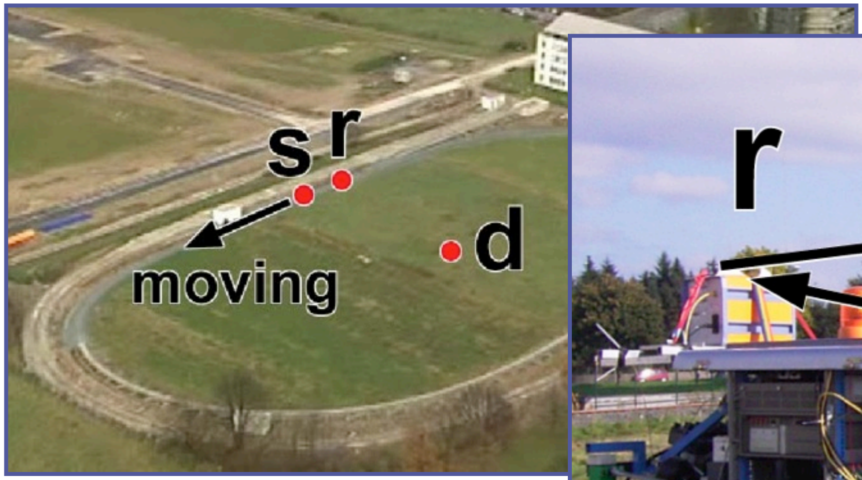


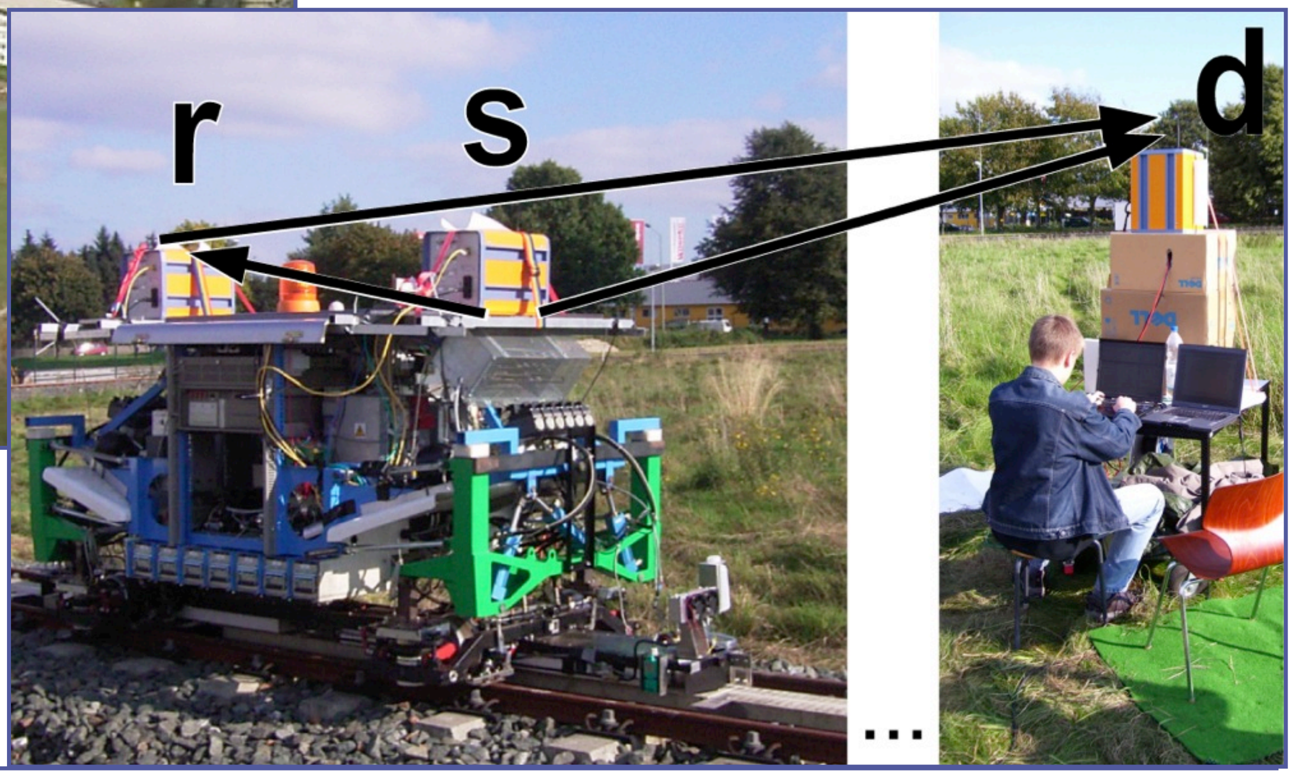
- Clearly shows diversity gain: In line with theory and later experiments [24]
- Only with cooperative signaling: In line with theory [28]

Mean SNR Γ [dB]

Field Measurements: Vehicular Scenario

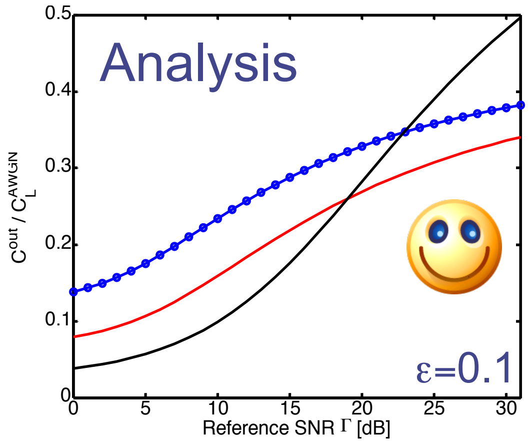
- Intention: 2 users cooperate in a train with medium mobility
  - Environment: RailCab test track (v=5 m/s), LOS, outdoor
  - Between neighbors in train (*s,r*): Small, constant distance (1.6 m)
  - To basestation (*d*): Distance from 44 to 90 m

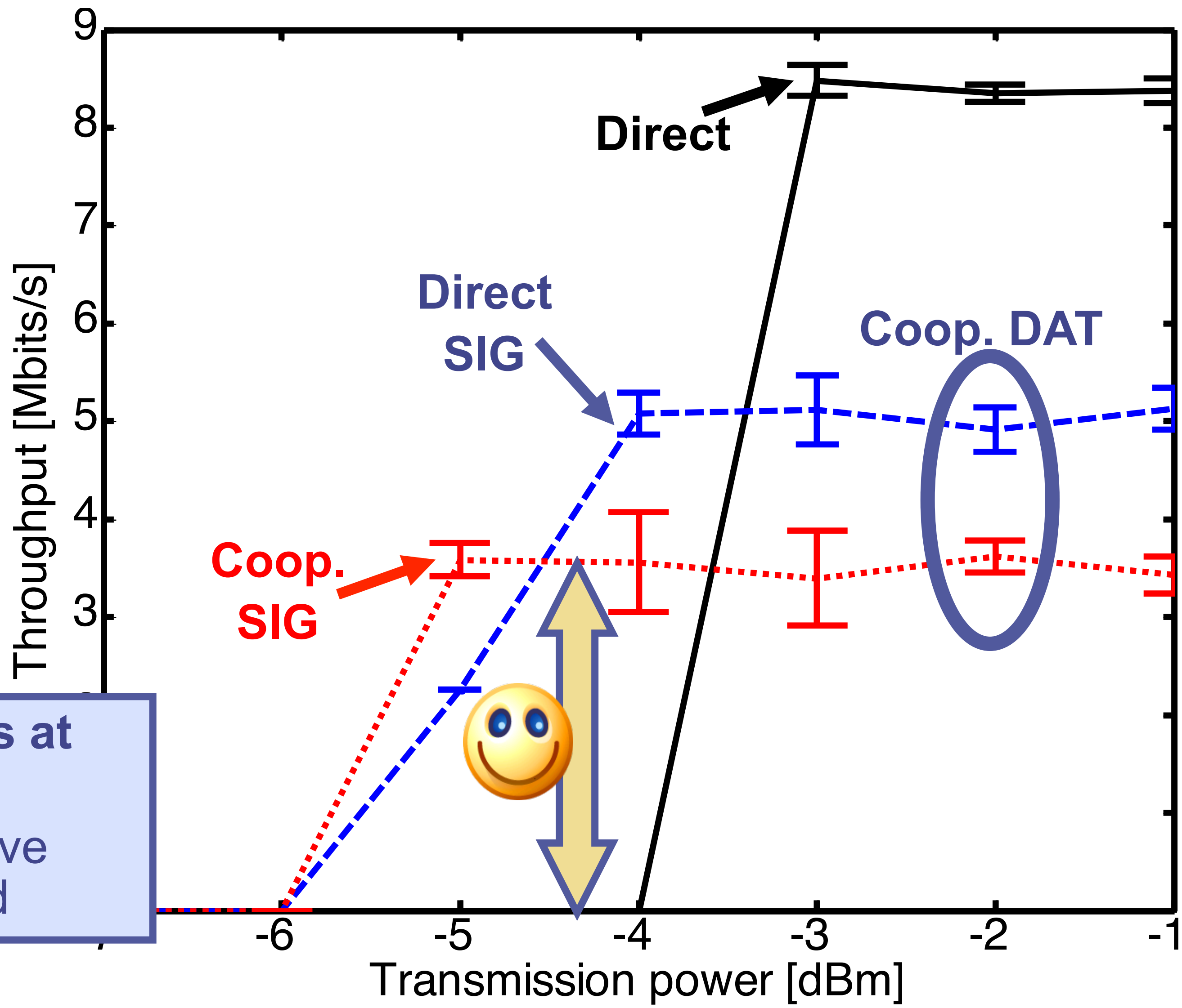




Valentin, Lichte, et al., 2008 [26]

Results: Vehicular Scenario – UDP Throughput

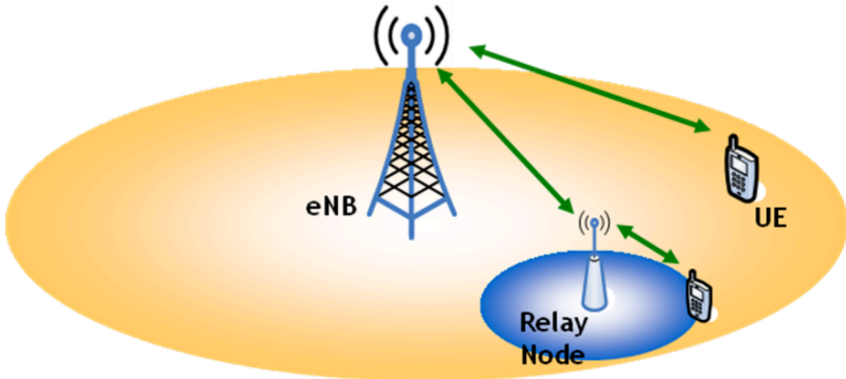




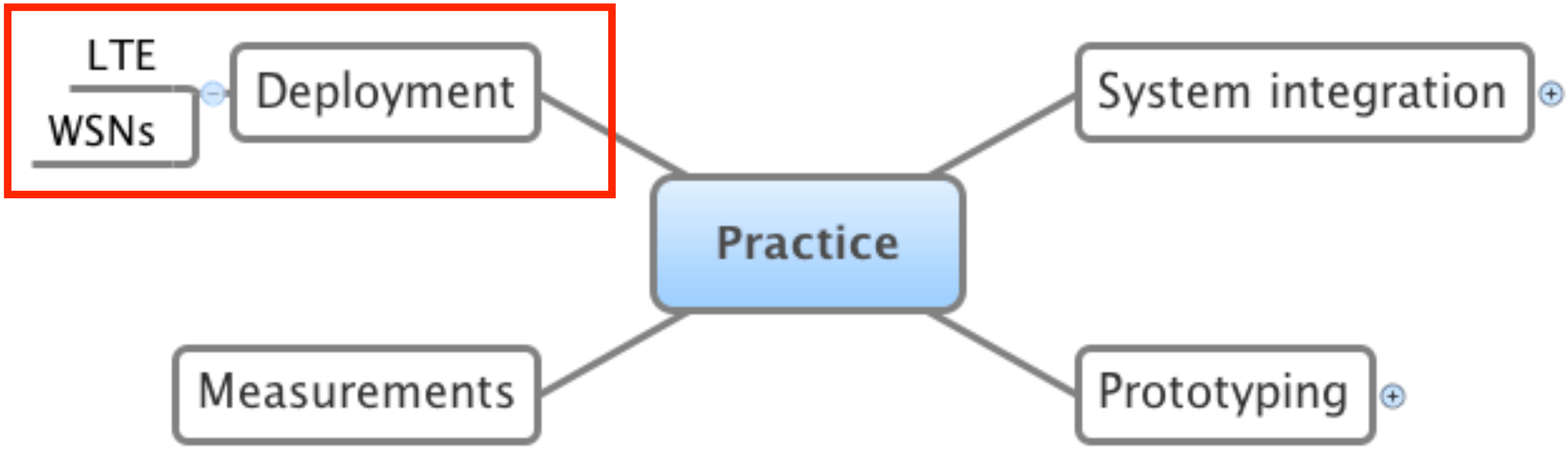
- **Direct SIG works at medium power**
- Below: Cooperative signaling required

Bell Labs: LTE Relay Demonstration

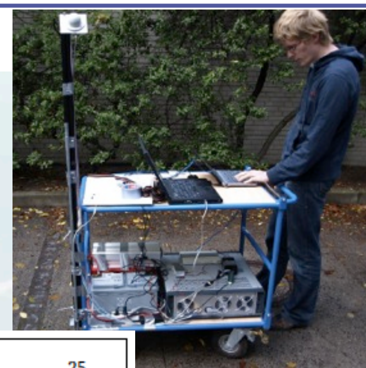
- Presented May 2011 at Bell Labs Open Day in Shanghai
  - Type I mode: LTE compliant MAC
  - Pre-Type II mode:
    - Adaptive relay selection, LTE signaling via BS for compatibility
    - Access node coordination between BS and relay
- Flexible testbed with programmable baseband
- **Demonstrated: Highly improved video quality for cell edge users**
  - **Promising: CoMP relays**

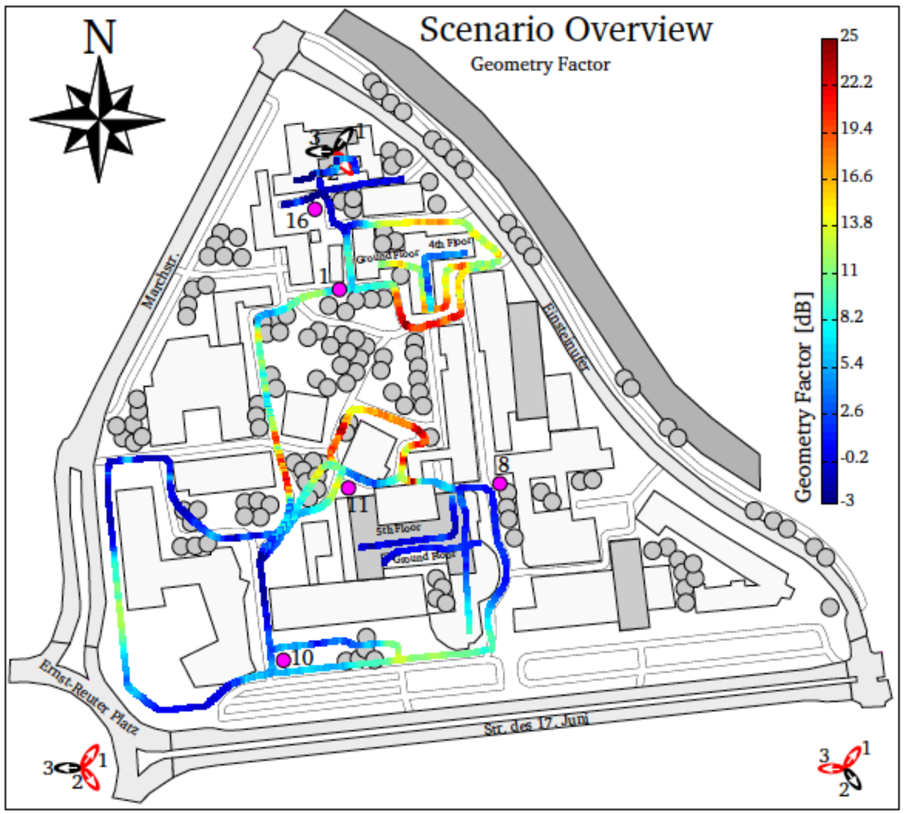


Practice: System Integration, Prototypes, and Measurements



Berlin LTE-Advanced Testbed

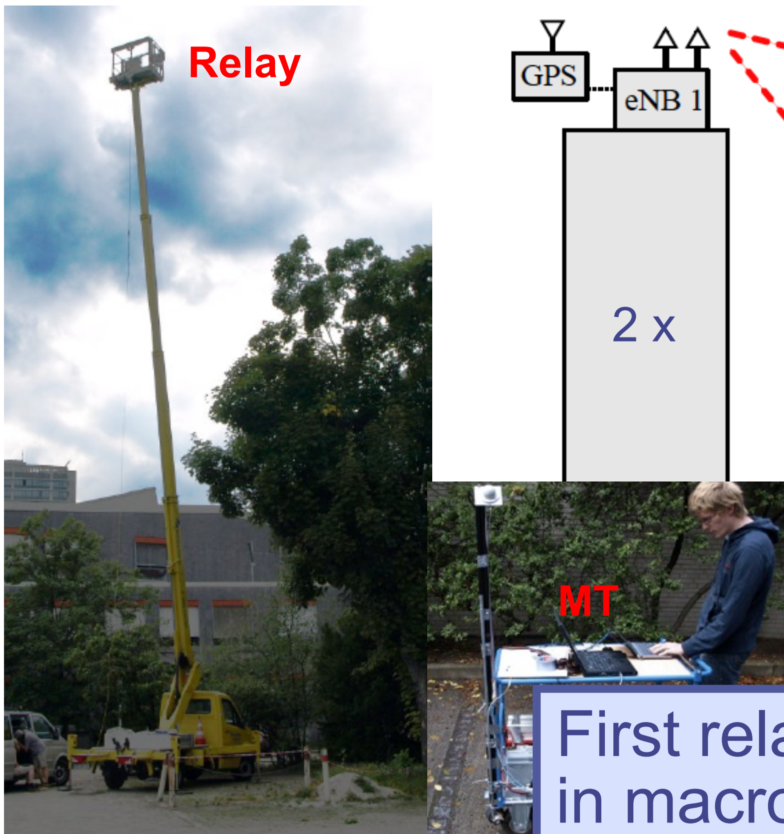


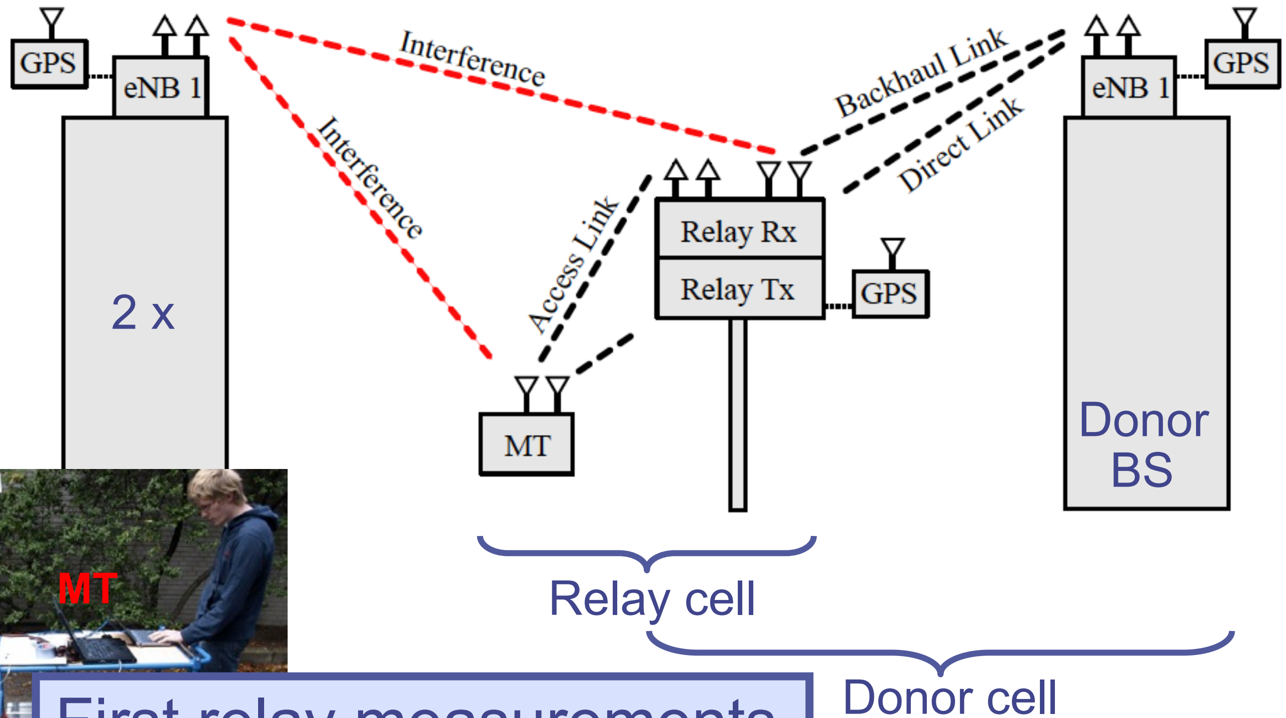


Pictures: Fraunhofer Heinrich Hertz Institute (HHI)

Field Measurements: Cellular Scenario

- Measure 2x2 propagation channel with an outdoor relay node
- SINR measurements: No relay strategy implied
  - Directly applies to LTE Type 1 relays, i.e., DF with repetition coding

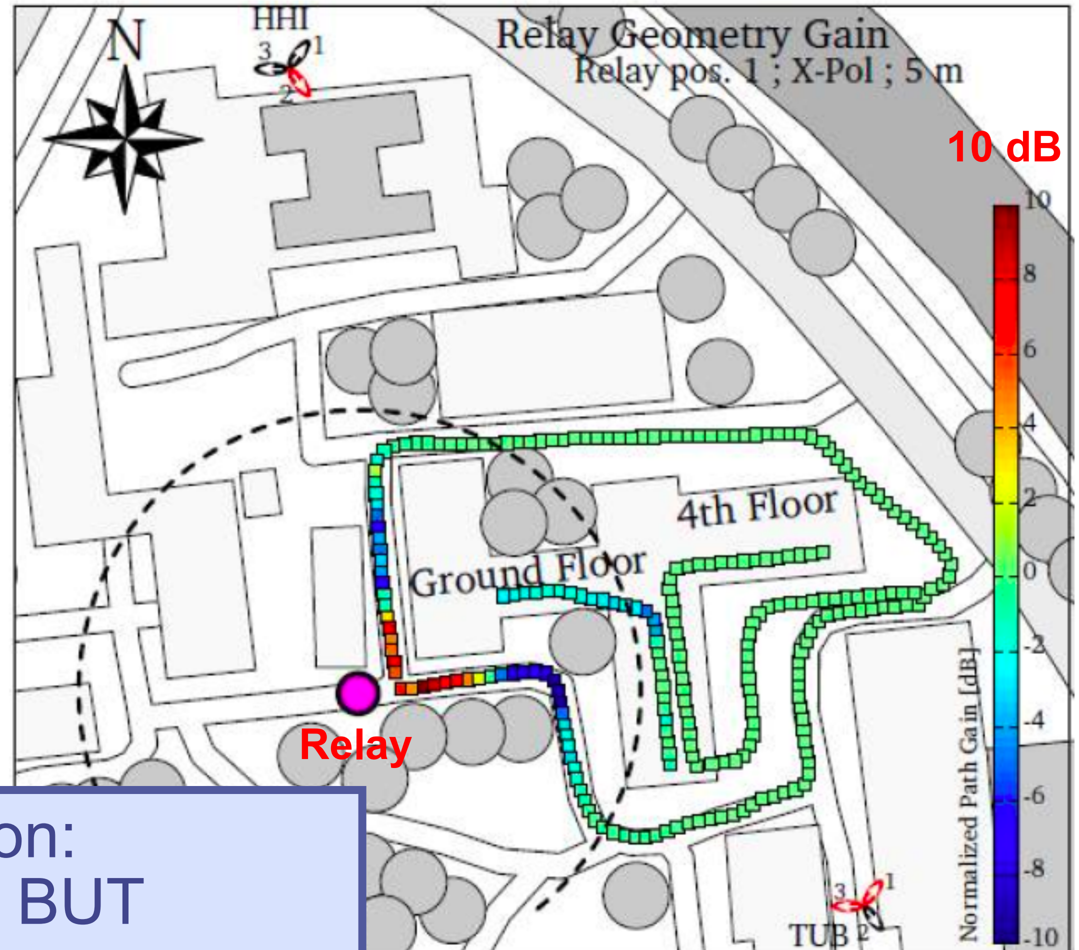




First relay measurements in macrocellular scenario

Results: Cellular Scenario

- Outdoor:
  - 5 relay positions
  - 5 interfering macro cells
- Indoor:
  - MT in 2 Buildings
  - Walls: Ferroconcrete
  - Windows: With and without thermal insulation



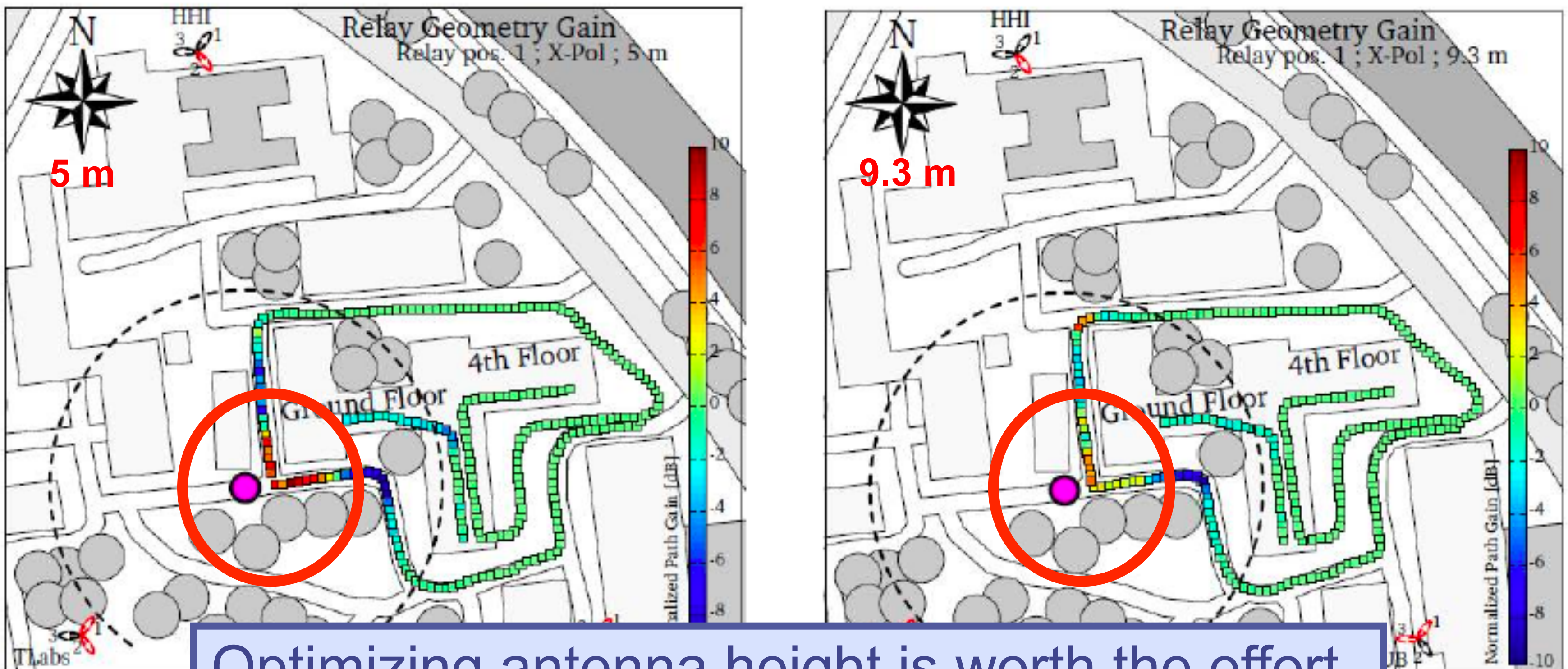
- Windows without insulation: SINR gains even indoors BUT
- SINR decreases in neighboring cells

=> Prefer indoor stations, e.g., Femto

Deploying Cellular Relays: Antenna Height

- Antenna height: 5 m often outperforms higher antennas
  - Reason: Low enough to limit interference to adjacent cells but high enough for good link to mobiles

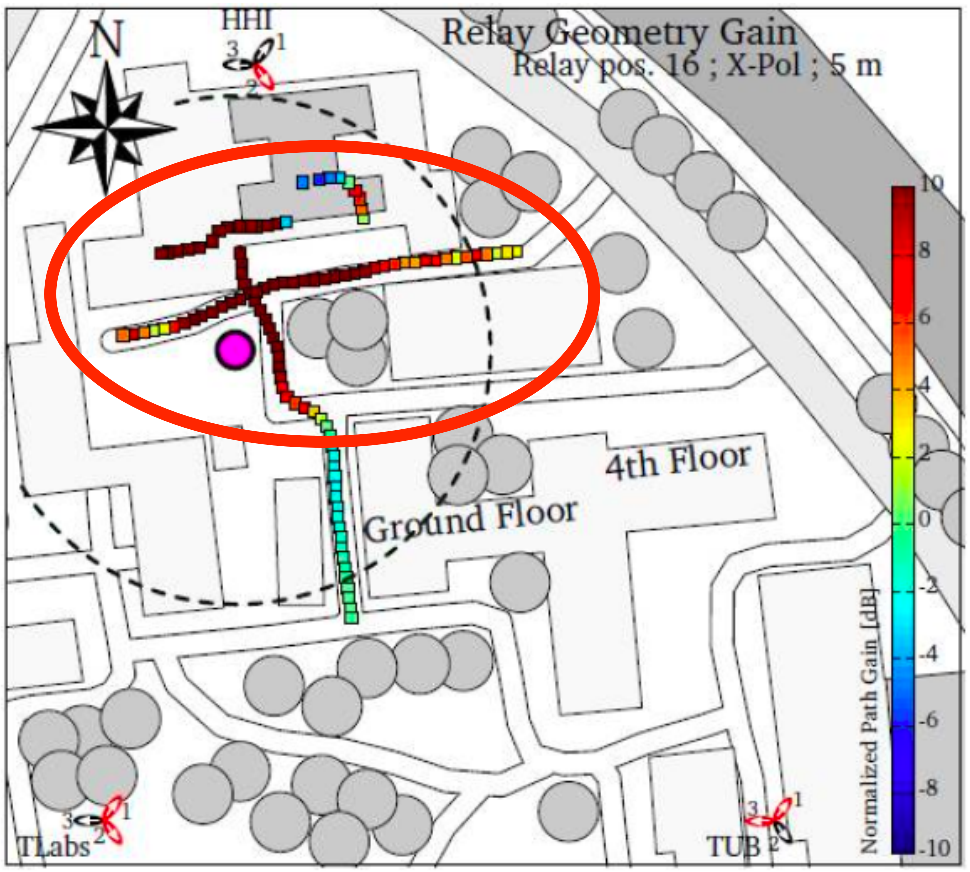
  => Good news for lamppost deployments

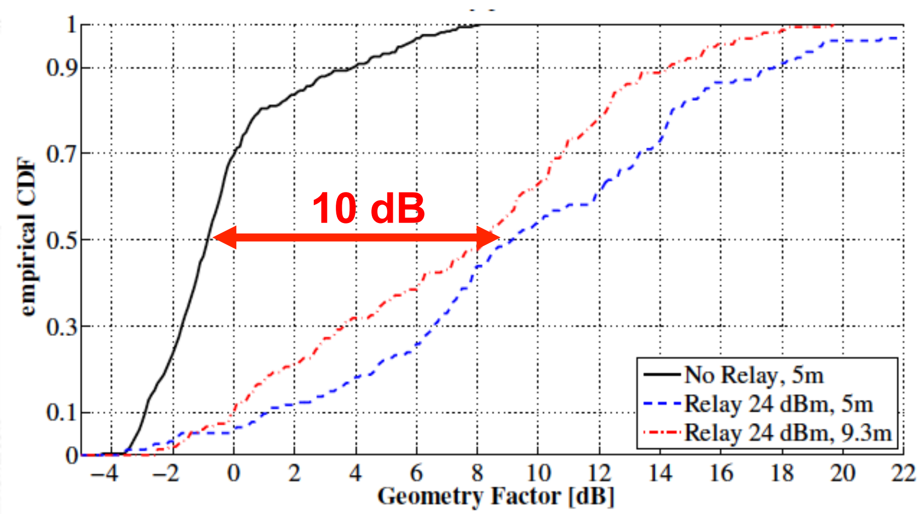


Optimizing antenna height is worth the effort

Deploying Cellular Relays: Coverage Holes

- Relays can be used to: Improve throughput in coverage holes or at cell edge



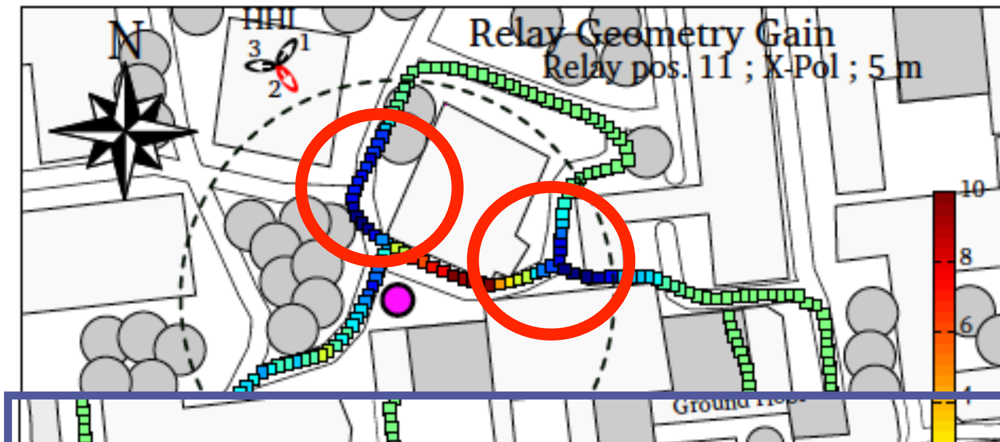


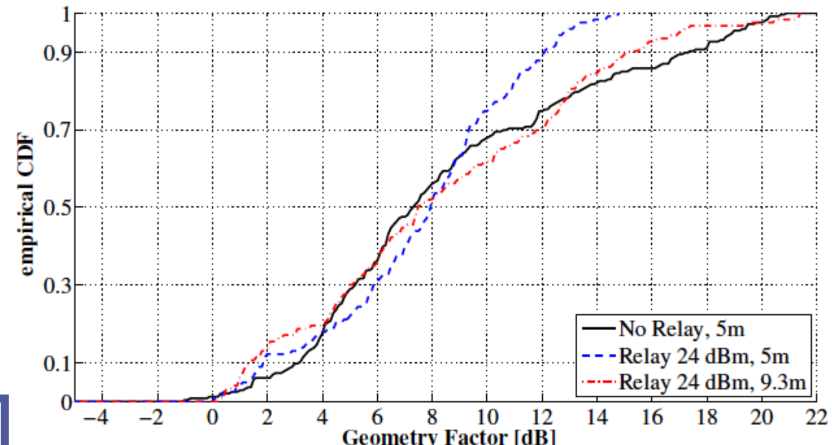
For coverage holes:
Relay highly improves throughput BUT...

Deploying Cellular Relays: Spatial Isolation

... assure that covered regions are isolated

- Without isolation: Relay interferes with neighboring cells





Messages from the field:

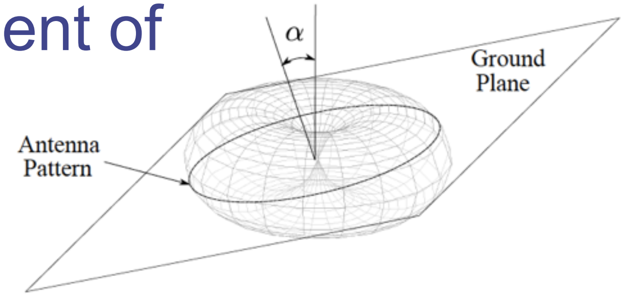
1. Outdoor relays: Promise large SINR gains but require careful deployment
2. Relay height is an important parameter
3. Spatial isolation must hold: Not easy to track in advance

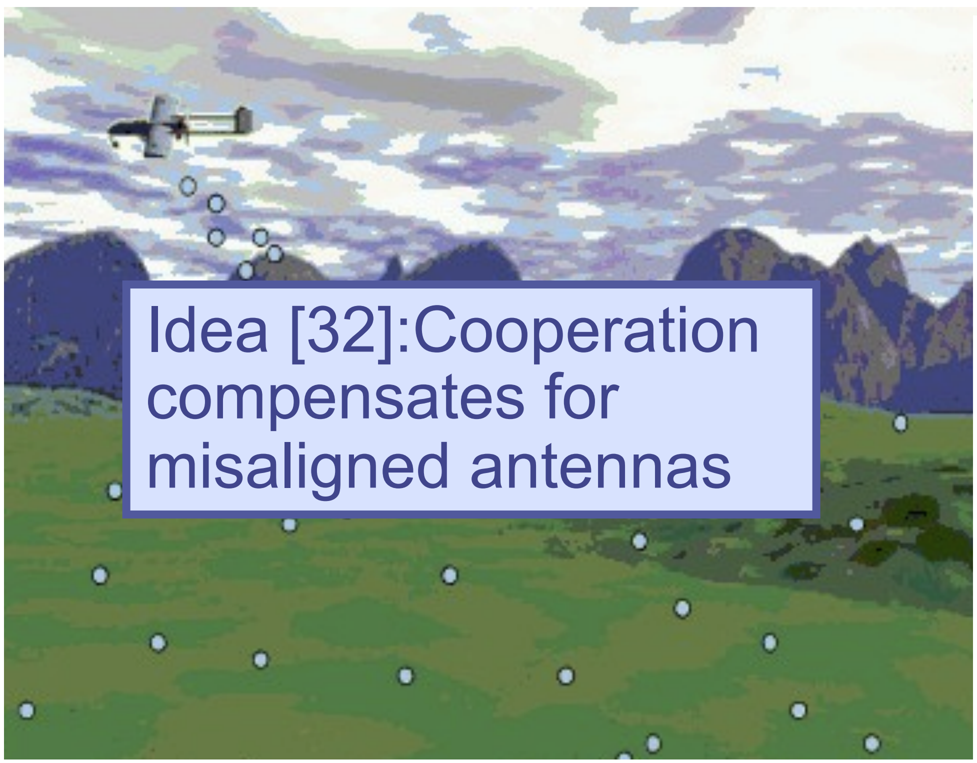
=> Need to adapt at runtime (e.g., power, ICIC)

Jaeckel, Jungnickel, et al. [31],

An what about other networks? Cooperative WSNs

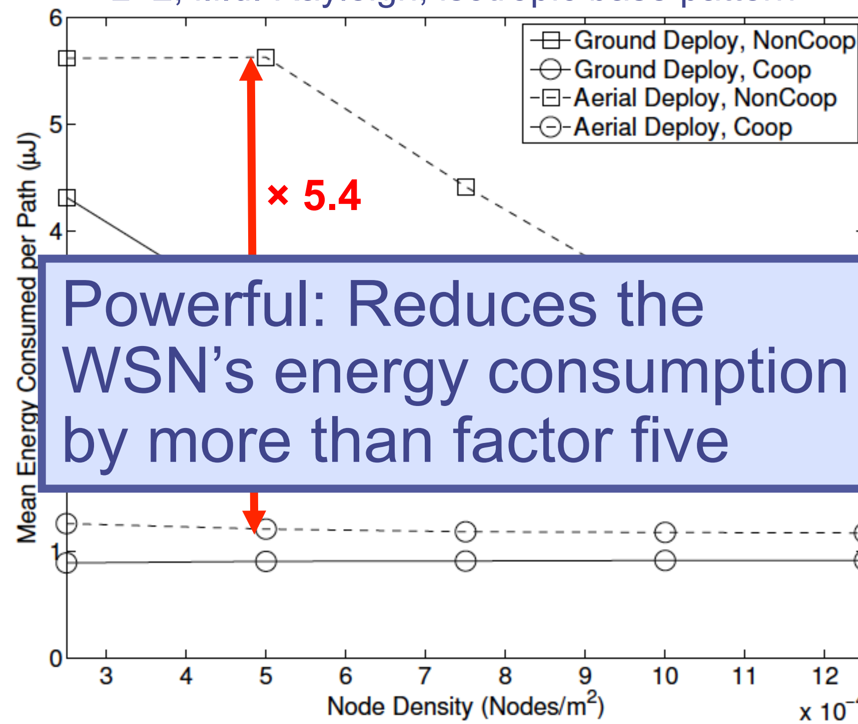
- Cooperation can assist aerial deployment of Wireless Sensor Networks (WSNs)
- Problem: Sensor nodes land with arbitrary antenna orientation





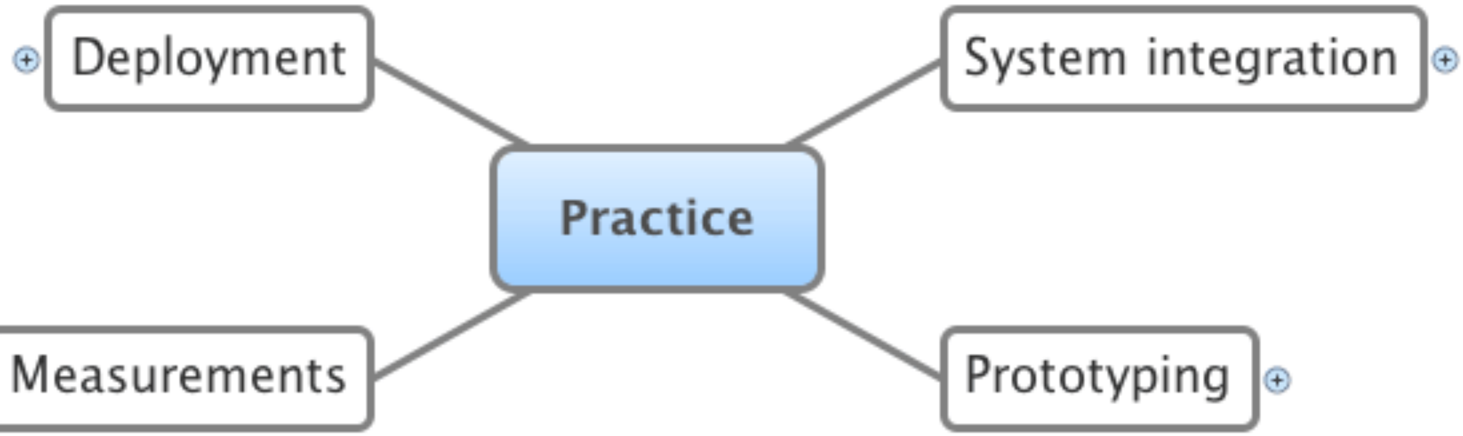
Idea [32]:Cooperation compensates for misaligned antennas

L=2, i.i.d. Rayleigh, isotropic base pattern



Powerful: Reduces the WSN's energy consumption by more than factor five

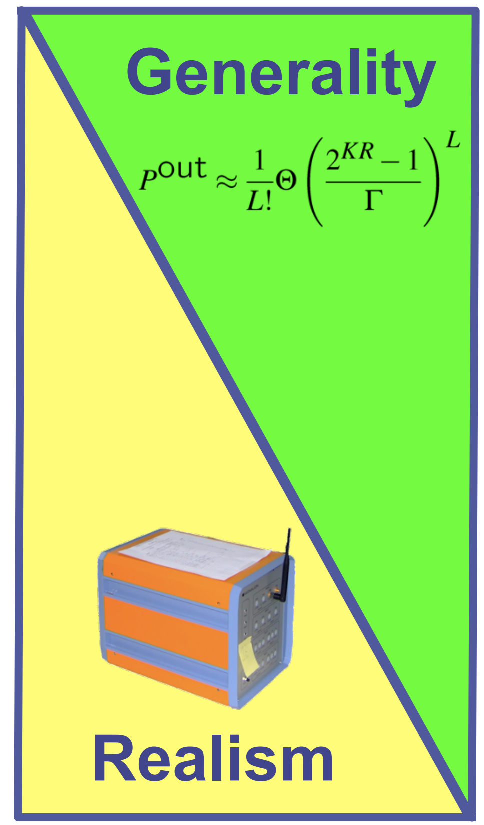
Summary: System Integration, Prototypes, and Measurements



- System integration: Keep it simple
  - For coverage gains: No sophisticated coding and combining needed
  - CSI feedback, MAC protocol and scheduling are more elaborate
- Prototyping and measurement: Diversity and coverage
  - Theoretically promised gains reproduced by experiments
- Deployment: Prefer isolated scenarios and **be creative!**
  - LTE: High gains come at the risk of interfering neighboring cells
  - WSNs: We can cope with more than just fading and path loss

Outline

- Technologies
- Application
- Theory
- Practice
- **Conclusion and Discussion**



Summary and Conclusion

- This tutorial provided an overview on:
  - The theory behind Cooperative Relaying
  - Tools and models to capture practical limits even by theory
  - Possibilities and activities in system design and prototyping
  - Recent measurements and field tests

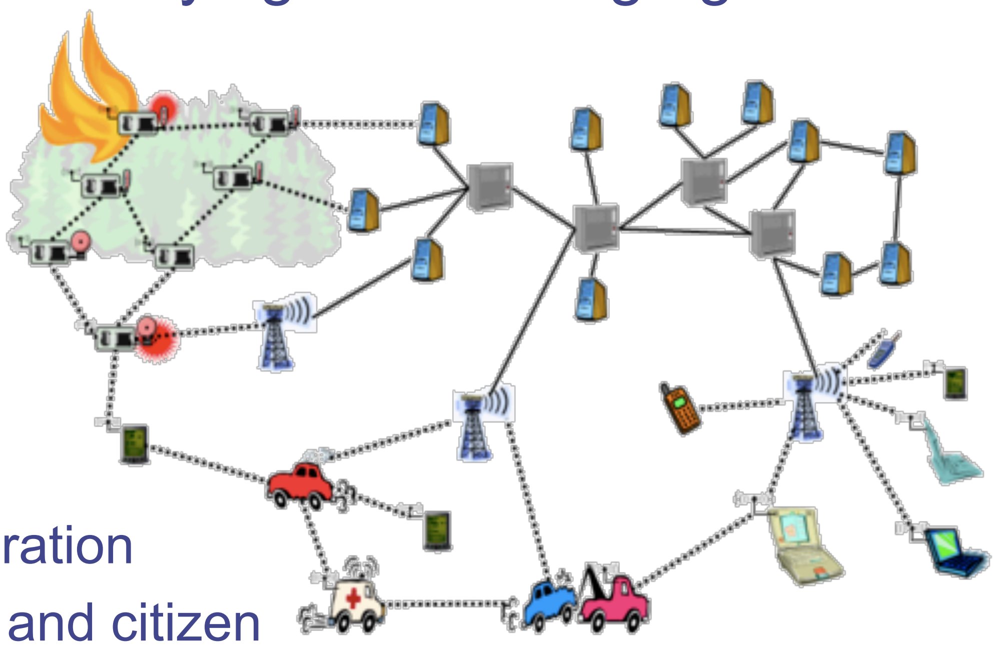
- The presented material shows:
  - Based on a strong theory: Cooperative Relaying has become a mature technology
  - Prototyping and measurements show: Implementation issues seem solvable within 3 years
  - Integration issues in systems and standards remain for capacity improving relays
  - Deploying relays requires more theoretical and practical studies

Future Work and Recommended Research

- In wireless systems: Do cooperative gains add to the gains of current diversity and multiplexing techniques?
  - For instance: Gain by cooperative relaying with HARQ in place?
  - Extensive system simulation required but most system simulators are single-link based => Model link interactions
- Theory: Resource allocation for cooperation
  - Optimize the users' slot/subband/relay allocation
  - Solved recently for DF with multiple sources and destinations [36]
  - Promising: Dense deployment of adaptive relays to cope with dynamic load
- Practice: Relays for interference control
  - "Smart Box": Combining relaying, advanced feedback, interference cancellation and control
  - Part of distributed scheduler for small or Femto cells

Discussion: Where to Apply?

- Time or frequency diversity often beats cooperative diversity: No (s,r) link
- Consequence: Cooperative Relaying reaches high gains if
  - Bandwidth is costly
  - Channel variation is slow
  - Delay constraints are tight



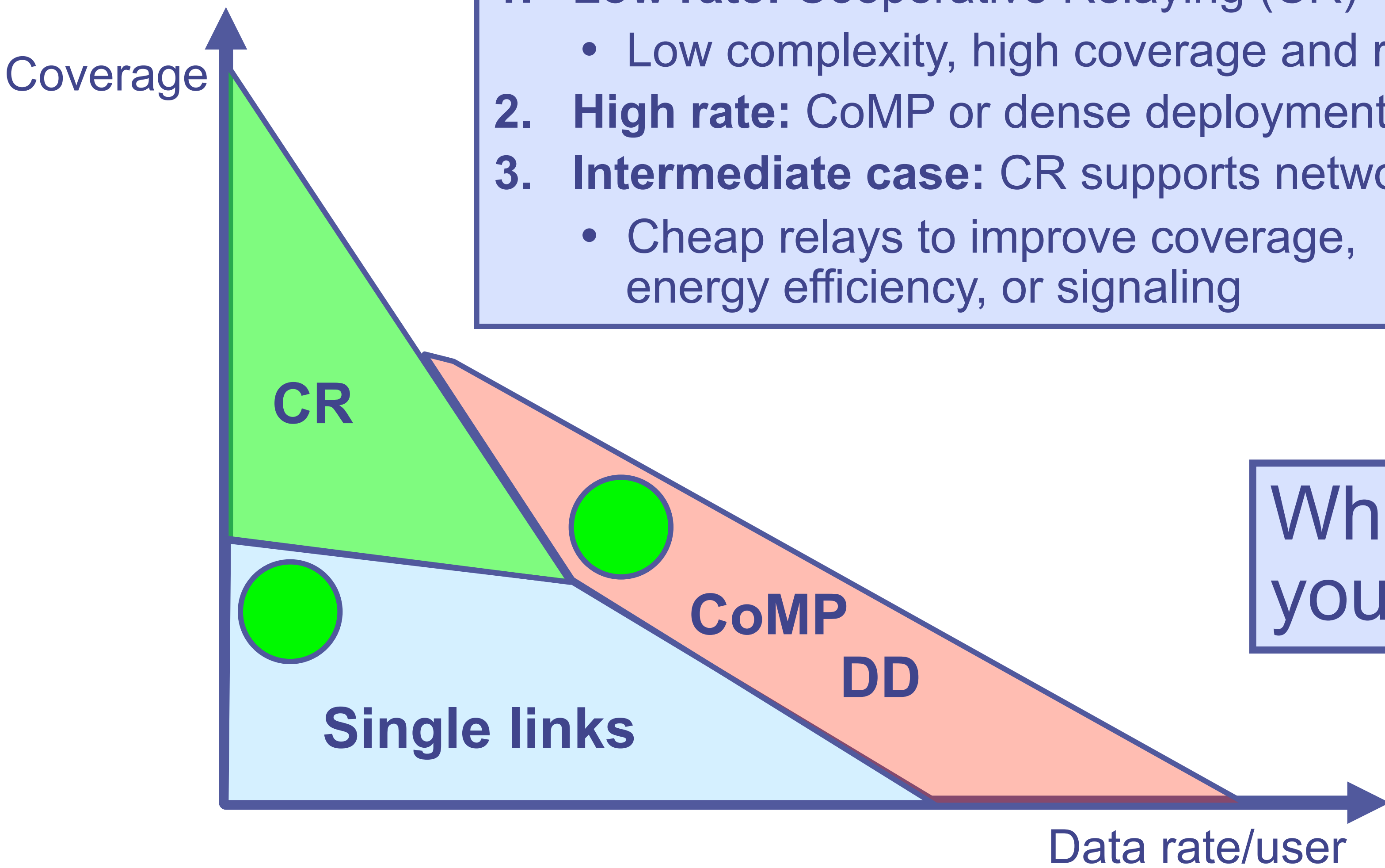
- Promising scenarios:
  - WSN: Monitoring and exploration
  - WLANs: Coverage for rural and citizen networks (e.g., FON, TIER), ad-hoc networks
  - Cellular networks: Coverage for cell boundary, rural scenarios, robust communication for signaling and machine-to-machine

Picture: Holger Karl, UPB

Discussion: The Future of Cooperative Communication?

Basic use cases:

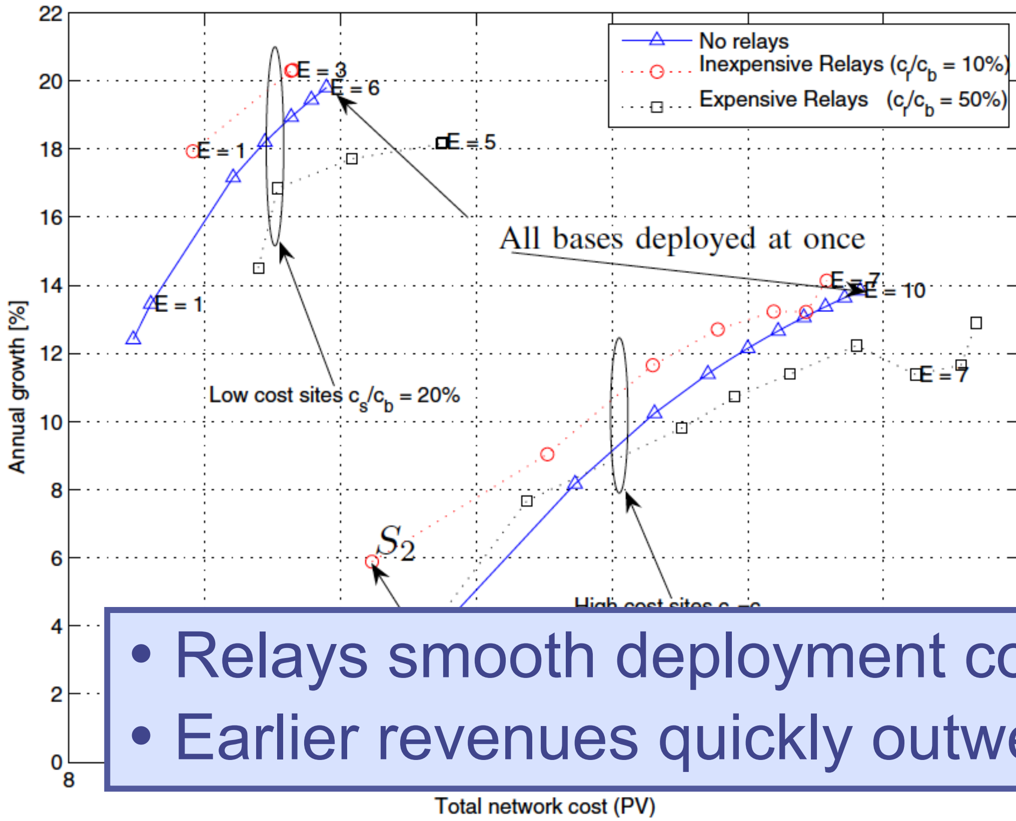
1. **Low rate:** Cooperative Relaying (CR)
   - Low complexity, high coverage and robustness
2. **High rate:** CoMP or dense deployment (DD)
3. **Intermediate case:** CR supports network
   - Cheap relays to improve coverage, energy efficiency, or signaling

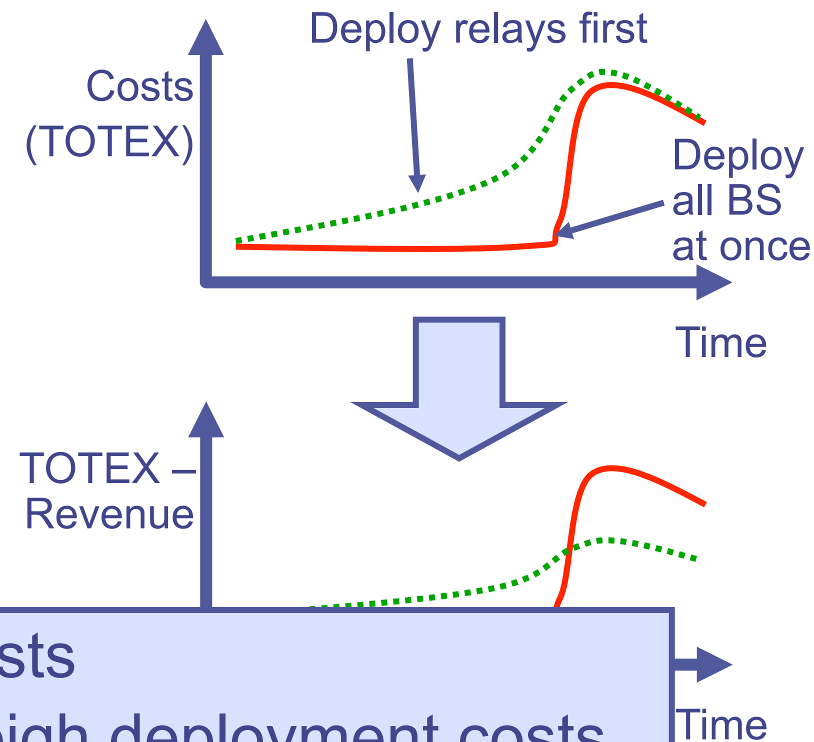


What do you think?

Intermediate Case: Relays as Support Technology

- A financial perspective
  - Incremental deploying: Cheap relays first, full BS later
  - Network grows faster with early revenues from relays
  - Revenues partially reinvested to deploy BS





- Relays smooth deployment costs
- Earlier revenues quickly outweigh deployment costs

Timus, Hultell, et al., 2008 [33]

Recommended Reading

- Books/Thesis:
  - M. Dohler and Y. Li, *"Cooperative Communications: Hardware, Channel & PHY"*, Wiley, 2010.
  - H. S. Lichte, "Quantifying and Reducing the Cost of Cooperative Relaying in Wireless Multi-Hop Networks", *PhD thesis*, 2011. to appear.
  - S. Valentin and A. Tulino, *"Cooperative Relaying: From Theory to Practice"*, Cambridge University Press**, to appear 2012*. Related PhD thesis, available online.***

- Slidesets:
  - P. Rost, "Relaying in wireless networks", NT Seminar at Vodafone Chair, TU Dresden, 2006. ***available online***
  - R. W. Heath et al., "Where are the Relay Capacity Gains in Cellular Systems?", Communication Theory Workshop, 2010. ***available online***

- Papers:
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Thank you!

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