The New Radio Access Network (RAN) Paradigm: Multihop Mesh Networks and Cooperative Communications

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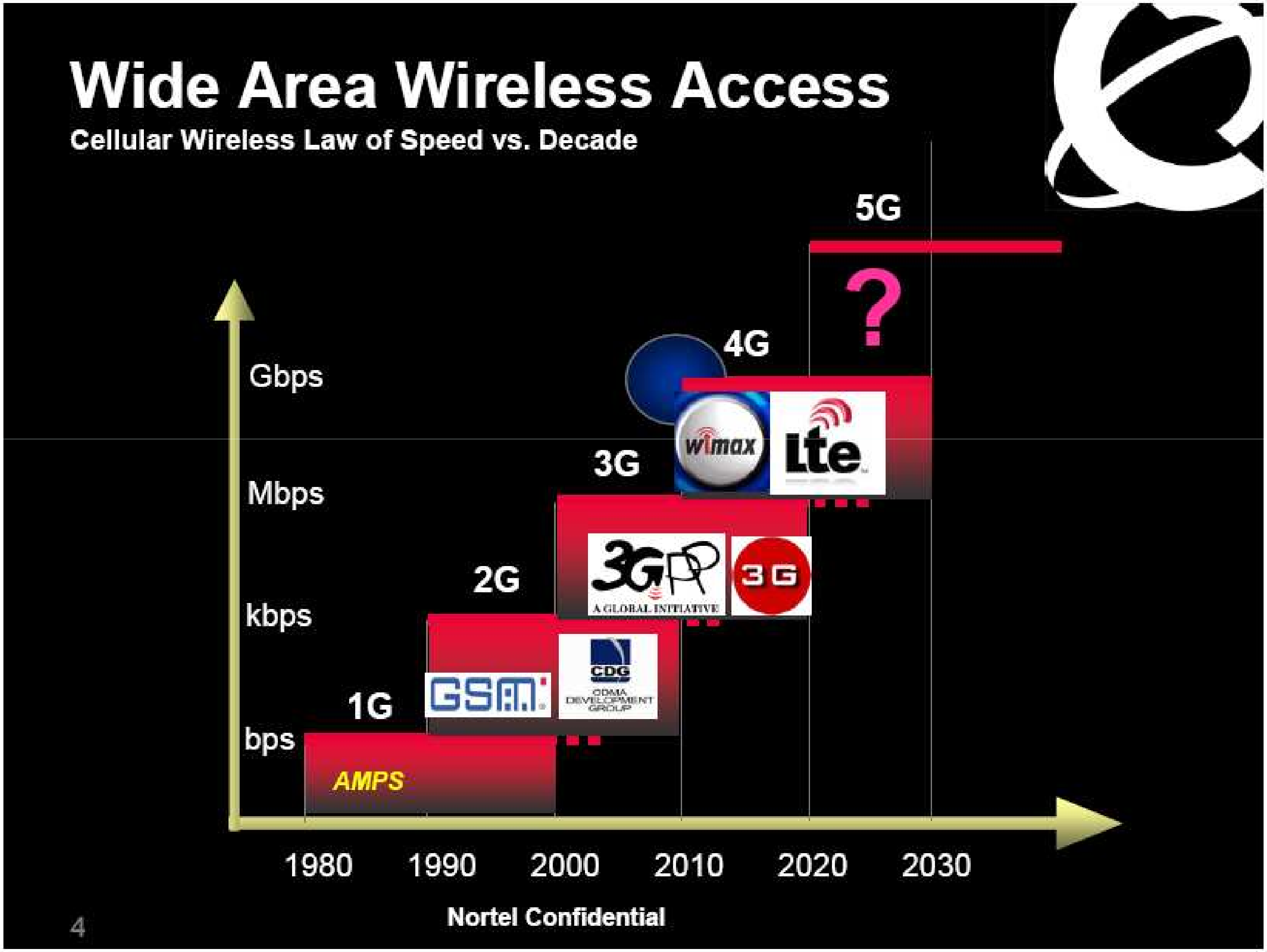
Outline

- Part I: Radio Access Network (RAN)
  - The fundamental capacity limit
  - Evolution of RAN and radio resource management (RRM)
  - Relaying: a cost-effective RAN architecture for ubiquitous high data rate coverage
- Part II: Relaying – A Closer Look
  - What can relaying offer
  - When to relay
  - Who relays
  - How to relay (types of relaying and protocols; cooperation, diversity)
  - What to do at destination
- Part III: Case Studies – Selected Research Results
  - Diversity-multiplexing tradeoff
  - Intelligent routing and scheduling
  - BS-relay coordination
  - Constellation rearrangement



Prepared by Dr. Wen Tong, WTL Director, Nortel

Expectations from 4G/5G Wireless Networks

- IMT-Advanced (4G)
  - mobile: up to 100 Mbps
  - stationary/nomadic: up to 1Gbps !!!
- 4G: LTE, LTE-Advanced, 802.16m
  - moving from research phase to development phase
- Beyond 4G (5G): Even higher rates

But how?

- More bandwidth needed (World Radio Conference, 2011)
- More bandwidth → more rates: it does not scale necessarily!
- High bandwidth & high carrier frequency
  - Tremendous stress on link budget

- advanced antenna technologies (MIMO, smart)
- advanced signal processing (modulation, coding, equalization)
- advanced radio resource management techniques

necessary but not sufficient

✓A fundamental upgrade in the network architecture is needed

Expectations from 4G/5G Wireless Networks

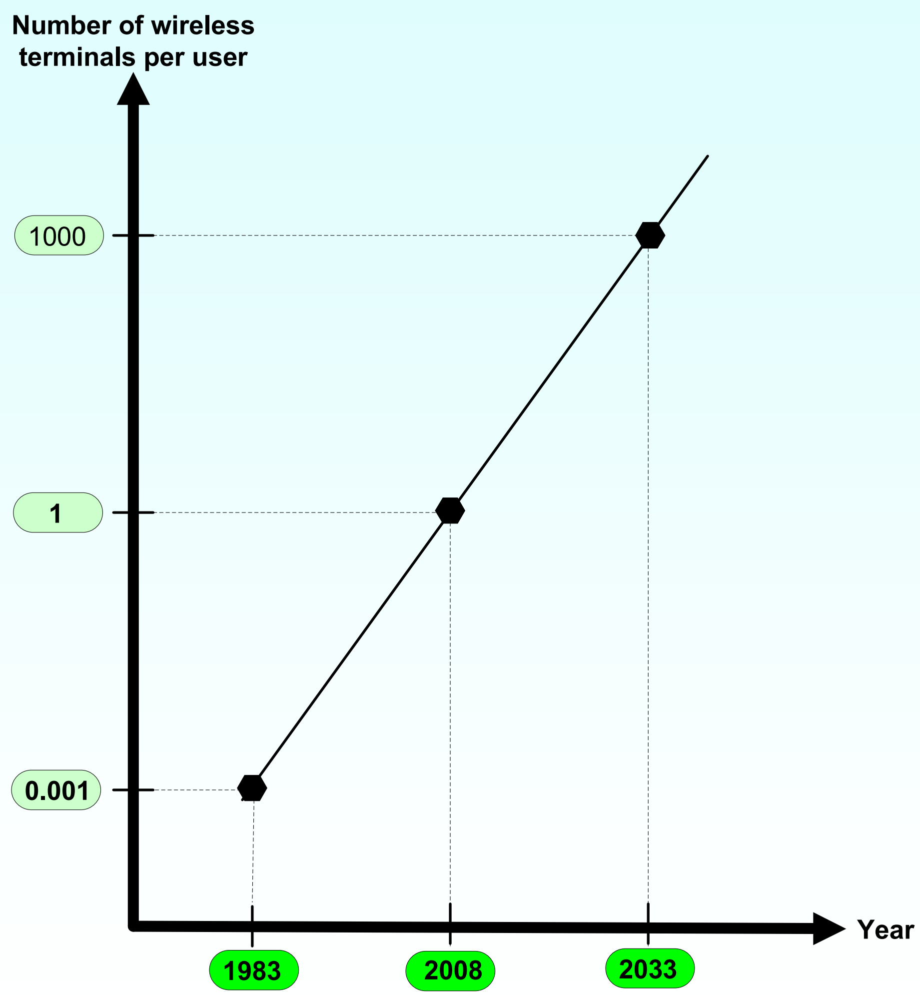
Goal: Design a wireless network which will provide (virtually) ubiquitous very high data rate coverage in a cost-efficient manner

Problem: $E_b/N_0 = (P_{rec}/R)/N_0$
For a target E_b/N_0, $P_{rec}\nearrow$ as $R\nearrow$
If P_{tx}: fixed → much less path-loss can be tolerated
Ex: $R\nearrow 1000x$ → 30 dB loss in link budget

Observation: Advances in PHY alone will not be enough to reach the goal

Solution: Advanced radio access network (RAN) architectures
Advanced radio resource management (RRM) techniques
Cross-layer and across network design
Other enabling concepts

Projections



Terabits/second Wireless (?)

Fundamental dynamics: 3 + 1 rule

- Bandwidth (W)
- Received power (P_s)
- No of antennas (n)

} $R = n\,W\log(1+\text{SNR}) = n\,W\log(1+[P_s/R]/N_0])$

+

- Reuse (SNR → SINR → SIR)

Remark: Reuse scales without a bound!

Primary Challenge: Very High Data Rate Coverage

(Potential) Capacity per BS:

$$R = n\,W \log(1+\text{SNR}) = n\,W \log(1+P_s/[RN_0])$$

High rates → high bandwidth and high spectral efficiency → high P_s

High P_s → low path-loss → shorter distances

Deploying more BSs for high data rate coverage: expensive & impractical

Ubiquitous high data rate coverage

→ must use advanced RAN architectures to distribute the capacity throughout the cell area

Advanced RAN, high reuse, high interference

→ must use advanced RRM techniques

Network Capacity

- Potential cell capacity = *f* (channel)
  → Actual cell capacity << Potential cell capacity

- Actual network capacity << Σ Actual cell capacity
  (due to dynamic non-uniform loading)

- Brute-force solution: deploy a high number of BSs for providing coverage and coping with dynamic load
  → bad design, gross over-engineering!

- Question: Actual network capacity ~~ Σ Potential cell capacity

- Answer: YES, through RAN and RRM! (virtually ubiquitous coverage)

Wireless Overview

I. Wired Communications

point-to-point, isolated, AWGN channel

link problem (modulation, coding, BER analysis, …) [PHY]

communications → communications theory & information theory

II. Wireless Communications

(perceived as natural extension of wired communications)

point-to-point, isolated, fading channel

link problem (modulation, coding, BER analysis, …) [PHY]

wireless communications → comm & info theory for wireless channels

Wireless Overview

III. Wireless Communications → Wireless Networks

wireless is more than just PHY!

L2: distinguishing layer

multiple access (very different from multiplexing)

+ broadcast + reuse (interference) → tangled links

RRM (including multiple access) makes it work!

network view

L1 + L2 + L3: cross-layer design

Wireless Overview

IV. Wireless Multihop

cooperative communications → cooperative diversity

once again, started as a link problem [PHY]

V. Wireless Cooperative Multihop Mesh Networks

(more than the "current hot topic")

advanced RAN architecture

+ advanced RRM techniques

+ cooperation at all layers (L1, L2, L3, cross-layer)

Cellular Design Fundamentals

I)

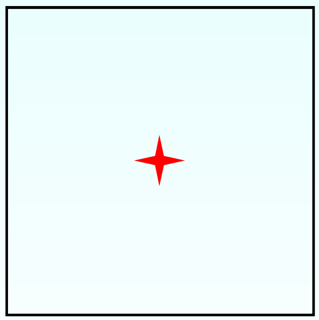
QoS → E_b
R: Data Rate

} $R.E_b = P_r$
P_t

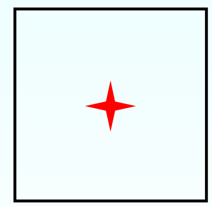
} Pathloss
Propagation Conditions

} Cell Size

Low Data Rate



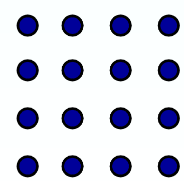
High Data Rate



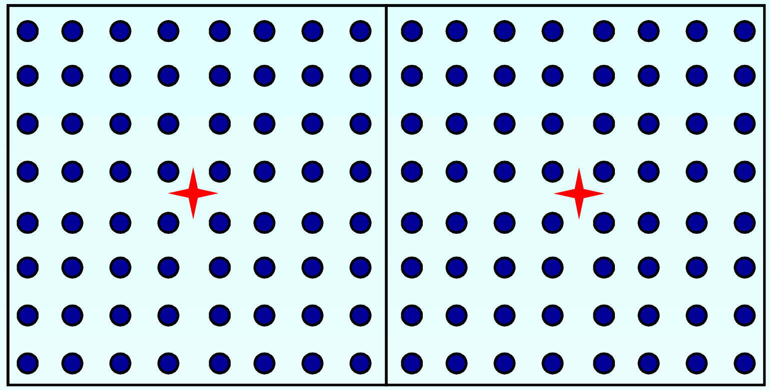
II)

BW
PHY

} Cell Capacity



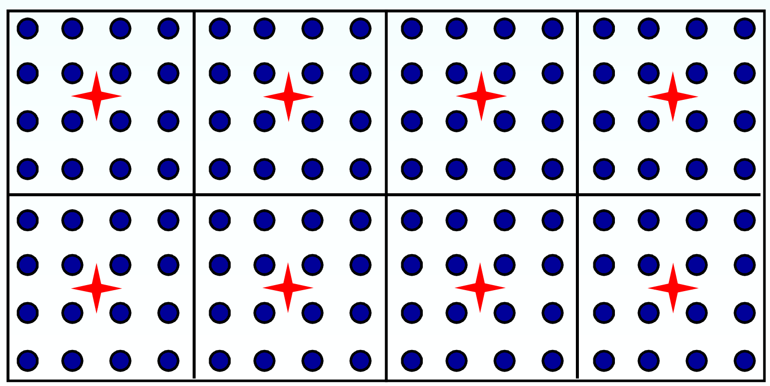
Capacity-Limited Networks



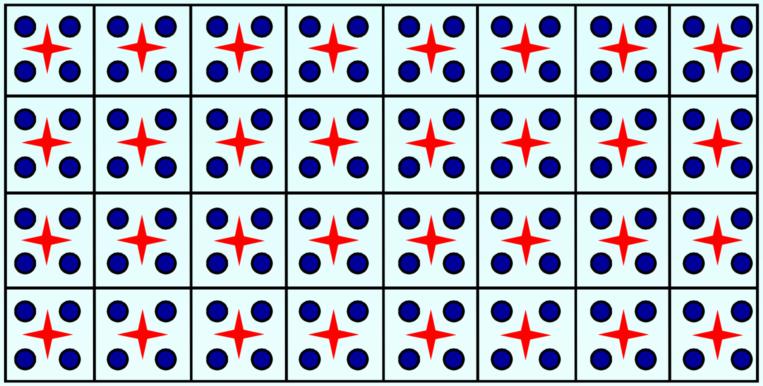
available capacity / cell < capacity demand

→ capacity limited

Solution: cell splitting



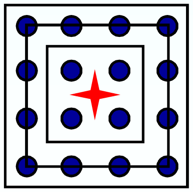
Coverage-Limited Networks



available capacity / cell > capacity demand

→ coverage limited

Solution: range extension



Capacity-Limited vs Coverage-Limited Networks

1G
2G } Capacity limited → network grows as needed
→ great success

3G

4G
5G } Ubiquitous high data rate coverage limited
→ very high deployment cost from the beginning
→ great challenge

WLAN: low deployment cost → great success

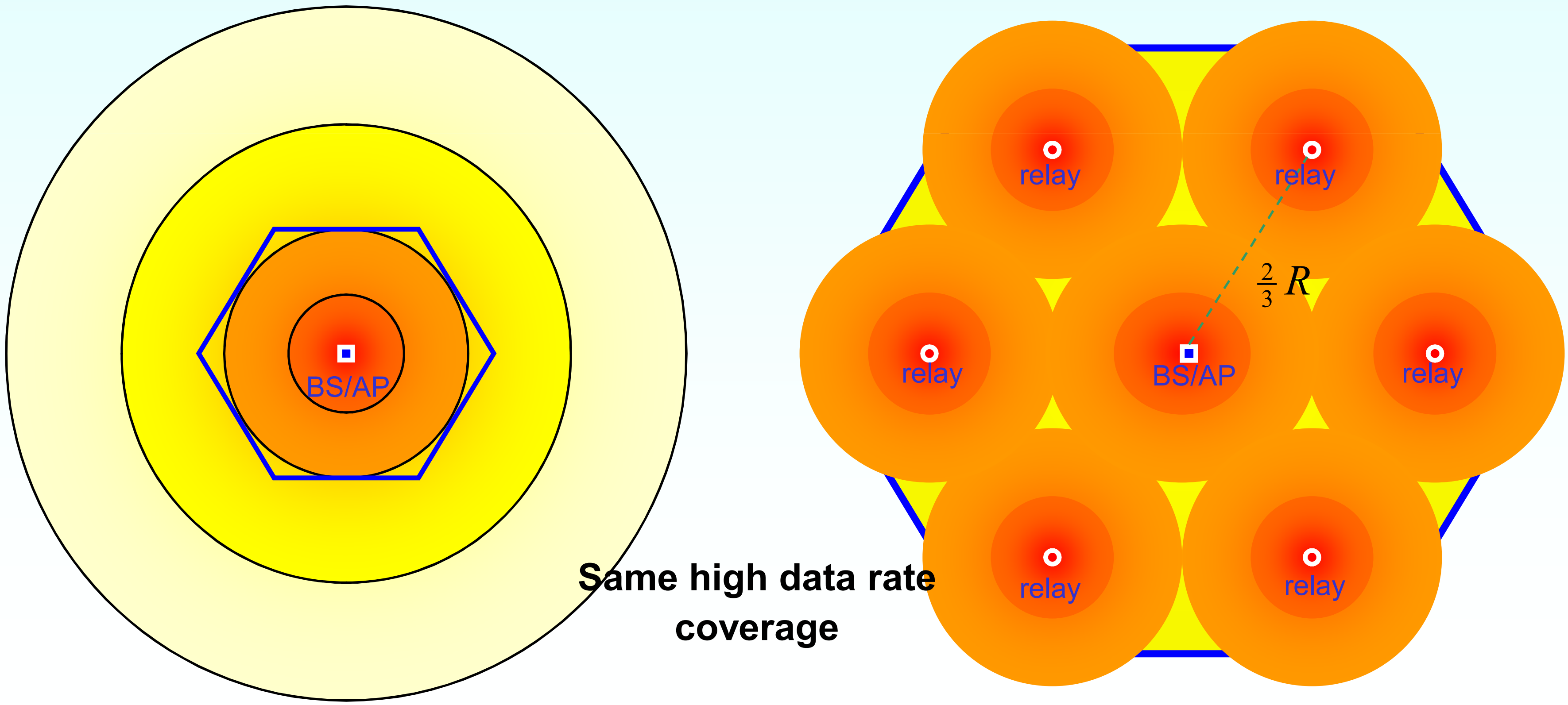
Coverage Extension (Cell-Edge Coverage) through Digital Fixed Relays

- Low cost digital fixed relays located at strategic locations

  No wired internet connection at relays

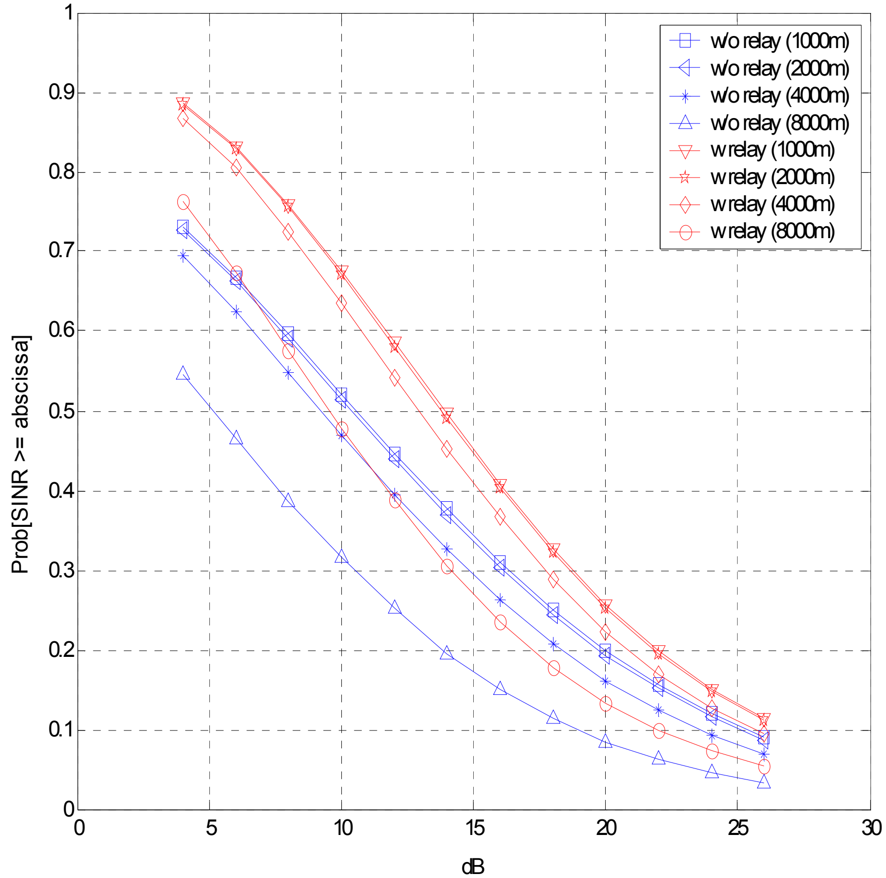
What is a relay?

- Different from conventional repeaters (selective relaying)
- Different from ad hoc networks (routing is less of an issue)

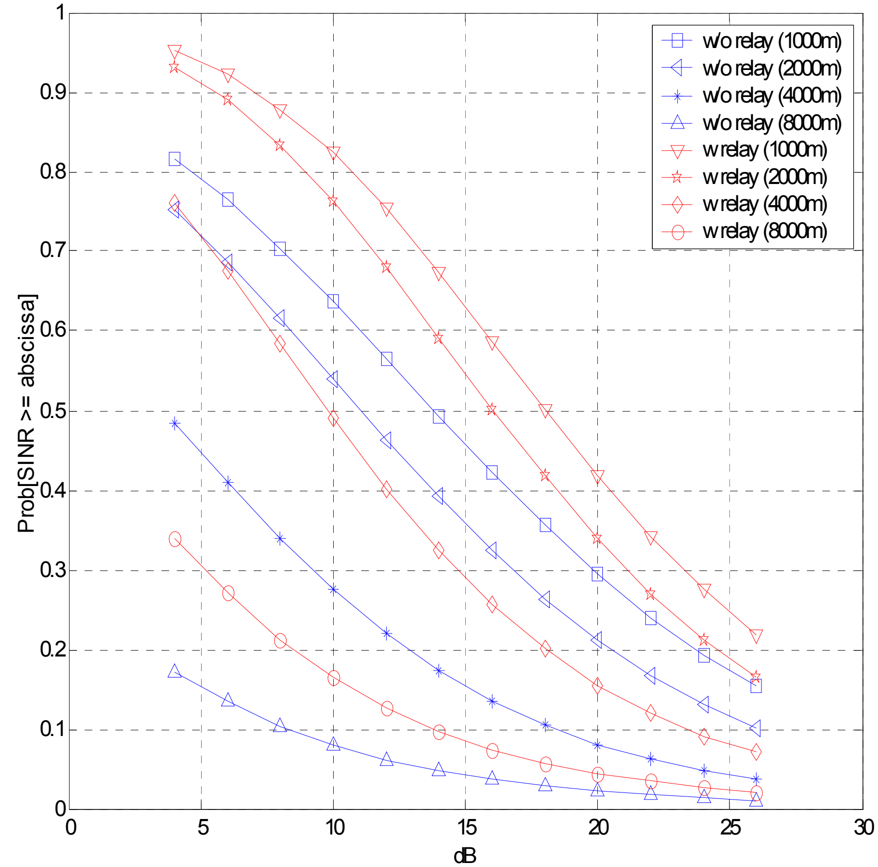


Coverage CDFs

H. Hu, H. Yanikomeroglu, D.D. Falconer, S. Periyalwar
“Range Extension w/o Capacity Penalty in Cellular Networks with Fixed Relays”, *Globecom 2004*

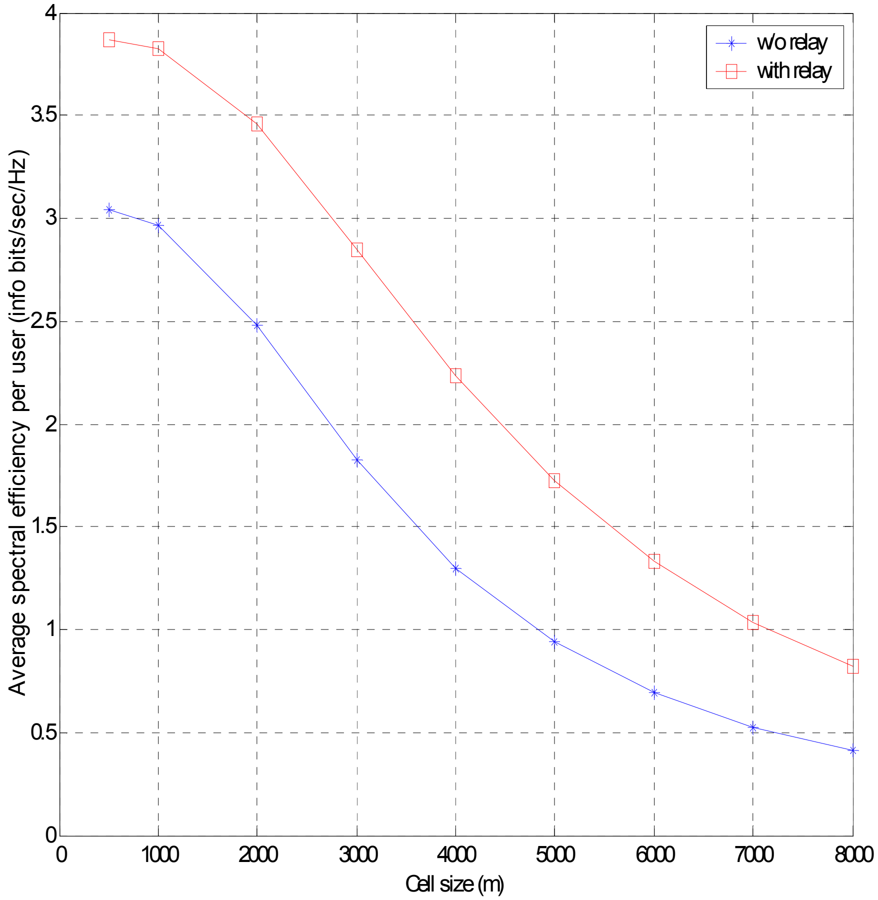


propagation exponent = 3

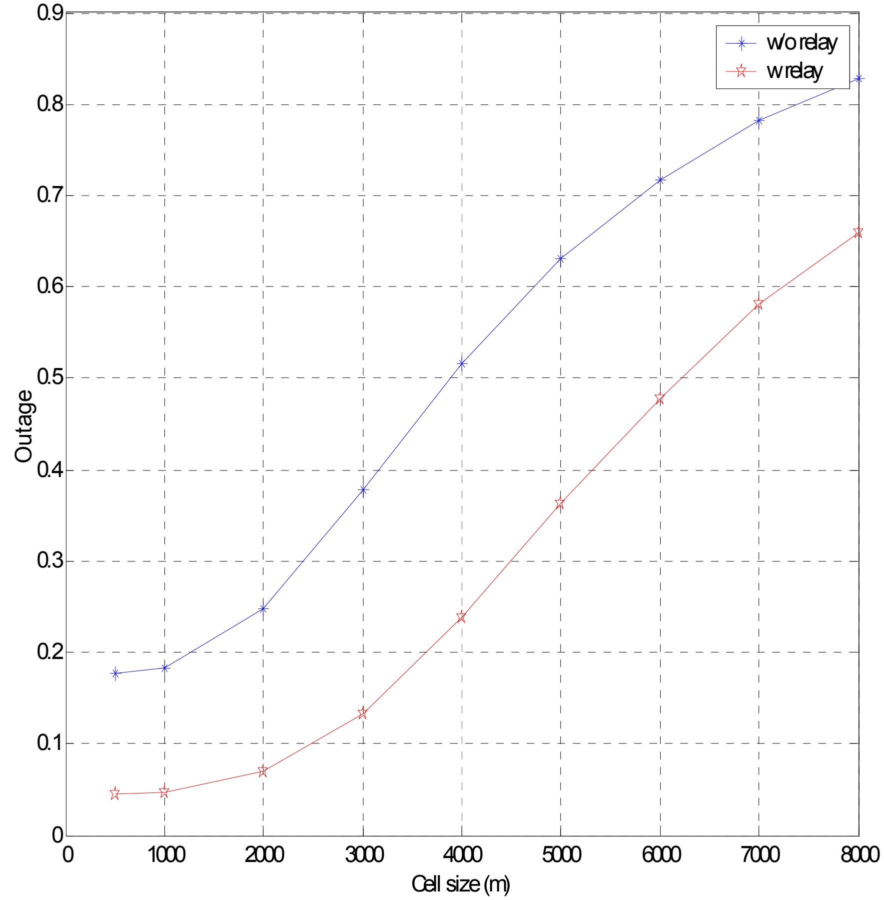


propagation exponent = 3.5

Average spectral efficiency w.r.t. cell size



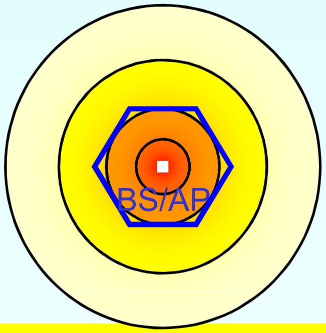
Outage w.r.t. cell size

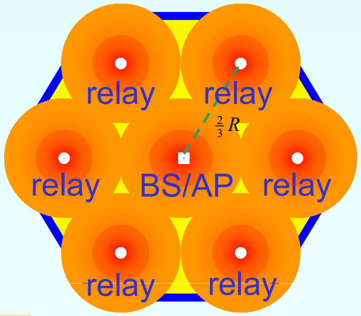


propagation exponent = 3.5

Cost-Efficient Range Extension

- Same "average spectral efficiency" and "outage" w.r.t. cell size trends are observed for different values of
  - Propagation exponent
  - Cluster size
  - Shadowing standard deviation
  - BS transmit power





Relay networks: significant potential for range extension

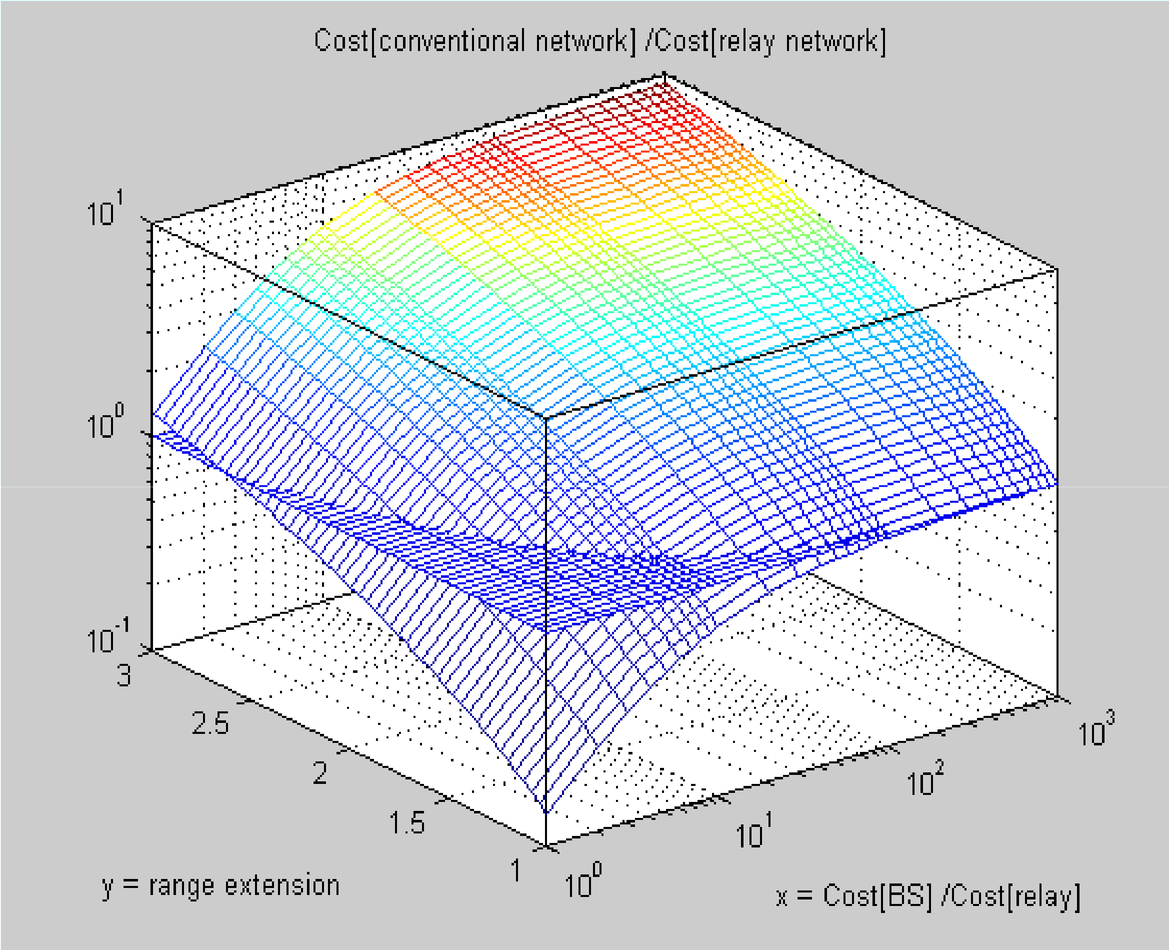
Ex: Range extension = x2 Cost [micro-BS] / Cost [relay] = 10

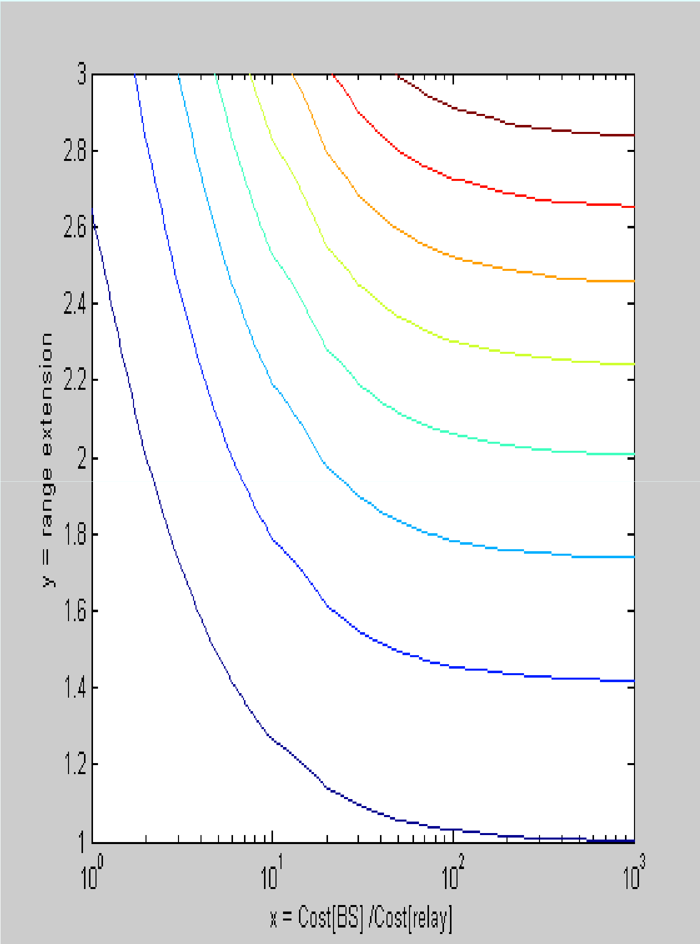
Cost [microcellular network] / Cost [relay network]

= Cost [L micro-BSs] / (Cost [L/4 micro-BSs] + Cost [6L/4 relays])

= 40/16 = 2.5

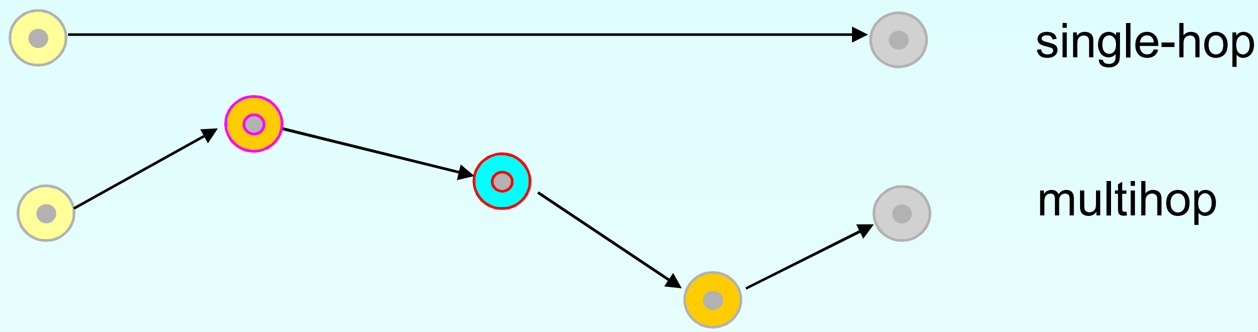
(IEEE Globecom 2004)





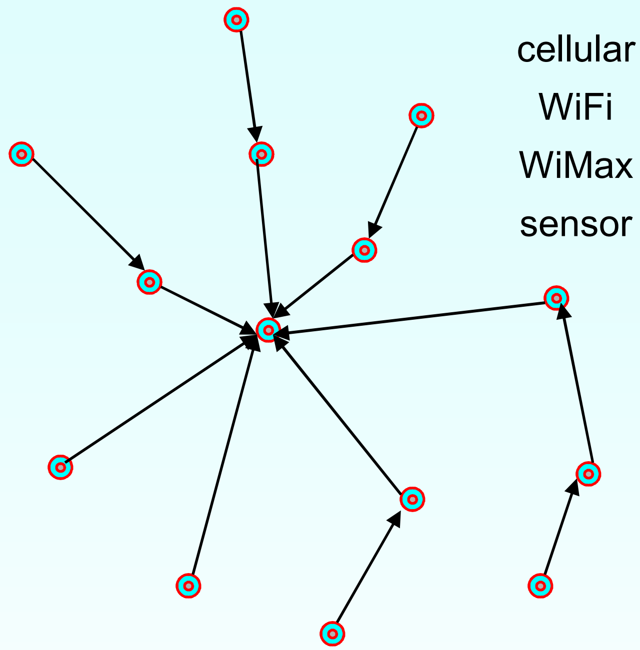
Cost [conventional network] / Cost [relay network]: $z = y^2 \dfrac{x}{x+6}$

RELAYING: Very many variations



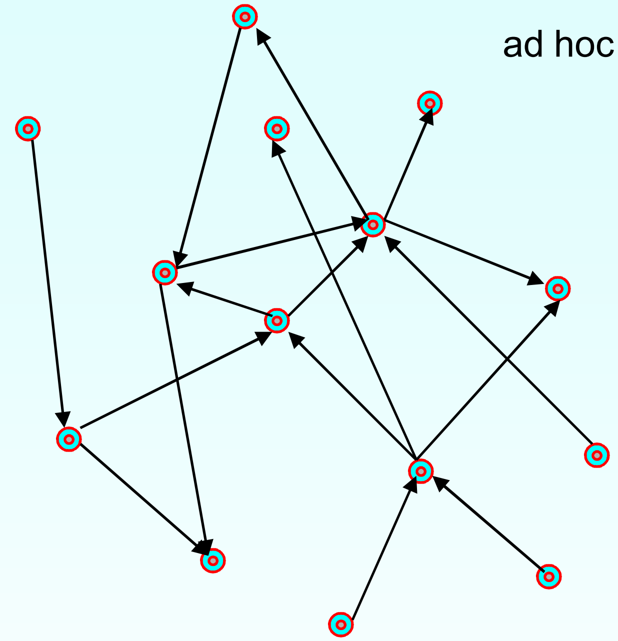
- What type of multihop relay network?
  - Cellular, WiMAX, WLAN, sensor, ad hoc, PAN, …
- What type of relay?
  - Fixed relay, nomadic relay, moving relay, terminal relay, sensor relay, wired relay, …
- What type of operation?
  - Half-duplex, full-duplex
  - Amplify-and-forward (analog), decode-and-forward (digital), process-and-forward
  - L1 layer, L2 layer, L3 layer
- What type of cooperation?

Infrastructure-based vs Infrastructure-less Multihop Networks



infrastructure-based multihop network

BS/AP → common source or sink



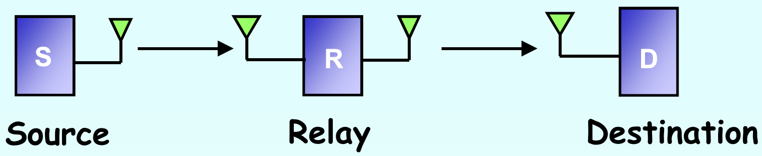
infrastructure-less multihop network

Centralized vs Non-Centralized Multihop Networks

systems & networking layers: many differences

physical layer: many similarities

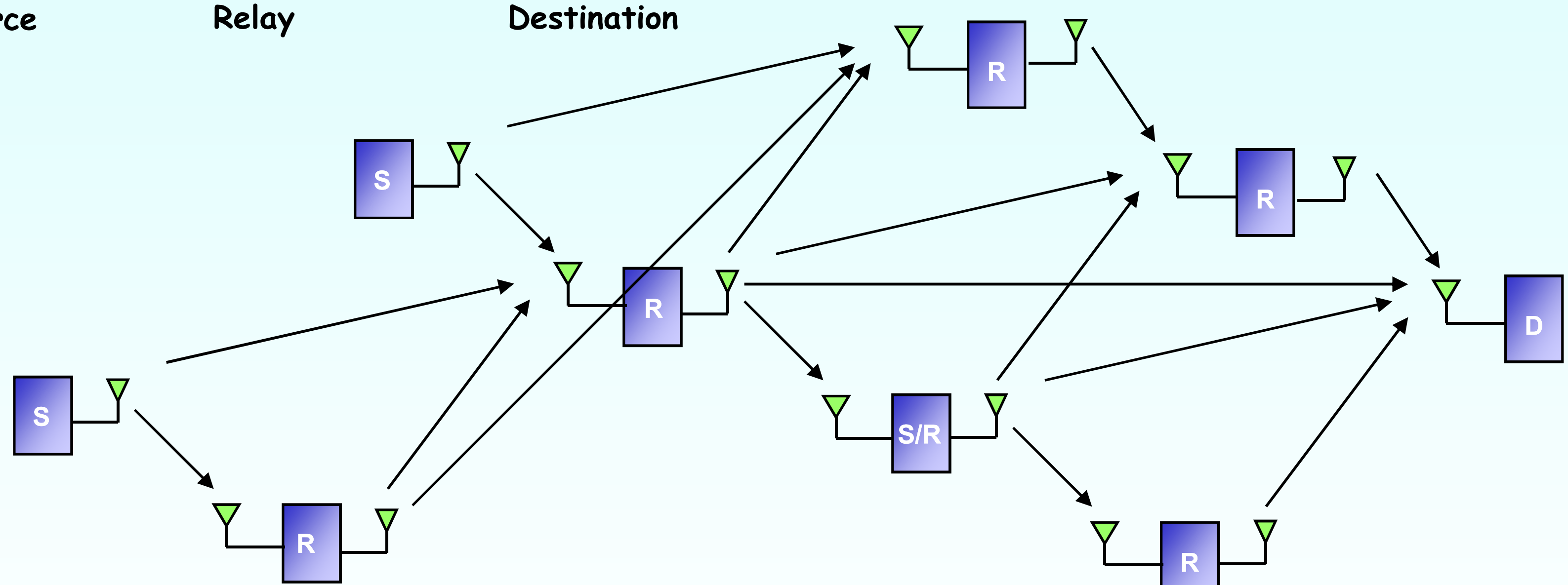
Relaying: New Perspective vs Old Perspective



Conventional relaying: for coverage when high pathloss

Analog/digital dump (non-selective) repeaters

Satellite, microwave, cellular, deep space, …

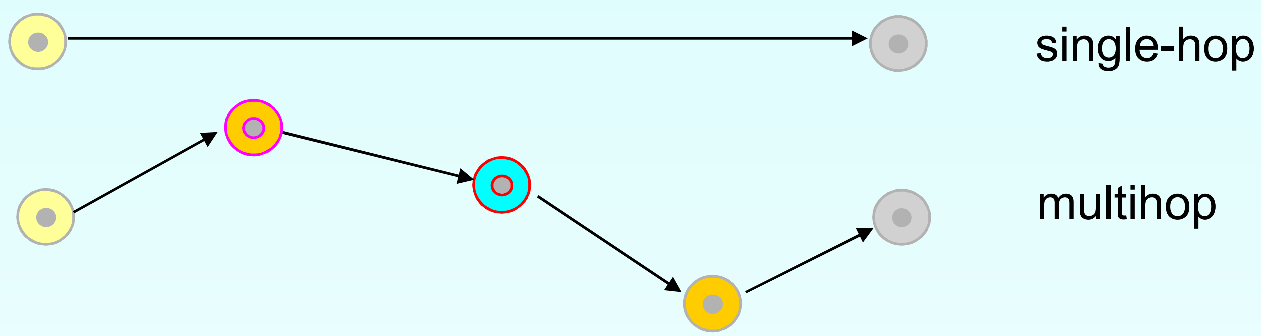


Relay/mesh/multihop networks: for coverage when high data rates (throughput, QoS, …, through cooperation)

Old perspective: inadequate service due to heavy shadowing
→ fixed repeaters (analog, on channel)

New perspective: inadequate service due to high rates
→ fixed/terminal relays (digital/analog, half-duplex, selective, cooperative, smart)

Relaying…



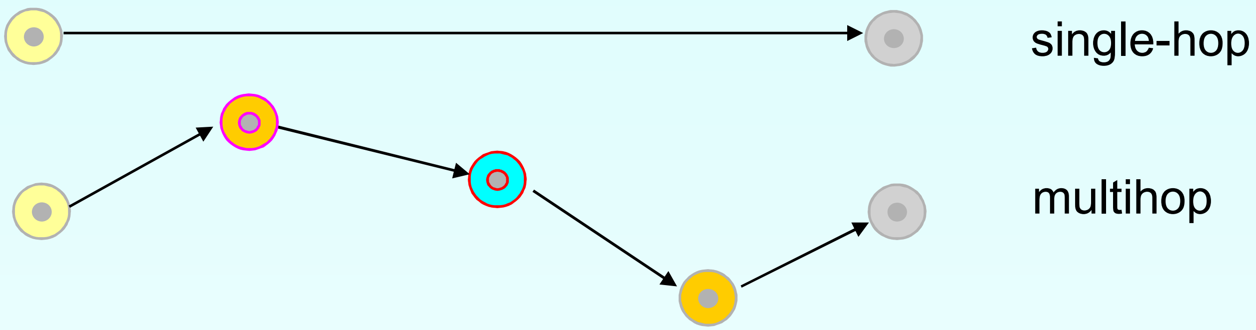
Relaying: paradigm shift in systems level

wired AWGN → wireless fading → wireless mesh

→ Impact in all layers of wireless communications

* propagation
* physical layer (PHY+IT+DSP) [channel capacity, cooperative relaying,…]
* multiple access layer (MAC) [RRM, scheduling, CAC, …]
* networking layer [load balacing, routing, handoff, …]
* higher layers and protocols

Relaying…



Relaying: great interest in academia and industry

* great interest does not necessarily mean successful realization
* new network architecture → network problem
    physical layer: just one element
    MAC, networking, protocols: important
* time to realization:
    TX diversity (Alamouti), turbo codes: 4-5 year
    CDMA: 15 years
    ad hoc networks: ∞
    relaying: will take some time, but will become a reality

Relaying: Comprehensive Investigation Required

Simple example:

- Relaying: links (hops) with less path-loss
  higher spectral efficiency in each link

- Relay: cannot receive and transmit at the same channel (half-duplex)
  2-hop link → 2 channels (time or frequency)
  n-hop link → 2 to n channels

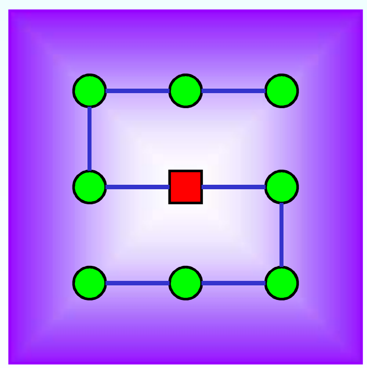
- Capacity gain or loss?

Radio Access Network (RAN)

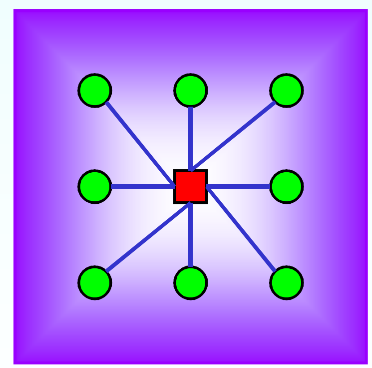
Goal: efficient ways of distributing the signals and collecting them

- Conventional cellular (with cell-splitting)
- Multihop relaying
- DAS: Distributed antenna system (radio-over-fibre, wired relay, microcellular with antenna remoting)
- COMP: Coordinated multipoint transmission; network MIMO
- Femtocell

RAN: key component in B4G/5G
(**advanced RAN needs advanced RRM)**



Distributed Antennas



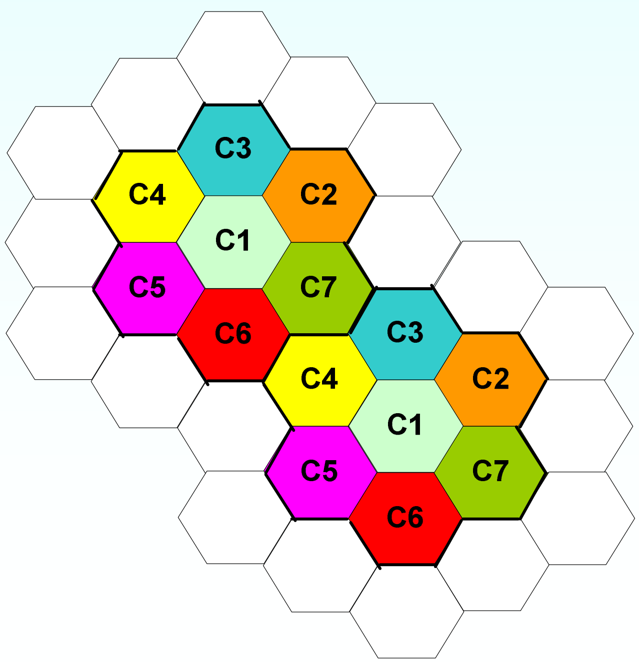
Microcellular Network

Evolution of Cellular RAN

- Large cells → small cells
- Cluster size: 7 → 1
- RNC: for soft handoff in CDMA

Overall, no substantial change in the last 25 years

- More drastic changes in RAN architectures are needed for cost-efficient, ubiquitous high data rate coverage



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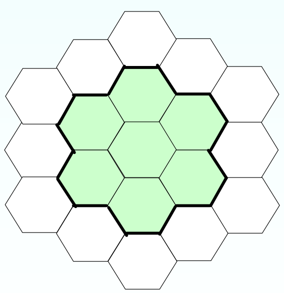
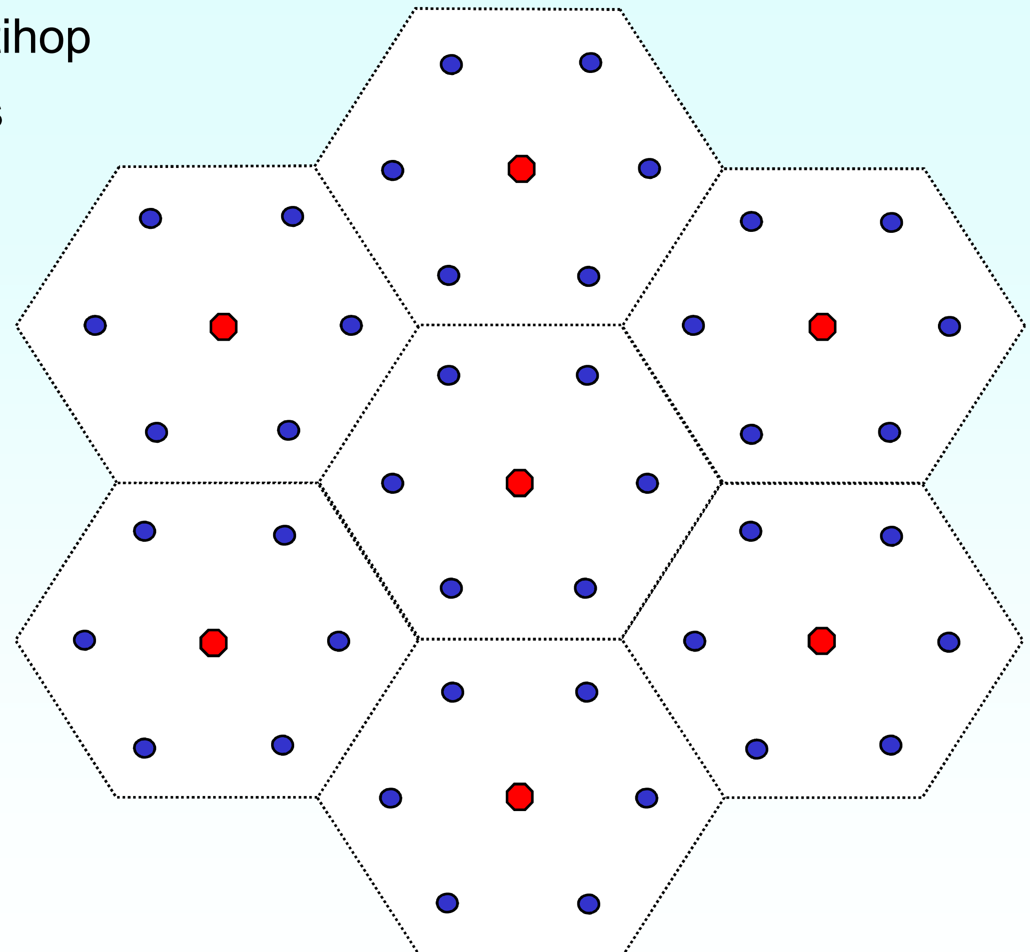


Evolution of Radio Access Network (RAN)

Augmentation of multihop

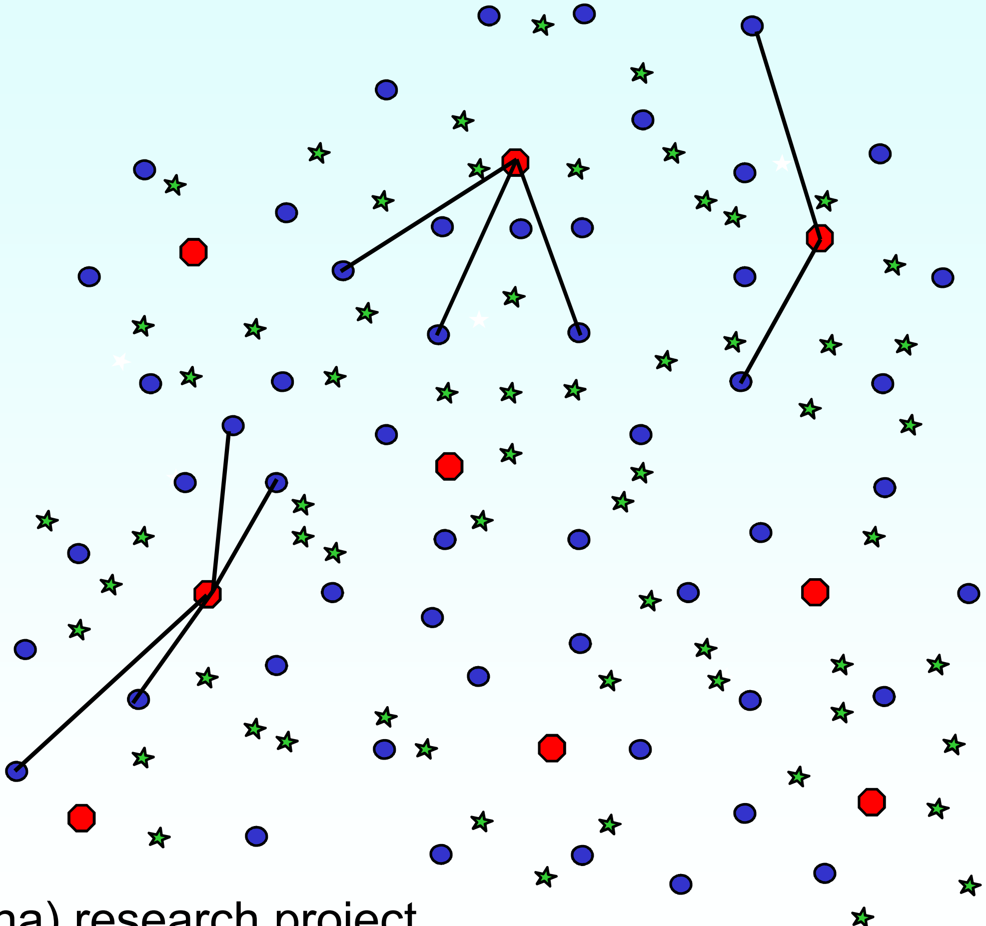
Relay enhanced cells

Fixed relays



Evolution of Radio Access Network (RAN)

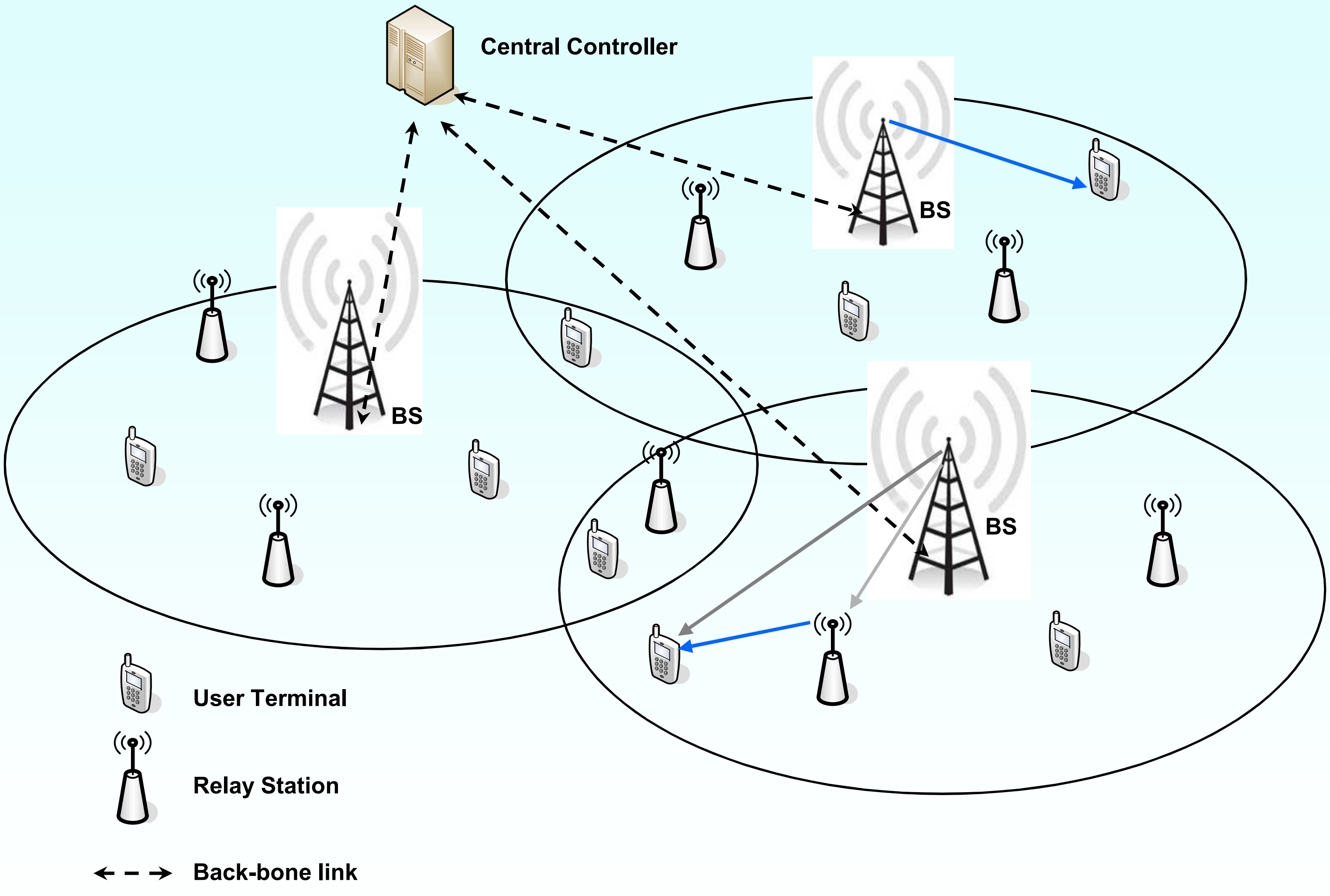
Very different from conventional cellular



- base station
- fixed relay
- nomadic relay
- moving relay
- terminal relay
- distributed antenna

Carleton – Huawei (China) research project

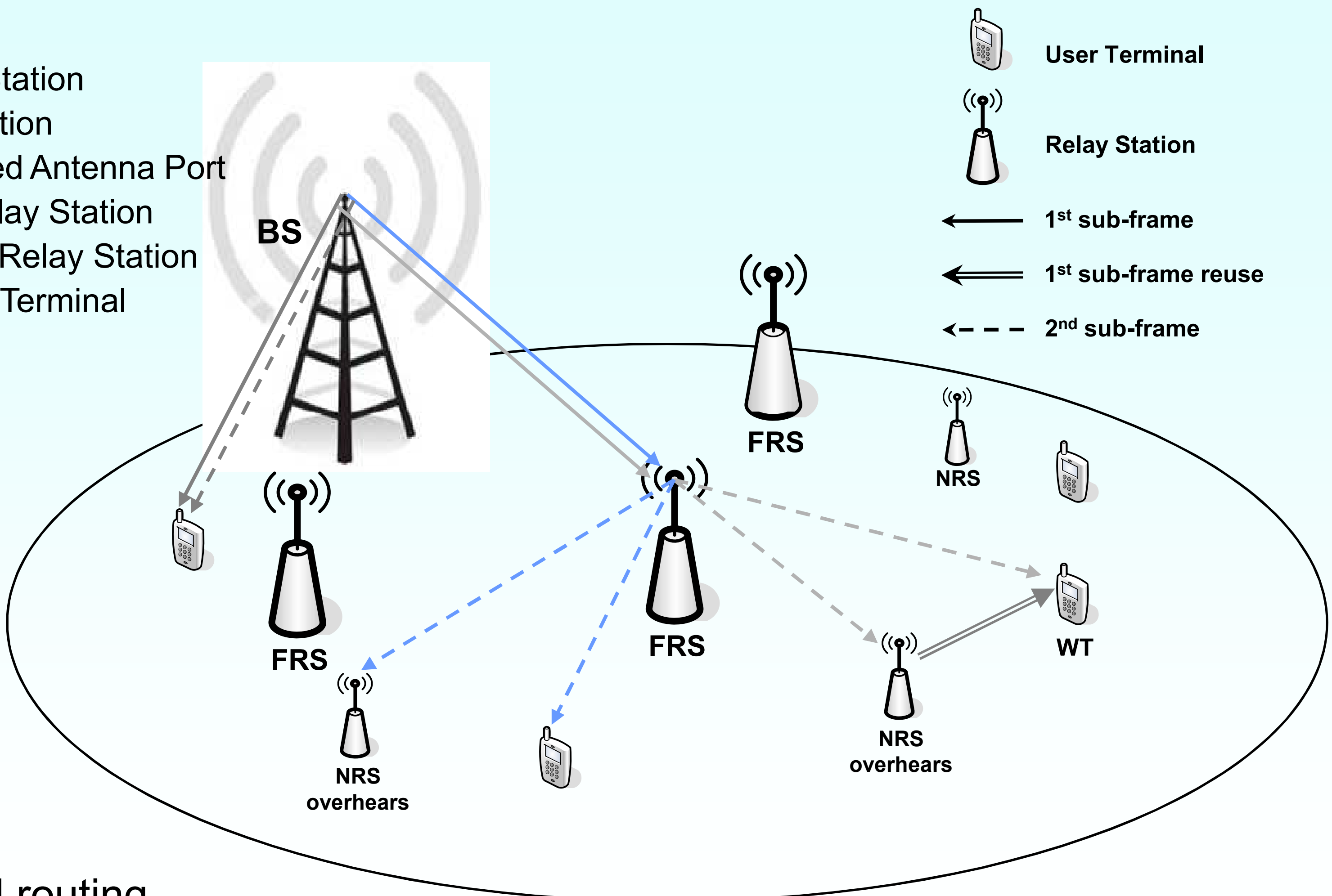
Carleton – Samsung (Korea) research project


Central Controller
BS
BS
BS
User Terminal
Relay Station
Back-bone link

Advanced Cellular RAN Architecture

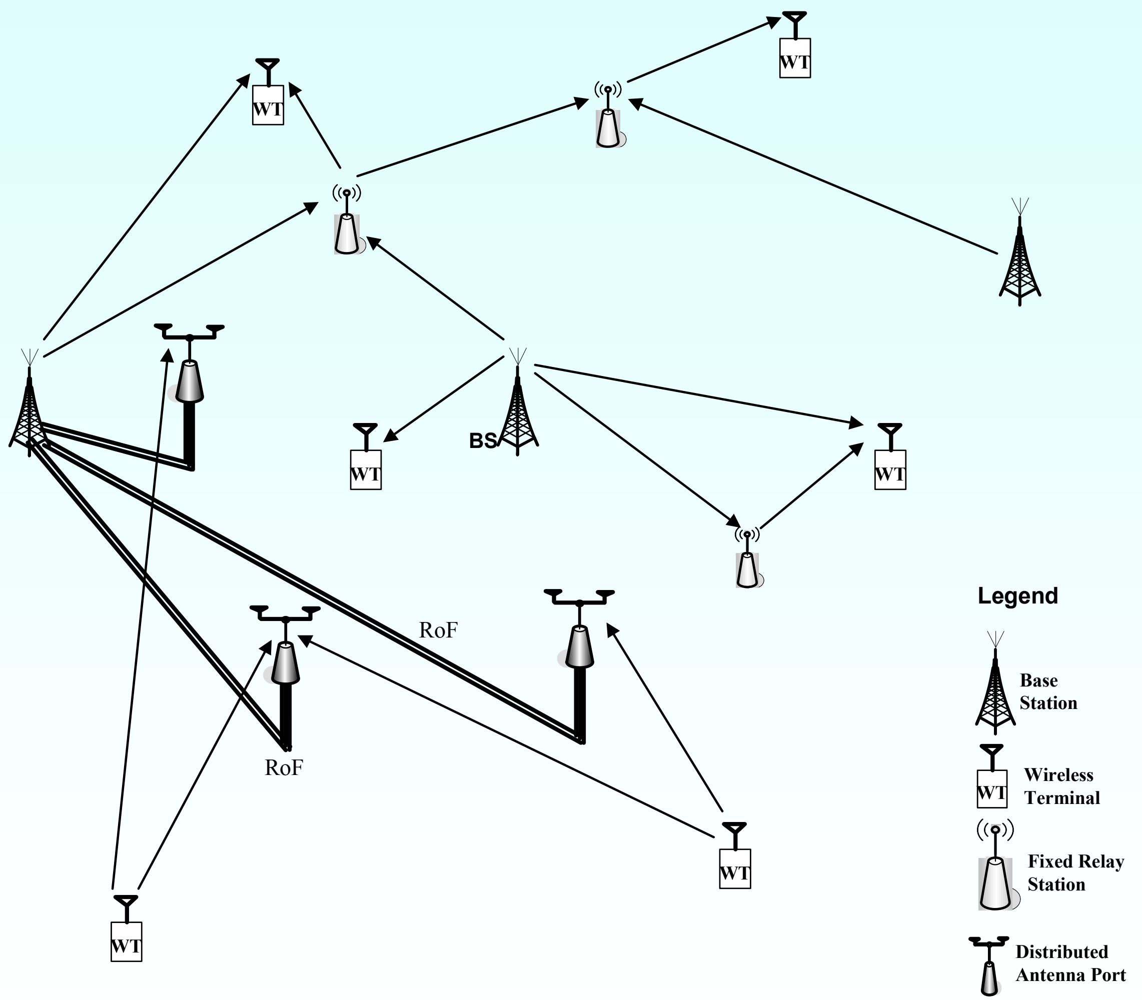
RAN Elements

CS: Central Station
BS: Base Station
DAP: Distributed Antenna Port
FRS: Fixed Relay Station
TRS: Terminal Relay Station
WT: Wireless Terminal



Intra-cell routing

Advanced RAN Architecture



Across network routing

RAN Elements

- BS, DAP: connected to the backhaul through the wired medium (fibre)
- BS, DAP: different in the processing capability and functionality
  - DAP: wired relay with limited functionality (in comparison to full-fledged BSs) in order to achieve cost-effective deployment
- FRS, TRS: do not have wired connection to the backhaul
- FRS: likely to have much more functionality and capability (signal processing, MIMO, security, RRM, etc.) in comparison to a TRS.
- FRS: continuous DC power source from an outlet
- TRS: battery-powered

Co-existence of DAPs and FRSs

- Main argument for FRS: deployment cost advantage (in comparison to micro-BS)
- Even if

  complexity & functionality of FRS = complexity & functionality of BS,

  FRS is still cost-effective because it does not require wired backhaul
- On the other hand, fiber penetration is relatively high in certain parts of the world (such as South East Asia), and this penetration is increasing

  → DAP may be a better choice than FRS if fibre is readily available
- DAPs and FRSs may coexist in the same network
- RRM makes all network elements work together

Advanced RAN with Advanced RRM

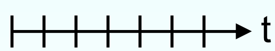
- Any fixed assignment is inefficient
  - cannot adapt to or exploit channel conditions
- All decisions are dynamic and opportunistic
  - No a-priori partitioning of radio resources
  - No WT-BS assignment (dynamic routing in the mesh)
- Reuse may be > 1
- Wired elements (BS, DA) and fixed relays:
  Cooperative RRM for interference management and avoidance
- Nomadic, moving, and terminal relays:
  Robust, distributed, plug-and-play, low-overhead, sub-optimum RRM algorithms
  → cognitive radio (spectrum, OSA), dynamic feedback control, machine learning, artificial intelligence → inter-disciplinary
- Very different from conventional cellular networks

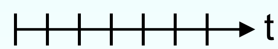
Evolution of RRM

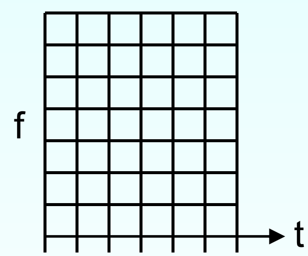
single-cell → (multi-cell) across network

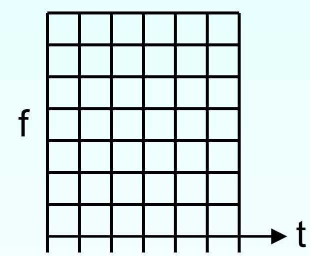
single carrier → OFDMA

fixed assignment → opportunistic assignment → dynamic power control AMC









time-channel assignment (scheduling)

power and AMC assignment

time-channel and sub-carrier assignment with fairness

time-channel, sub-carrier and geographic reuse assignment with fairness

Assignment Problems

Centralized Coordination in RRM

- Advantages
  - Potentially superior performance
- Disadvantages
  - Computational complexity and cost
  - Spectrum overhead (for CSI transmission)
  - Wired backbone overhead
  - Latency
  - Scalability

Distributed Cooperation in RRM

- Advantages
  - Low latency
  - Low complexity
  - Low overhead
  - Scalability

- Disadvantages
  - Potential performance loss
  - Robustness, stability, and convergence concerns

Partly Centralized and Partly Distributed RRM

- Wired elements (BS, DAP, FRS)
  → centralized coordination
  Coordinated RRM for interference management and avoidance

- Wireless elements (TRS, nomadic relay, moving relay)
  → distributed cooperation
  Robust, distributed, plug-and-play, low-overhead, efficient RRM
  Cognitive radio (opportunistic spectrum access): important

- Cellular FRS: (more) centralized
  Mesh FRS: (more) distributed

Feedback (Channel-State Information)

- Dynamics of L2 & L3 feedback are different than dynamics of L1 feedback
  - RRM algorithms are robust wrt imperfect CSI
  - RRM algorithms are robust wrt less frequent CSI

Enabling Concepts and Analytical Tools

- Optimization
  - Essential tool
- Cognitive Radio
  - with which TRSs to cooperate, to what extent, and in which capacity
  - when to transmit, at which subcarriers, and at what power levels
  - which DAP or FRS or BS to connect to
- Game Theory
- Machine Learning
- Dynamic Feedback Control
- Artificial Intelligence

} unconventional concepts

Concluding Remarks (Part I)

- NET (wireless IP) and CS (abstract) researchers vs PHY researchers
  Lack cross-layer design view

- L1: 60 years of research, tremendous background [ex: log(1+SNR)]
  Matured analytical tools, part of undergrad and grad curriculum

- RRM research: started much later
  Cellular architecture: mid-1970's
  RAN and protocols: simple (until recently)
  Power control: early/mid-1990's
  OFDMA RRM in conventional RAN: late 1990's → ongoing
  Advance RAN + advance RRM: in its infancy
  Some analytical tools (operations research, optimization): not part of u/g ECE and grad communications curricula

- L1: mature; returns: in the order of 1 dB (channel coding: 0.1 dB)
  L2, L3, X-L: not mature yet; returns: possibly substantial

- Cost-efficient and virtually ubiquitous ultra-high data rate coverage:
  Advanced RAN + advanced RRM
  Highly-complex cross-layer and across-network design
  Substantial research and performance enhancement opportunity

Tutorial/Overview/Perspective Papers on RAN and RRM

- Petar Djukic, Halim Yanikomeroglu, and Jietao Zhang, “User-centric RRM and optimizable protocol design for beyond-4G RANs”, *WWRF22 Meeting*, 5–7 May 2009, Paris, France.

- Halim Yanikomeroglu and Jietao Zhang, “Beyond-4G cellular networks: advanced radio access network (RAN) architectures, advanced radio resource management (RRM) techniques, and other enabling technologies”, *WWRF21 Meeting*, 13–15 October 2008, Stockholm, Sweden.

Tutorial/Overview/Perspective Papers

- H. Yanikomeroglu "Fixed and mobile relaying technologies for cellular networks", *Second Workshop on Applications and Services in Wireless Networks (ASWN'02)*, pp. 75-81, 3-5 July 2002, Paris, France.

- H. Yanikomeroglu, "Cellular multihop communications: infrastructure-based relay network architecture for 4G wireless systems", *the 22nd Queen's Biennial Symposium on Communications (QBSC'04)*, 1-3 June 2004, Queen's University, Kingston, Ontario, Canada; invited paper.

- R. Pabst, B. H. Walke, D. C. Schultz, P. Herhold, H. Yanikomeroglu, S. Mukherjee, H. Viswanathan, M. Lott, W. Zirwas, M. Dohler, H. Aghvami, D. D. Falconer, and G. P. Fettweis, “Relay-based deployment concepts for wireless and mobile broadband radio”, *IEEE Communications Magazine*, vol. 42, no. 9, pp. 80-89, September 2004.

- R. Bruno, M. Conti, and E. Gregori, “Mesh networks: commodity multihop ad hoc networks”, *IEEE Communications Magazine*, vol. 43, vol. 3, pp. 123-131, March 2005.

PART II: Relaying – A Closer Look

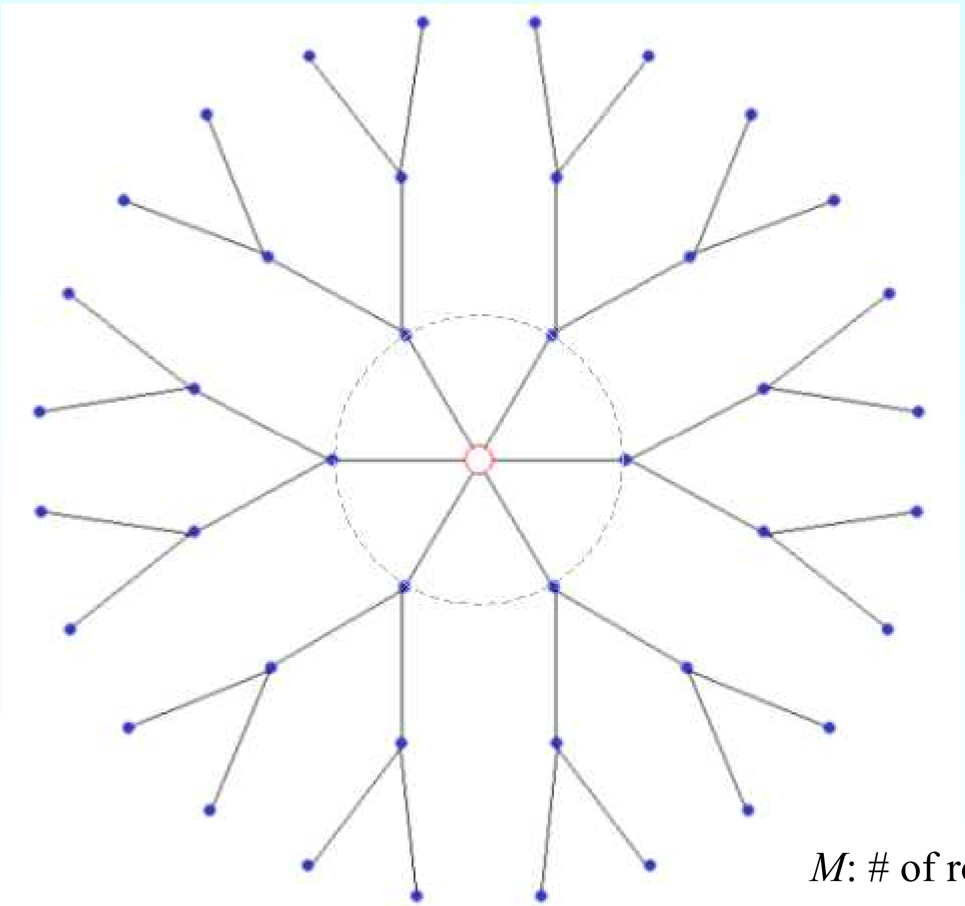
- What can relaying offer
- When to relay
- Who relays
- How to relay (types of relaying and protocols; cooperation, diversity)
- What to do at destination

What can relaying offer?

How much aggregate capacity (throughput) improvement does relaying offer?

- The most advanced RAN with all types of relays
- The most advanced RRM
- The most advanced cooperation schemes

Capacity of Cellular Fixed Relay/Mesh Networks



o : Central Node (CN)

• : Relay

—— : Wireless Link

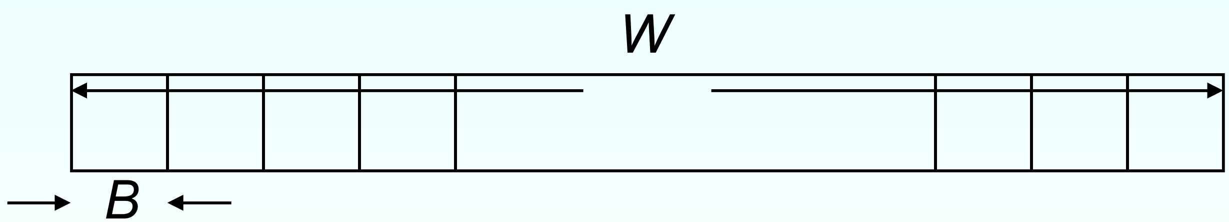
- Only CN is connected to the backhaul
- No Tx & Rx on the same channel for a relay
- Nodes have two kinds of antenna
- Direct link with only the neighbor nodes
- Same BW for each primary link

M: # of root nodes (trees)

N: # of nodes per tree

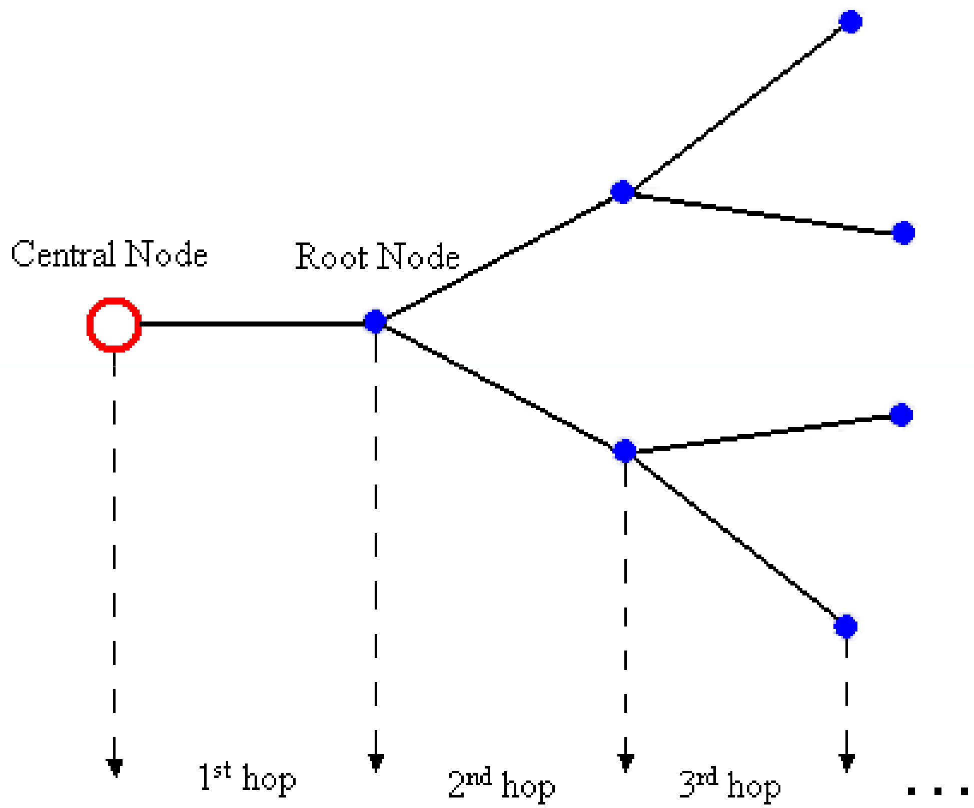
MN+1: # of nodes per cell

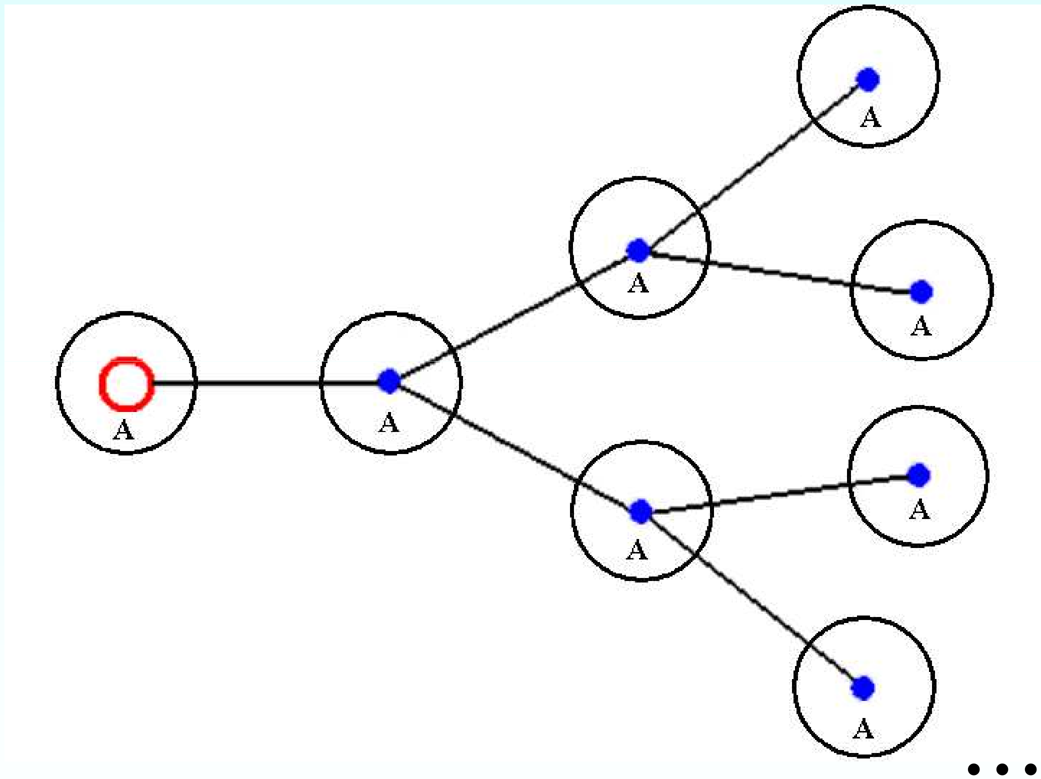
W (Hz) : Total available bandwidth for a cell
B (Hz) : Available bandwidth for a relay
R_{CCN} (bits/sec) : Capacity of the Conventional Cellular Network (CCN)
R_{CFRN} (bits/sec) : Capacity of the Cellular Fixed Relay Network (CFRN)
R_B : Capacity of a relay
M : Number of the root nodes
N : Number of nodes of a tree



$R_{CCN} = R_W$: Capacity of CCN is a function of W

$$R_{CFRN} = (M.N+1)R_B \approx M.N.R_B$$


Central Node
Root Node
1st hop
2nd hop
3rd hop
. . .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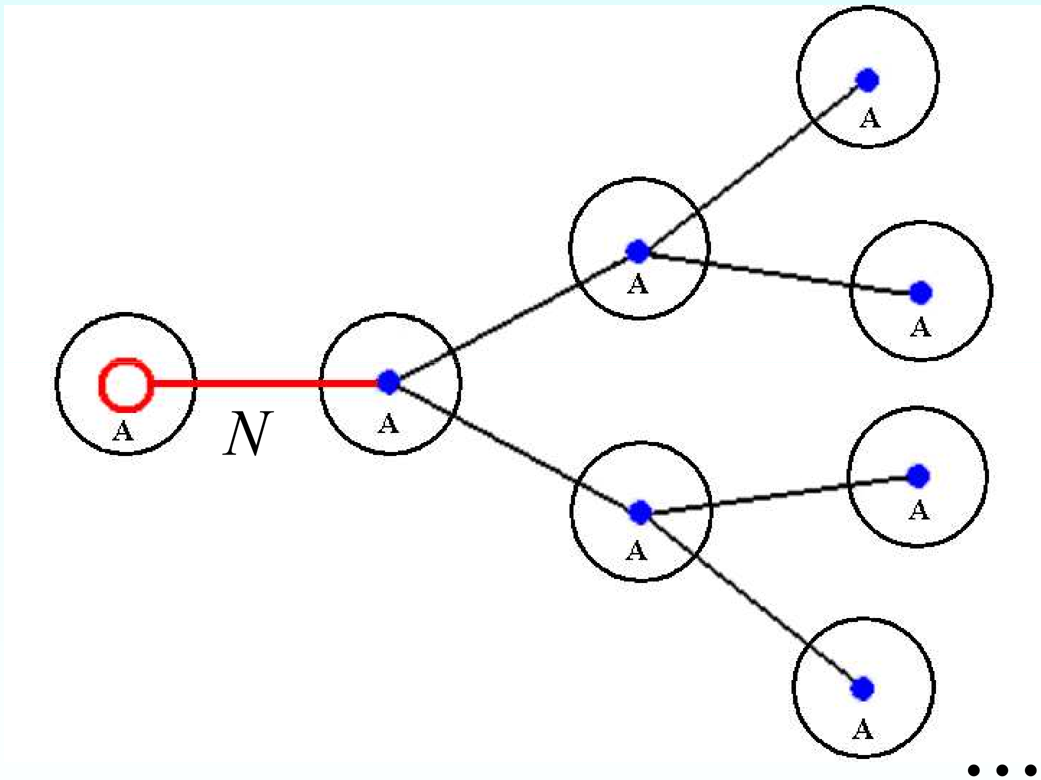
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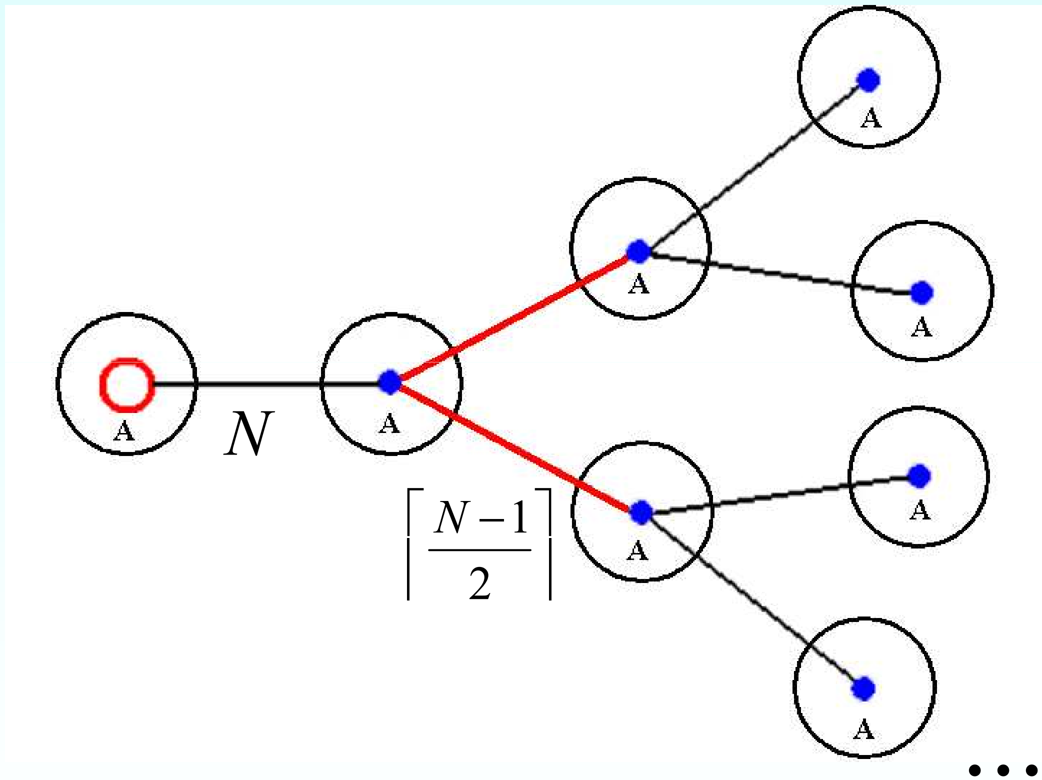
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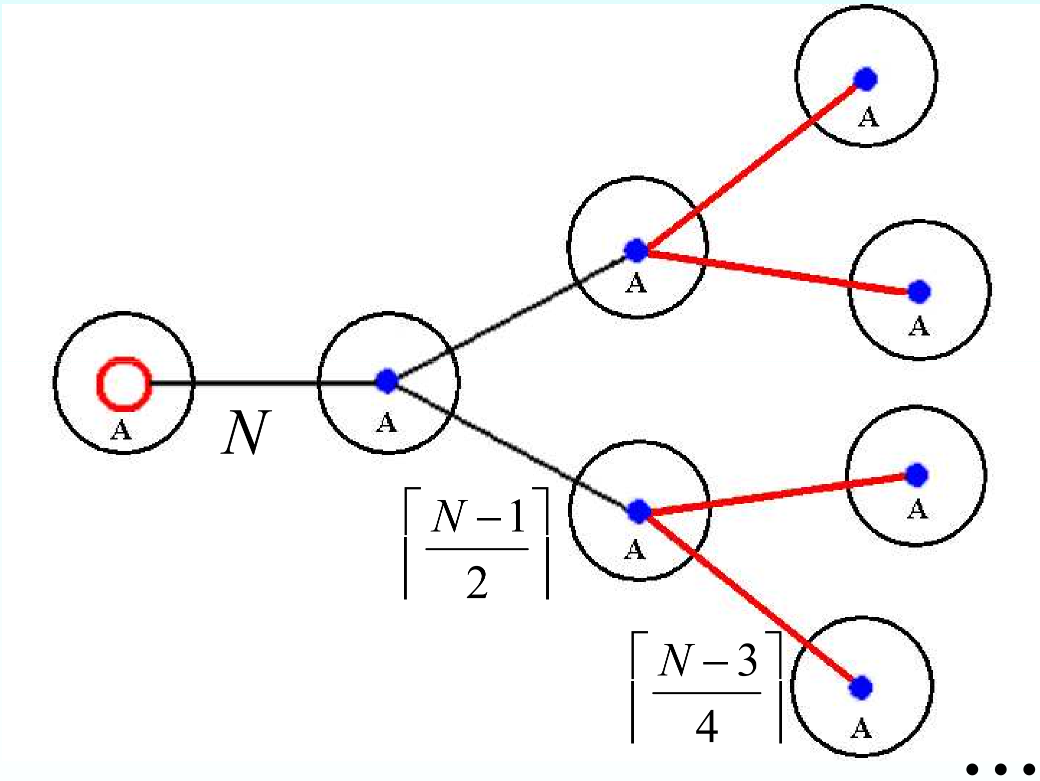
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$\left\lceil \frac{N-3}{4} \right\rceil$
• • •

Total Number Channel Groups: $$W / B = N + \left\lceil \frac{N-1}{2} \right\rceil + 1$$

$$\Rightarrow W = \left\{ N + \left\lceil \frac{N-1}{2} \right\rceil + 1 \right\} B$$

$$\Rightarrow R_W = \left\{ N + \left\lceil \frac{N-1}{2} \right\rceil + 1 \right\} R_B$$

Previously it is stated that: $R_{CFRN} \approx M.N.R_B$

Then, $$\Rightarrow R_{CFRN} \approx \left(\frac{N}{N + \left\lceil \frac{N-1}{2} \right\rceil + 1} \right) (M.R_W)$$

$$\Rightarrow R_{CFRN} \approx \left(\frac{2}{3} \right) (M.R_W)$$

In general, if each node has p child nodes:

$$R_{CFRN} \approx \frac{p}{p+1}(M.R_W) = \frac{p}{p+1}(M.R_{CCN})$$

Total number channel groups when all the hop links use orthogonal channel groups:

$$N_T = N + \sum_{k=2}^{q} \left(\frac{N - \left(\frac{p^{k-1} - 1}{p-1} \right)}{p^{k-1}} \right) + 1 = N + N \sum_{k=2}^{q} \frac{1}{p^{k-1}} - \sum_{k=2}^{q} \frac{p^{k-1} - 1}{p^{k-1}(p-1)} + 1$$

Then:

$$R_{CFRN} \approx \left[\lim_{N \to \infty} \left(\frac{N}{N + N \sum_{k=2}^{q} \frac{1}{p^{k-1}} - \sum_{k=2}^{q} \frac{p^{k-1} - 1}{p^{k-1}(p-1)} + 1} \right) \right] (MR_W) = \frac{p-1}{p} (MR_W)$$

Capacity Comparisons

- When every other 'hop' links reuse the same channel groups:

$$R_{CFRN} \approx \frac{p}{p+1}(M.R_{CCN})$$

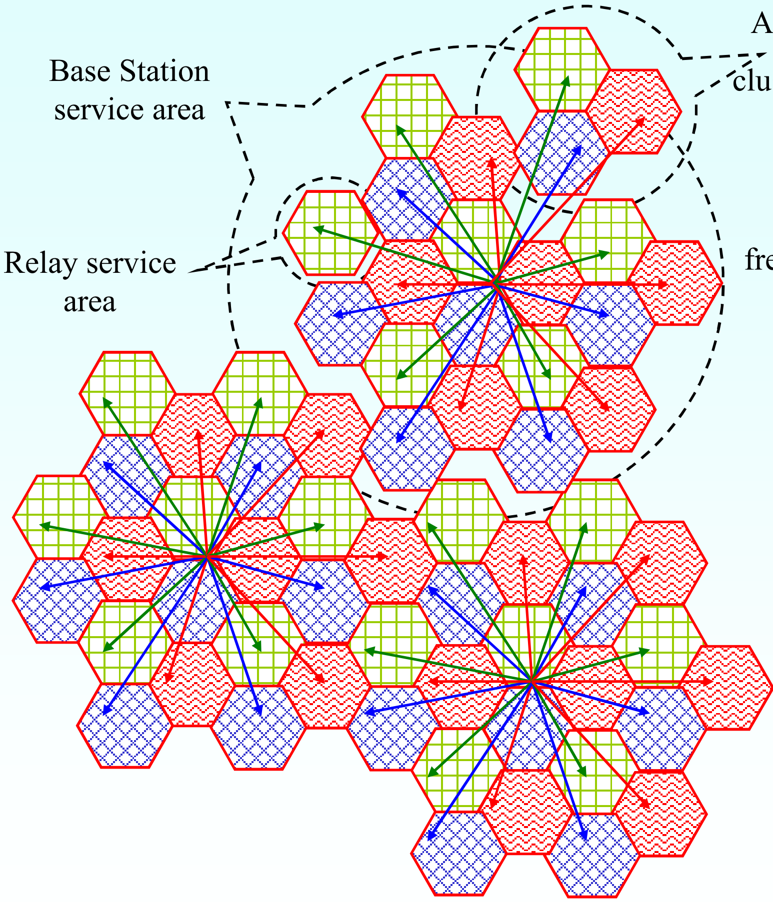
- When all of the links use orthogonal channel groups:

$$R_{CFRN} \approx \frac{1}{\log_p(N+1)+1}(M.R_{CCN})$$

Bandwidth Allocation to Access and Feeder Systems

Florea, Yanikomeroglu

IEEE WCNC'06



B_T: Total BW

B_A: total Access BW

B_F: total Feeder BW

B_a: access BW for each relay

B_f: feeder BW for each relay

μ_a: spectral efficiency for access

μ_f: spectral efficiency for feeder

n_r: number of relays

$$B_T = B_A + B_F$$

$$B_A = NB_a$$

$$B_F = n_r B_f$$

$$B_f \mu_f = B_a \mu_a$$

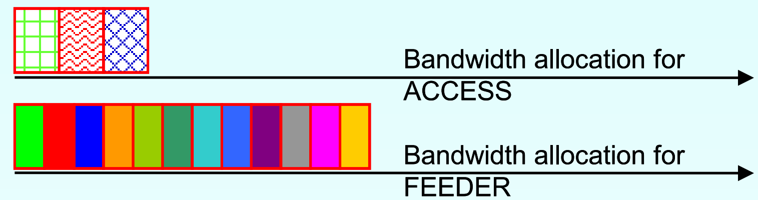
Bandwidth Allocation to Access and Feeder Systems

$$\frac{B_A}{B_T} = \frac{1}{1 + \frac{n_r}{N}\frac{\mu_a}{\mu_f}}$$

access portion

$$\frac{B_F}{B_T} = \frac{1}{1 + \frac{N}{n_r}\frac{\mu_f}{\mu_a}}$$

feeder portion



if $n_r \rightarrow \infty$, then $B_A/B_T \rightarrow 0$ and $B_F/B_T \rightarrow 1$

Throughput: $T = n_r B_a \mu_a = \dfrac{B_T}{\dfrac{N}{n_r \mu_a} + \dfrac{1}{\mu_f}}$

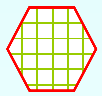
if $n_r \rightarrow \infty$, then $T \rightarrow \mu_f B_T$

Ex: $n_r = 25$, $\mu_f = 4$, $\mu_a = 2$

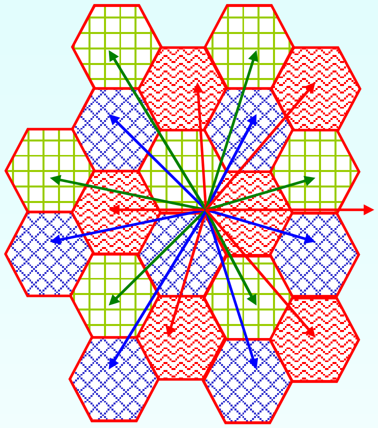
	access, feeder	throughput
$N = 3$	19%, 81%	$3.2\ B_T$
$N = 1$	7%, 93%	$3.7\ B_T$

Bandwidth Allocation to Access and Feeder Systems

Why to use relays?



→



100 Mbps – only in this small area

67 Mbps – in a much larger area

Cellular Relay Network vs Conventional Cellular Network

Potential capacity = $n\ W \log(1+SNR)$: remains more or less the same

Usable capacity: increases (outage decreases) due to better coverage

Relays distribute the total capacity throughout the coverage region

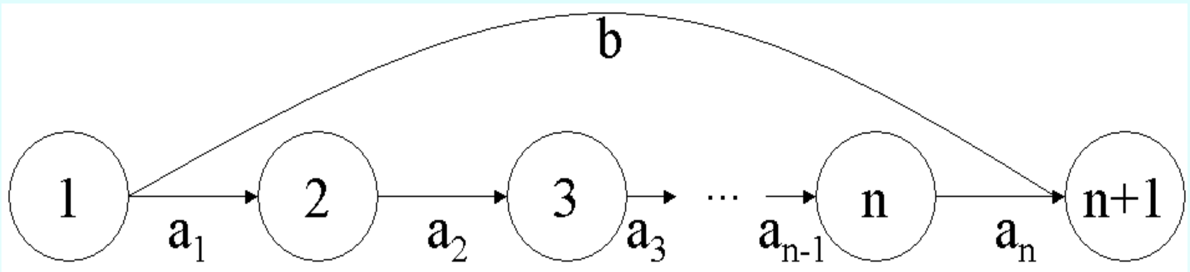
	Relay Network	Cellular Network
Cost-effective high data rate coverage	excellent	moderate
Capacity (aggregate throughput)	moderate	excellent

Rule of Thumb in Design:

* Deploy as many BSs/APs as needed according to capacity demand

* Then distribute the capacity in the coverage region evenly using as many relays as needed

Spectral Efficiency of n-hop Link with Orthogonal Channels



b : spectral efficiency of single-hop link

a_i : spectral efficiency in hop i

a_c: net (overall) spectral efficiency of n-hop link

M: message size

W: bandwidth

T: message transfer time

$$T_{MH} = T_1 + T_2 + \ldots + T_n \quad \text{(assuming orthogonal channels)}$$

$$T_{MH} = M/(Wa_1) + M/(Wa_2) + \ldots + M/(Wa_n) = M/(Wa_c)$$

$$a_c = \frac{1}{\frac{1}{a_1} + \frac{1}{a_2} + \frac{1}{a_3} + \ldots + \frac{1}{a_n}}$$

Multiplexing Loss in Multihop Relaying with Orthogonal Channels

- When does it make sense to break a single-hop into multiple hops?

- Low SNR case

  Single-hop with 4 dB SNR → ½-rate QPSK: 1 b/s/Hz

  Two hops each with 12 dB SNR → ¾-rate 16-QAM: 3 b/s/Hz

  Net spectral efficiency: 1.5 b/s/Hz → use multihop

- High SNR case

  Single-hop with 26 dB SNR → full-rate 64-QAM: 6 b/s/Hz

  Two hops each with 34 dB SNR → 128-QAM: 7 b/s/Hz

  Net spectral efficiency: 3.5 b/s/Hz → use single-hop

Rule of thumb: low SNR → multi-hop
high SNR → single-hop

opportunistic relaying

Multi-Hop Criterion

Florea, Yanikomeroglu
IEEE Globecom'05

If single-hop SNR (γ) satisfies

$$\gamma < \frac{(n+1)^{pn}}{n^{p(n+1)}}$$

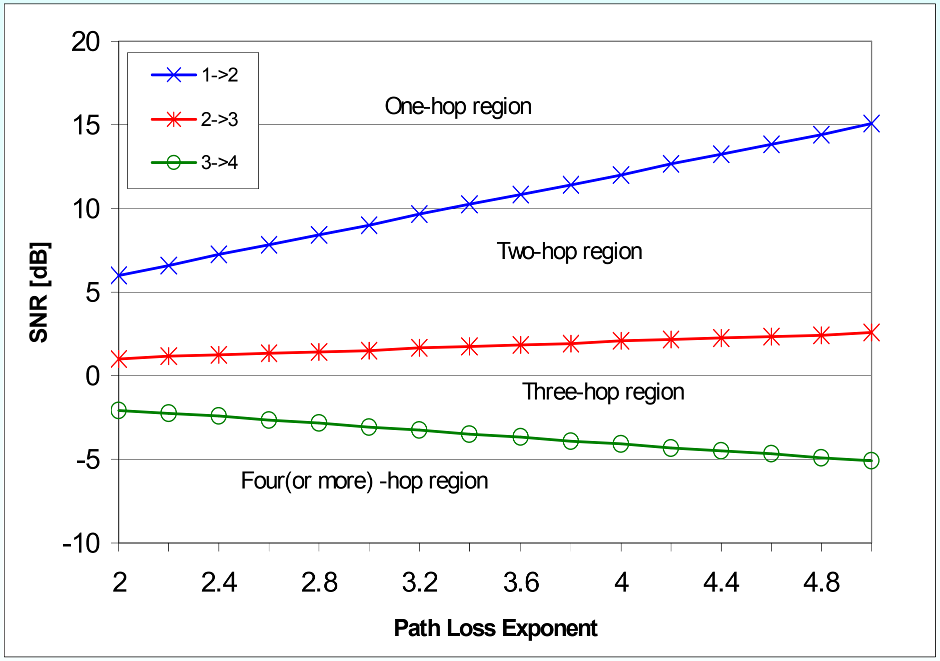
then

[*net spectral efficiency*]$_{n+1}$ >
[*net spectral efficiency*]$_{n}$

- *n* - number of hops
- *p* - path loss exponent

Assumptions:

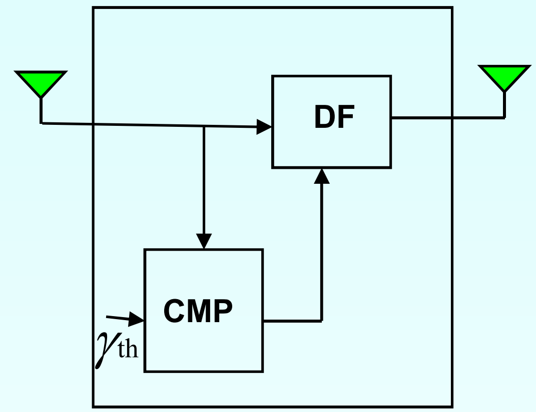
- all links have same path loss exponent *p*
- All relays are placed uniformly on a in straight line from source to destination



SNR values under which there exists a (*n+1)*-hop link with better spectral efficiency compared with an *n*-hop link

Analog Relaying vs Digital Relaying

- Digital relaying (router, bridge)
  Regenerative relaying
  Decode-and-forward (detect-and-forward) relaying
  Adaptive (selective) decode-and-forward



digital relay

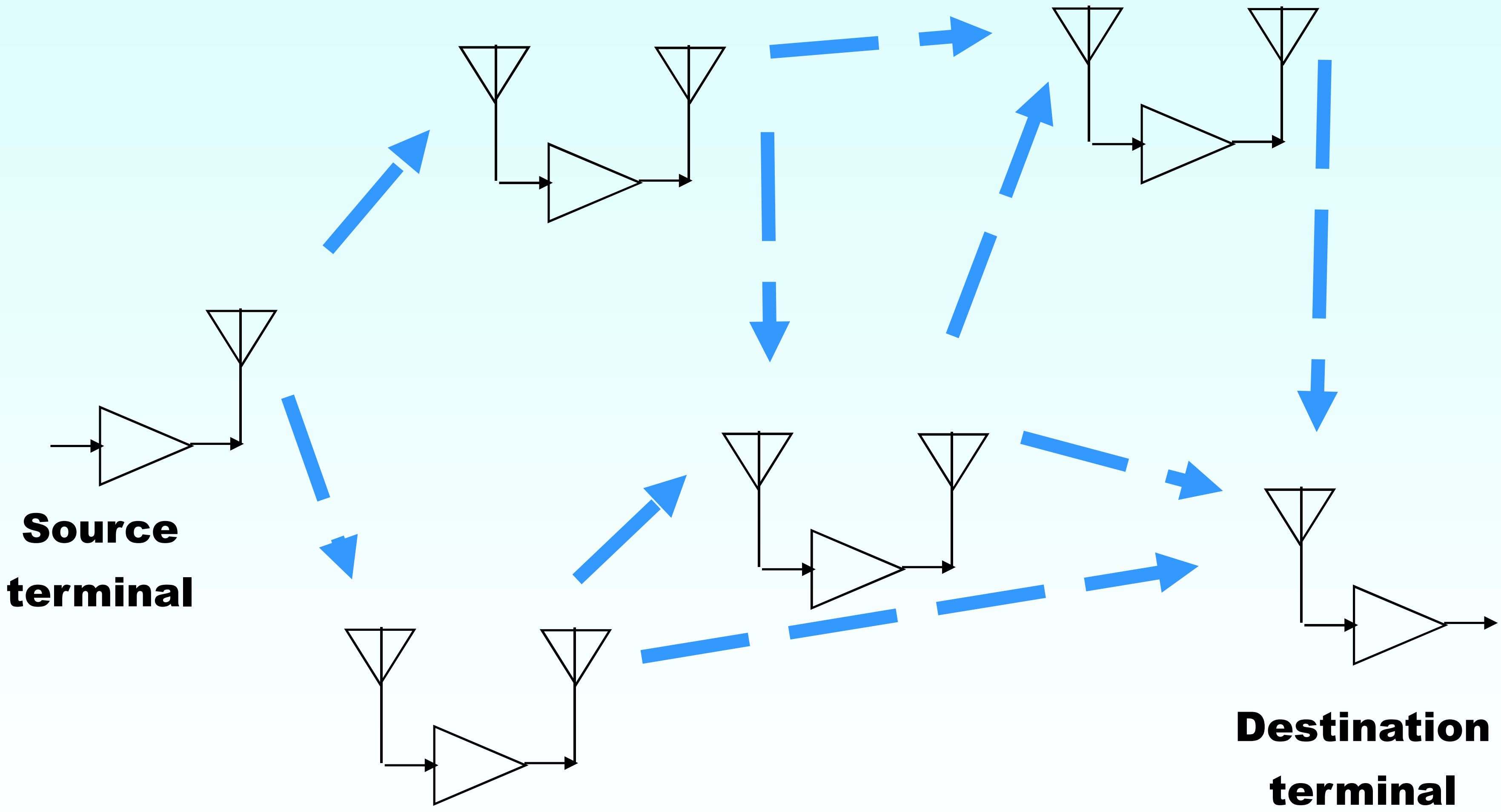
- Analog relaying
  Non-regenerative relaying
  Amplify-and-forward relaying
  - On channel
  - With frequency translation

- Process-and-forward relaying

- Analog relaying → noise propagation
  Digital relaying → error propagation

- Analog relaying may be better than digital relaying in certain scenarios
- Hybrid analog/digital relaying: another possibility

Amplified Relaying

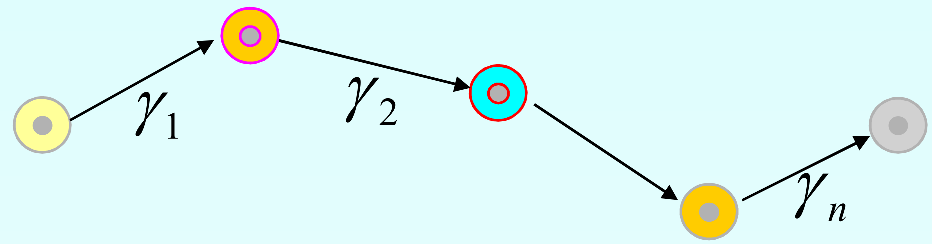


Analog Relaying

Non-regenerative relaying
Amplify-and-forward relaying

- Rationale: simplicity (was the case 20 years ago)
- Interest in the literature: partly due to easier analysis!
- Not very suitable for exploitation above the physical layer
- Digital relaying: better option in many scenarios
- New context for analog relaying: sensor networks

Analog Relaying – E2E SNR



$$\gamma_{E2E,2} = \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2 + 1}$$

$$\gamma_1 << \gamma_2 \rightarrow \gamma_{E2E,2} \approx \gamma_1$$

Hasna & Alouini

$$\gamma_{E2E,3} = \frac{\gamma_1 \gamma_2 \gamma_3}{\gamma_1 \gamma_2 + \gamma_1 \gamma_3 + \gamma_2 \gamma_3 + \gamma_1 + \gamma_2 + \gamma_3 + 1}$$

$$\gamma_1 << \gamma_2, \gamma_1 << \gamma_3 \rightarrow \gamma_{E2E,2} \approx \gamma_1$$

$$\gamma_{E2E,n} = \frac{\prod_i \gamma_i}{\prod_i (\gamma_i + 1) - \prod_i \gamma_i}$$

Analog Relaying – Advantageous Scenarios

Hammerstroem, Rankow, Wittneben

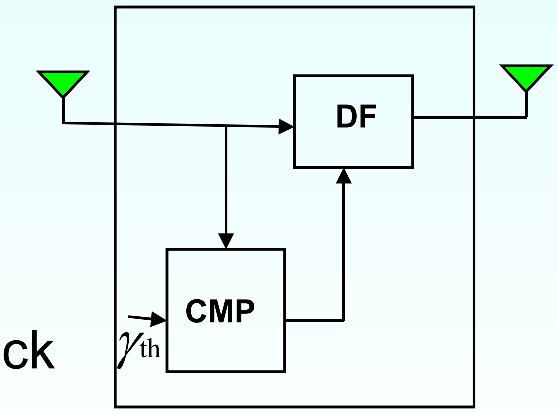
- Heterogeneous networks
  - Analog relaying: transparent to air-interface and the # of tx & rx antennas
- Single-antenna analog relays: active scatterers in a rank-deficient MIMO system
  - Digital relaying will result in rate loss
- Cooperative beamforming over orthogonal transmission (2nd hop)
  - Advantages:
    - No bandwidth (multiplexing) loss
    - Array gain in addition to diversity gain
  - Disadvantages:
    - CSI of both hop channels needed
    - Global phase reference needed (not easy!)

Digital Relaying

Regenerative relaying

Decode-and-forward (detect-and-forward) relaying

- Digital relaying: causes error propagation
  → adaptive (selective) decode-and-forward
- Threshold-based symbol-by-symbol relaying assumption
- CRC-based adaptive (selective) block-by-block relaying: more realistic



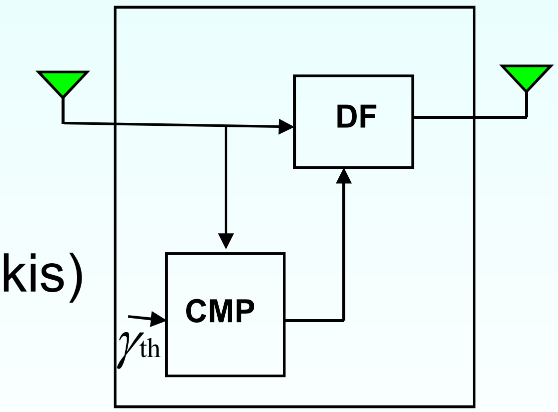
threshold-based selective digital relay

Digital Relaying – Error Propagation

- Threshold relaying
  (Atay Onat, Yanikomeroglu, et al.
  IEEE TWireless Nov'08, *IEEE TWireless* Dec'08)

- Complex receiver (Laneman)

- Link-adaptive relaying – LAR (Wang, Giannakis)



threshold-based selective digital relay

Fixed Relaying vs Terminal/Mobile Relaying

- Terminal relaying: rich theoretical area, full of potentials

- But, many technical challenges
  - No service guarantee
  - Increased energy consumption (fast battery draining)
  - Increased transmit power (in CDMA)
  - Additional hardware and functionality (higher terminal cost)
  - Security issues
  - Frequent hand-offs (especially in the presence of high mobility)

- Terminal relaying: any incentives?
  - Special applications: single team (law-enforcement, military, rescue)
  - Cooperative relaying with simultaneous mutual benefits (symmetric cooperation)
  - Personal area networks
  - Commercial applications: business plan needed (air time offers?)

- Ad hoc networks (infrastructureless): no internet connection!

Fixed Relaying vs Terminal/Mobile Relaying

- Routing: easier in infrastructure-based multihop networks than infrastructureless ad hoc multihop networks
  - Nodes with extra complexity and intelligence (BS/AP or fixed relays)
  - Common source or destination

  → Routing with more demanding goals: possible

- Expectations in 4G networks:
  - first, fixed relays
  - then, mobile/terminal relays

- Single-hop (infrastructureless) ad hoc networks: possible

  Multihop (infrastructureless) ad hoc networks: commercially difficult!

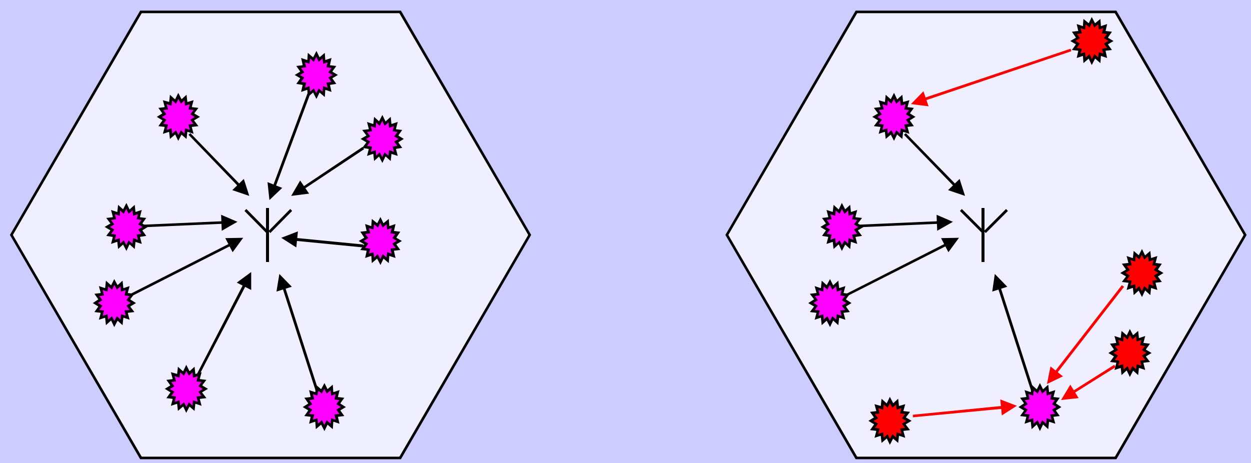
Heterogeneous (vs Homogeneous) Relaying

- Decoupling of access and backbone networks
  - Access: air interface A
  - Backbone (feeder): air interface B
- Customized air interfaces
- Easier interference management
- License-exempt bands can be utilized

Power Control

Walsh, Yanikomeroglu
IEEE CCECE'04

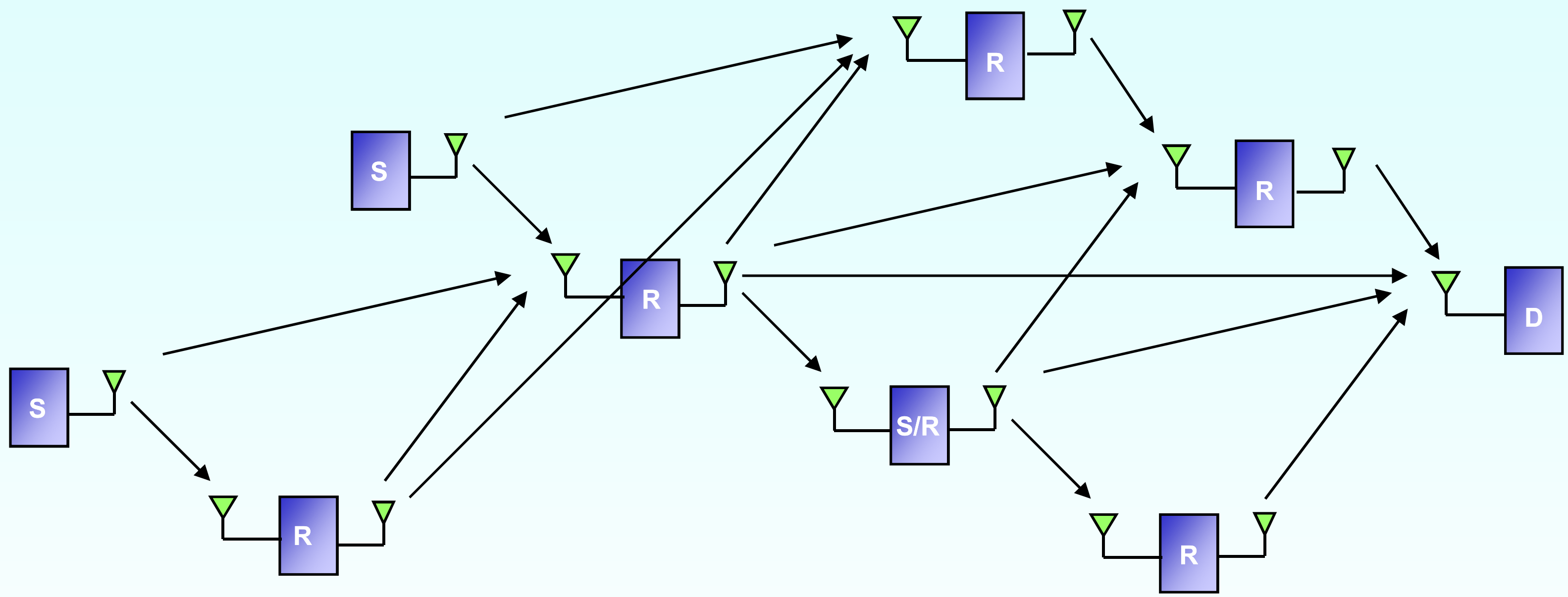
Becomes important again with dense channel reuse…



Single-hop PC

Two-hop PC

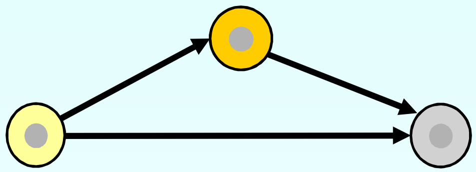
Cooperation Opportunities



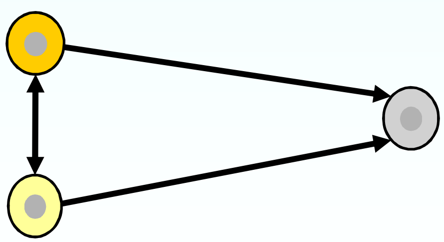
Cooperative relaying → virtual antenna array:
diversity, space-time coding, MIMO, …

Asymmetric vs Symmetric Cooperation

- Asymmetric Cooperation: relay terminal between source and destination
  - Only one terminal benefits
  - Pathloss gain



- Symmetric Cooperation: a pair of nearby terminals cooperate
  - Immediate benefit for both terminals
  - No pathloss gain



Early Com/Info-Theoretic Literature on Cooperative Communications

- Van der Meulen (68,71)
- El Gamal, Cover, Aref (79,80,82) [Stanford]
- Willems (83,85)

- Sendonaris, Erkip (98-…) [Rice]
- Laneman [Notre Dame], Wornell [MIT] (00-…)

- Gupta [ASU], Kumar [UIUC]
- Dohler [KCL]
- Nosratinia, Hunter [UTD]
- Tse [Berkeley]
- Hasna [Qatar], Alouini [Minnesota]
- Giannakis, Cai, Ribeiro [Minnesota]
- Host-Madsen [Hawaii]
- Pottie
- Zhang [ASU]
- Stefano [Brooklyn]
- Wittneben, Rankov, Hammerstroem
- Cho, Haas [Cornell]

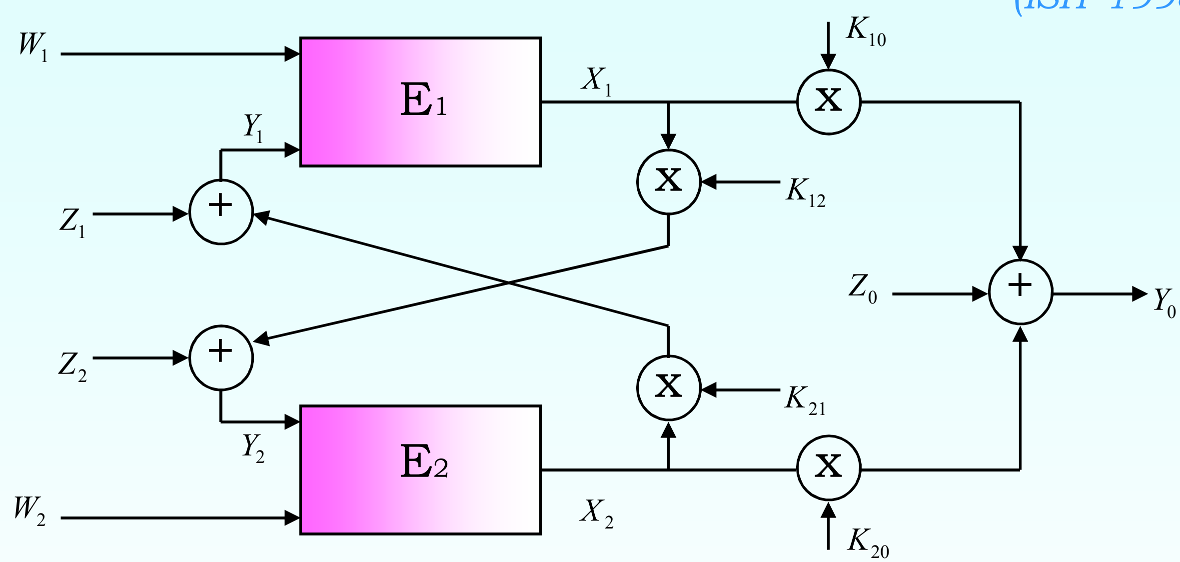
- Anghel, Emamian, Kaveh [Minnesota]
- Bolcskei, Nabar [ETH]
- Gastpar [Berkeley]
- Dawy [AUB]
- Kramer [Bell Labs]
- Franceschetti [UCSD]
- Herhold, Zimmermann [TUD]
- Vetterli [EPFL]
- Valenti
- Walke [Aachen]
- Karagiannidis [AU Thessaloniki]
- …

A few conference papers → explosion in literature

User Cooperative Diversity

Sendonaris, Erkip, Aazhang
IEEE T-COM, Nov. 2003
(*ISIT 1998*)

Channel Model (full-duplex assumption)



$$Y_0(t) = K_{10}X_1(t) + K_{20}X_2(t) + Z_0(t)$$
$$Y_1(t) = K_{21}X_2(t) + Z_1(t)$$
$$Y_2(t) = K_{12}X_1(t) + Z_2(t)$$

Implementation case example: CDMA Resources Distribution codes $c_i(t)$, power allocation a_i and a_{ji}

No cooperation

$$X_1(t) = a_1 b_1^{(1)} c_1(t), \quad a_1 b_1^{(2)} c_1(t), \quad a_1 b_1^{(3)} c_1(t)$$

$$X_2(t) = \underbrace{a_2 b_2^{(1)} c_2(t)}_{\text{Period 1}}, \quad \underbrace{a_2 b_2^{(2)} c_2(t)}_{\text{Period 2}}, \quad \underbrace{a_2 b_2^{(3)} c_2(t)}_{\text{Period 3}}$$

Using the same number of codes as in no cooperation scenario

With cooperation

$$X_1(t) = a_{11} b_1^{(1)} c_1(t), \quad a_{12} b_1^{(2)} c_1(t), \quad a_{13} b_1^{(2)} c_1(t) + a_{14} \hat{b}_2^{(2)} c_2(t)$$

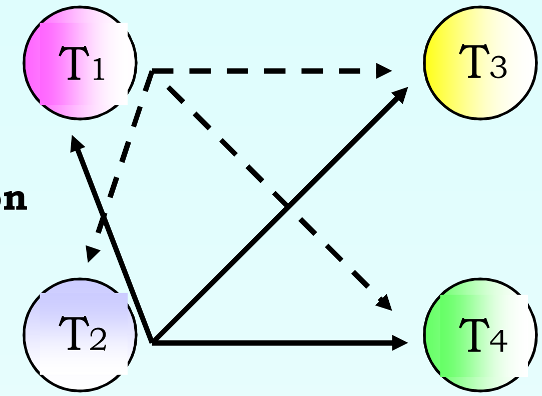
$$X_2(t) = \underbrace{a_{21} b_2^{(1)} c_2(t)}_{\text{Period 1}}, \quad \underbrace{a_{22} b_2^{(2)} c_2(t)}_{\text{Period 2}}, \quad \underbrace{a_{23} \hat{b}_1^{(2)} c_1(t) + a_{24} b_2^{(2)} c_2(t)}_{\text{Period 3}}$$

Users transmit to BS

Users exchange cooperative information BS may hear

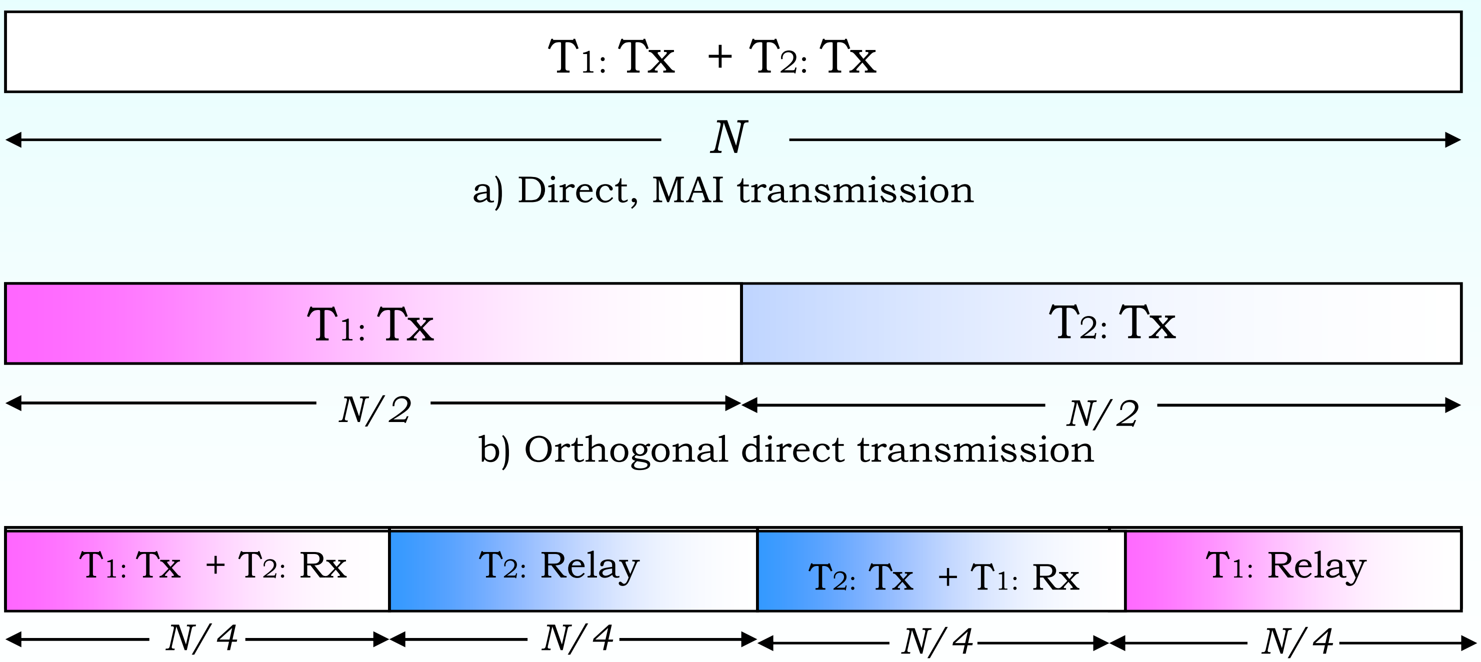
Constructed cooperative signals are sent to BS

Engaging terminals in cooperation



Laneman, Tse, Wornell
IEEE T-IT, Dec'04

Laneman, Wornell
IEEE T-IT, Oct'03



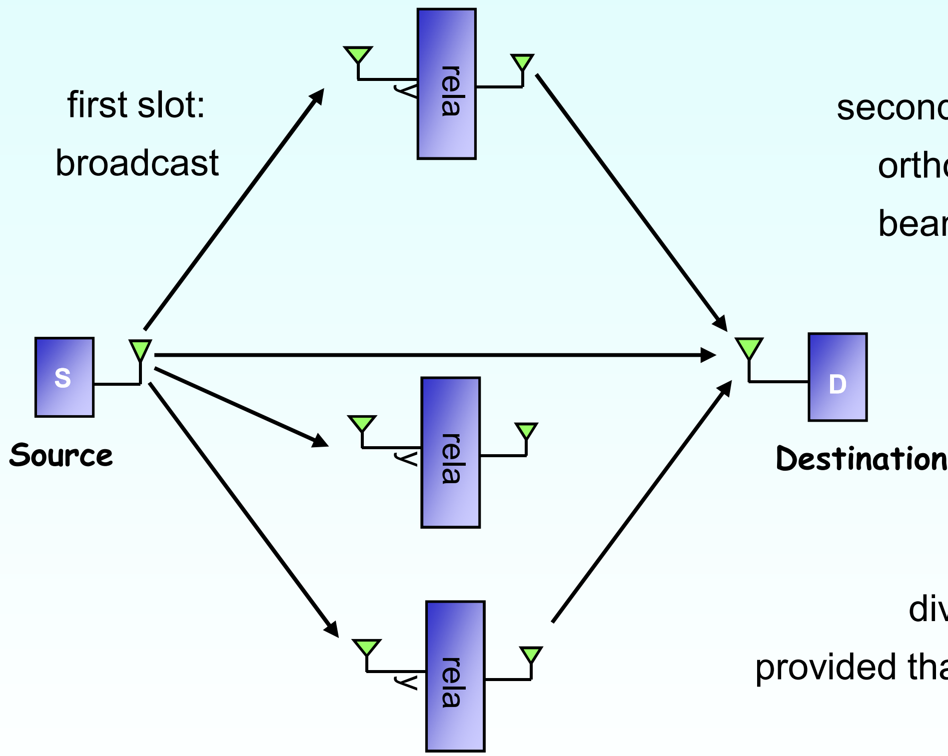
a) Direct, MAI transmission

b) Orthogonal direct transmission

c) Orthogonal cooperative diversity (slow fading channel)

Parallel Relays

first slot:
broadcast



second slot: multiple access

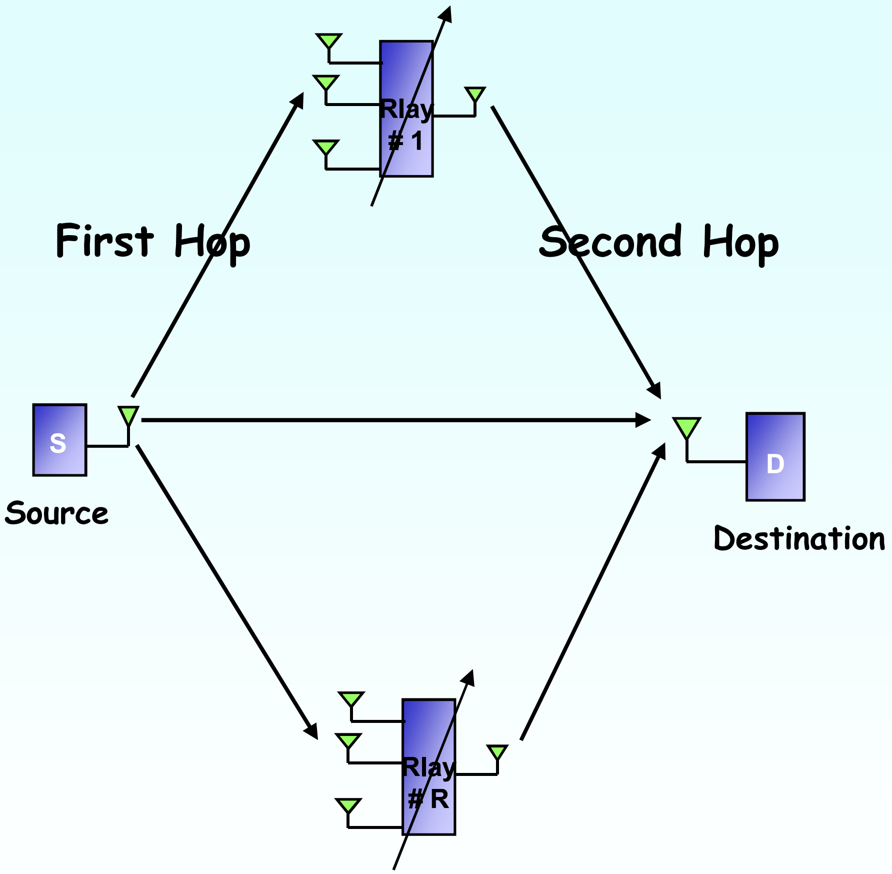
- orthogonal → multiplexing loss
- beamforming → CSI (overhead)

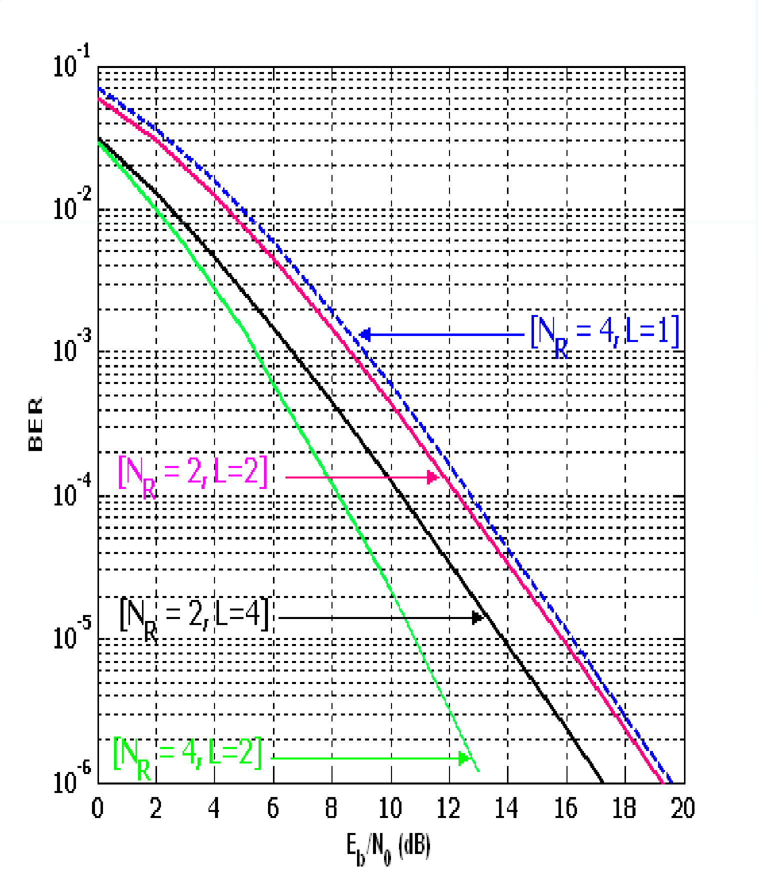
diversity order: up to R+1
provided that error propagation is prevented

Multi-Antenna Aspects of Cooperative Fixed Relays

Adinoyi, Yanikomeroglu
IEEE TWireless Feb'07, IEEE TWireless'10 (?)

use few relays with multi-antennas
(even with selection combining)
instead of many relays with single antennas





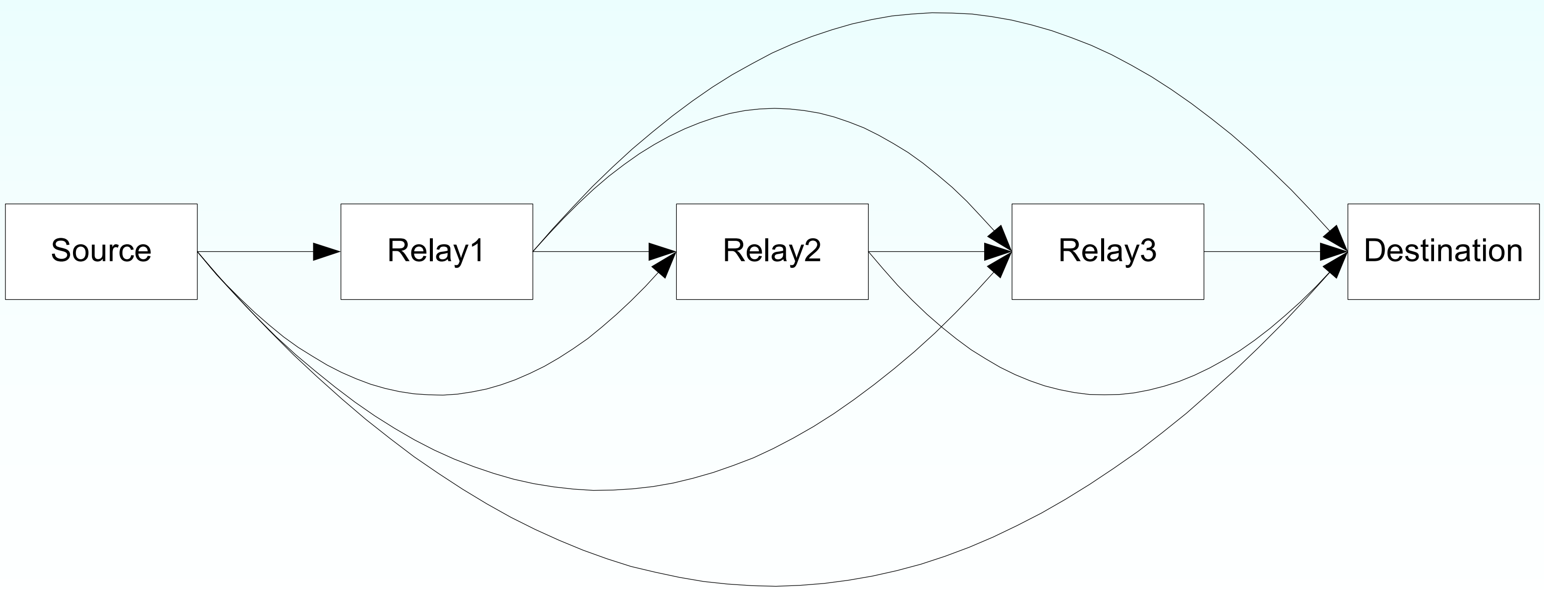
Multihop Diversity

- Analysis of multihop channels with diversity
  - Decoded relaying with diversity: intermediate terminals combine, digitally decode and re-encode the received signal from all preceding terminals
  - Amplified relaying with diversity: intermediate terminals combine and amplify the received signal from all preceding terminals
- Diversity in 2-Hop Links
  - Mazen Hasna, Mohamed-Slim Alouini
  - J. Laneman, Greg Wornell
- Diversity in n-Hop Links (for fully connected networks)
  - John Boyer, David D. Falconer, Halim Yanikomeroglu, "Multihop Diversity in Wireless Relaying Channels," *IEEE Trans. on Communications,* Oct. 2004
- Main Observations
  - Comparison of relaying and diversity schemes wrt BER
  - Multihop Diversity > Multihop > Singlehop
  - Amplified Relaying > Decoded Relaying
  - DRMD improves when intermediate terminals are closer to the source terminal
  - ARMD improves when intermediate terminals are closer to the destination terminal

Full-Diversity Relays and Destination

Boyer, Falconer, Yanikomeroglu
IEEE T-COM, Oct. 2004

- Full diversity reception at all receivers
- Requires n channels for n relaying hops
- Complex relay behavior (diversity combining)



Aggregate SNR of Amplified Relaying Channels

John Boyer, David D. Falconer, Halim Yanikomeroglu, “On the Aggregate SNR of Amplified Relaying Channels”, *IEEE Globecom 2004*.

- Aggregate Signal to Noise Ratio
  - “Aggregate”: inclusion of propagated noise terms in the SNR formulation.
  - Propagated noise terms are generated as amplified relaying terminals amplify both the information and noise portions of received signals indiscriminately.
- Motivated by findings indicating that the performance of amplified relaying can approach and in some cases exceed that of decoded relaying.
- Aggregate SNR expressions developed for amplified relaying channels with given source, destination, and relaying terminals, link connectivity, link attenuation, transmit power, and receiver noise.
- Aggregate SNR expression developed for following network connectivity:
  - Serial Amplified Relaying Channels (serial node connectivity)
  - Parallel Amplified Relaying Channels (parallel node connectivity)
  - General Amplified Relaying Channels (general node connectivity)

Part III: Case Studies – aSelected Research Results

- Composite fading
- Diversity-multiplexing tradeoff
- BS-relay coordination
- Bandwidth outage trade-off
- Intelligent routing and scheduling
- Combining signals with different modulation levels
- Constellation rearrangement

Example 1: Composite Fading

- Composite channel models take place in wireless communications (multi-path plus shadowing), radar cross section scattering of targets, reverberation in sonar, etc.

- Modeling such a phenomenon plays an important role in the design and analysis of different communication schemes over these environments.

- In wireless communications, emerging systems such as distributed antenna systems, network MIMO, comp (coordinated multipoint transmission), and cooperative relay networks require such modeling.

Models of Composite Fading

Multipath	Shadowing	Composite	Complexity	Appeared
Rayleigh	lognormal	Suzuki	No closed-form expression	Suzuki (1979)
Nakagami	lognormal	Gamma-lognormal	No closed-form expression	Lewinsky (1983)
Rayleigh	Gamma	Exponential-Gamma	Closed-form but limited	Jakeman (1976) Abdi & Kaveh (1998)
Nakagami	Gamma	Gamma-Gamma (Generalized-*K*)	Closed-form but Involved	Lewinsky (1983) Shankar (2004)
Nakagami	Gamma	Gamma	Simple	Al-Ahmadi & Yanikomeroglu (WCNC2009, GC 2009)

Example 2:
Diversity-Multiplexing Tradeoff Bounds for Relay Networks

- Spatial redundancy from multiple antennas in wireless relay networks can in theory be used to:
  - Increase the diversity gain for a particular data rate, and/or
- Increase the multiplexing gain (data rate) for a particular diversity gain.
- This paper derives bounds on the diversity-multiplexing tradeoff of wireless relay networks with any number of relay terminals and any possible combination of links between cooperating terminals.
  - Can then calculate maximum achievable diversity order.
  - Can then calculate maximum achievable multiplexing gain.
- In general, it is not possible to determine the diversity-multiplexing tradeoff from outage probability and diversity order results:
  - Terminals (or cut sets) that limit the diversity order may not necessarily be the same terminals (or cut sets) that limit the multiplexing gain.
  - Minimum number of independent fading realizations may occur at a different network location than minimum number of degrees of freedom.

Some Other Relevant Results / Publications

- Original formulation of diversity-multiplexing tradeoff:
  - L. Zheng and D. Tse, "Diversity and multiplexing: A fundamental tradeoff in multiple-antenna channels," *IEEE Trans. on Information Theory*, vol. 49, no. 5, pp. 1073-1096, May 2003.
- Early diversity-multiplexing results for

  cooperative channels:
  - K. Azarian, H. Gamal, and P. Schniter, "On the achievable diversity-multiplexing tradeoff in half-duplex cooperative channels," *IEEE Trans. on Information Theory*, vol. 51, Dec 2005.

  rank-deficient MIMO channels:
  - W. Chang, S. Chung, and Y. Lee, "Diversity-multiplexing tradeoff in rank-deficient and spatially correlated MIMO channels," *IEEE Int'l Symp. on Information Theory*, July 2006.
- Tight diversity-multiplexing tradeoff results for specific wireless relay network configurations:
  - M. Yuksel and E. Erkip, "Multi-antenna cooperative wireless systems: A diversity multiplexing tradeoff perspective," *IEEE Trans. on Information Theory, SI on Models, Theory, and Codes for Relaying and Cooperation in Comm Networks*, Oct 2007.

- Current paper takes the approach of deriving sometimes looser diversity-multiplexing tradeoff bounds for the most general wireless relay networks rather than tighter diversity-multiplexing tradeoff bounds for specific simpler sub-problems.

Relaying Method Classes

- Describe which terminals in the network must correctly decode the transmitted information signal for successful reception at the destination.

Comprehensive Decoding

- All cooperating terminals must correctly decode.
- Encompasses fixed decode-and-forward (DF) relaying and cooperative broadcasting.
- Diversity-multiplexing tradeoff curve upper bound: Minimization across the diversity-multiplexing tradeoff curves of all terminals in the network

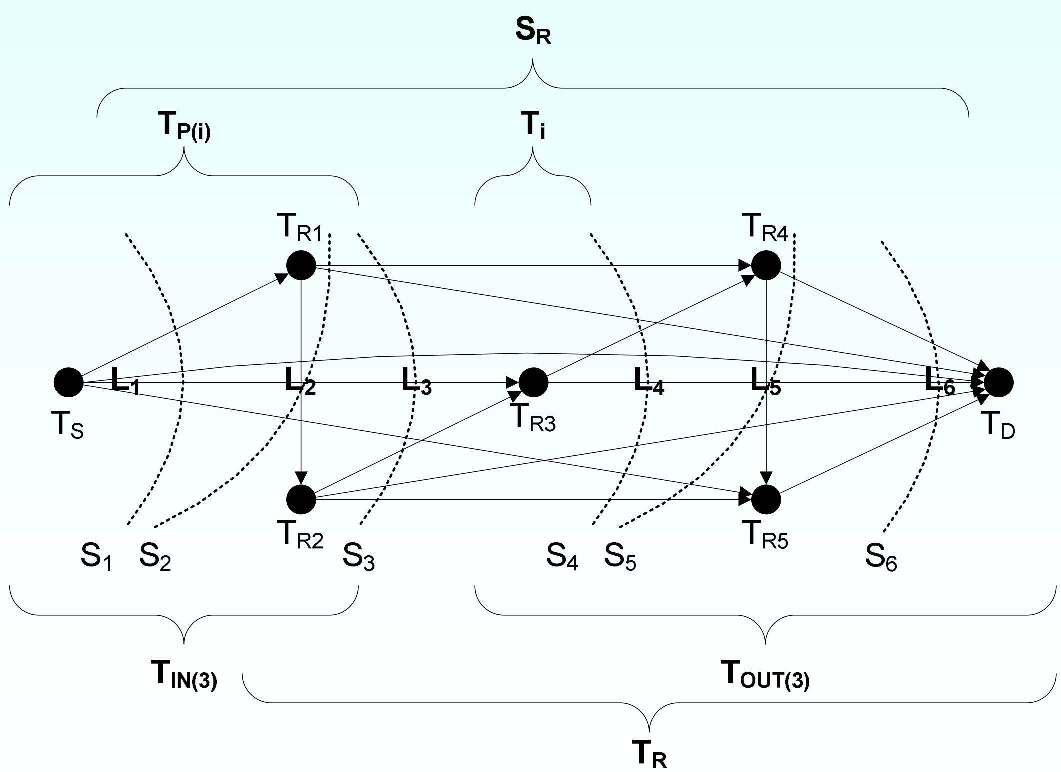
Destination Decoding

- Only the destination terminal must correctly decode.
- Encompasses adaptive or selective decode-and-forward (DF) relaying, and amplify-and-forward (AF) relaying.
- Diversity-multiplexing tradeoff curve upper-bound: Minimization across the diversity-multiplexing tradeoff curves of all cut sets in the network .

System Model

T_R All receiving terminals
S_R All cut sets
L_R All inter-antenna links
A_i Antennas at terminal T_i

$T_{P(i)}$ Terminals previous to terminal T_i
L_i Inter-antenna links for cut set S_i
$T_{IN(i)}$ Terminals on input side of cut set S_i
$T_{OUT(i)}$ Terminals on output side of cut set S_i



Comprehensive Decoding

$$MIMO-DMT:(r,d(r))$$
$$r=0,1,\ldots,\min(m,n)$$
$$d(r)=(m-r)(n-r)$$

- **Diversity-Multiplexing Tradeoff Curve**

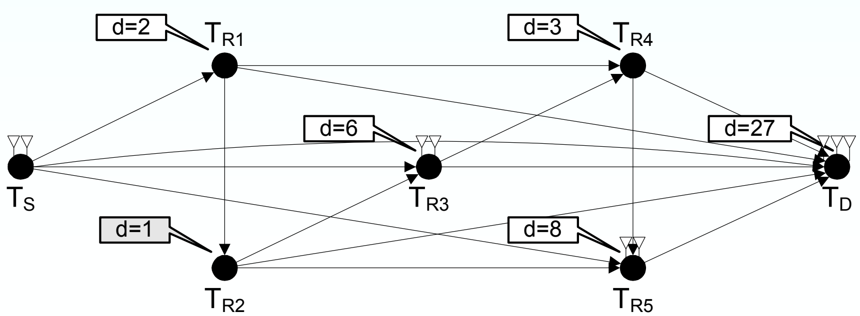
$$(r,d(r)),r=0,1/K,\ldots,\min_{T_i\in T_R}\left\{\min\left\{\sum_{T_k\in T_{P(i)}}|A_k|,|A_i|\right\}\right\}/K$$

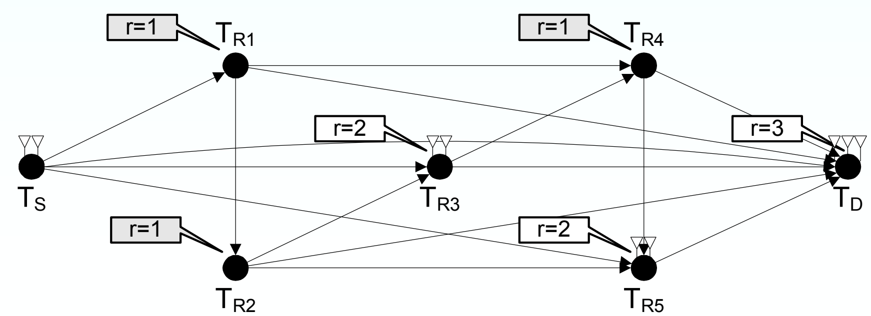
$$d(r)\le\min_{T_i\in T_R}\left\{\left(\sum_{T_k\in T_{P(i)}}|A_k|-Kr\right)(|A_i|-Kr)\right\}$$

- **Maximum Achievable Diversity Order and Multiplexing Gain**

$$d_{\max}=\min_{T_i\in T_R}\left\{\sum_{T_k\in T_{P(i)}}|A_k||A_i|\right\}$$

$$r_{\max}=\min_{T_i\in T_R}\left\{\min\left\{\sum_{T_k\in T_{P(i)}}|A_k|,|A_i|\right\}\right\}/K$$





Destination Decoding – Fully Connected Upper Bound

- **Diversity-Multiplexing Tradeoff Curve**

$$(r, d(r)), r = 0, 1/K, \ldots, \min_{S_i \in S_R} \left\{ \min \left\{ \sum_{T_k \in T_{IN(i)}} |A_k|, \sum_{T_l \in T_{OUT(i)}} |A_l| \right\} \right\} / K$$

$$d(r) \leq \min_{S_i \in S_R} \left\{ \left(\sum_{T_k \in T_{IN(i)}} |A_k| - Kr \right) \left(\sum_{T_l \in T_{OUT(i)}} |A_l| - Kr \right) \right\}$$

$$MIMO - DMT : (r, d(r))$$

$$r = 0, 1, \ldots, \min(m, n)$$

$$d(r) = (m - r)(n - r)$$

- **Maximum Achievable Diversity Order and Multiplexing Gain**

$$d_{\max} \leq \min_{S_i \in S_R} \left\{ \sum_{T_k \in T_{IN(i)}} |A_k| \sum_{T_l \in T_{OUT(i)}} |A_l| \right\}$$

$$r_{\max} \leq \min_{S_i \in S_R} \left\{ \min \left\{ \sum_{T_k \in T_{IN(i)}} |A_k|, \sum_{T_l \in T_{OUT(i)}} |A_l| \right\} \right\} / K$$

  - Loose result when cut set inputs & outputs are not fully connected.

- **How can we get a tighter result?**
  - Leverage the fact that when a wireless relay network is not fully connected, it can be modeled as a rank-deficient MIMO channel.

Destination Decoding – Rank-Deficiency Refinement

- **Diversity-Multiplexing Tradeoff Curve**

$$(r, d(r)), r = 0, 1/K, \ldots, \min_{S_i \in S_R}\{\kappa_i\}/K \quad \text{where} \quad \kappa_i \le \min\{\sum_{T_k \in T_{IN(i)}} |A_k|, \sum_{T_l \in T_{OUT(i)}} |A_l|\}$$

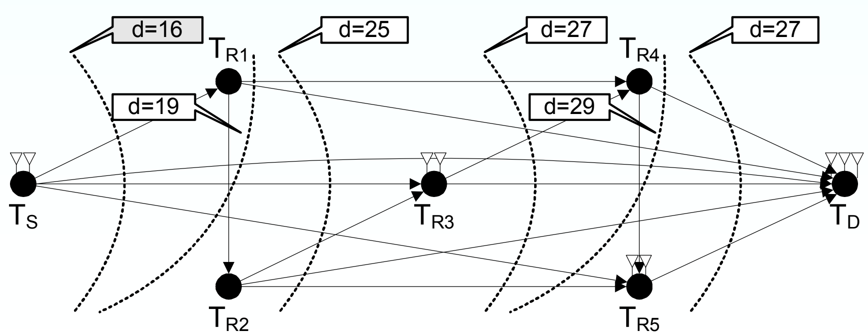
$$d(r) \le \min_{S_i \in S_R}\left\{|L_i| - (\sum_{T_k \in T_{IN(i)}} |A_k| + \sum_{T_l \in T_{OUT(i)}} |A_l| - Kr)Kr)\right\}$$

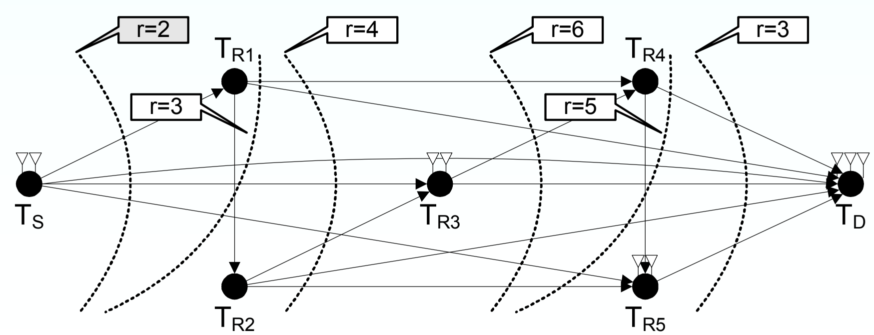
- **Maximum Achievable Diversity Order and Multiplexing Gain**

$$d_{\max} = \min_{S_i \in S_R}\{|L_i|\} \qquad r_{\max} = \min_{S_i \in S_R}\{\kappa_i\}/K$$

- **Degradation of Diversity Order and Multiplexing Gain**

$$\Delta d = \min_{S_i \in S_R}\left\{\sum_{T_k \in T_{IN(i)}} |A_k| \sum_{T_l \in T_{OUT(i)}} |A_l|\right\} - \min_{S_i \in S_R}\{|L_i|\} \quad \Delta r_{\max} = \min_{S_i \in S_R}\left\{\sum_{T_k \in T_{IN(i)}} |A_k|, \sum_{T_l \in T_{OUT(i)}} |A_l|\right\}/K - \min_{S_i \in S_R}\{\kappa_i\}/K$$





Example 3: Coordination among BSs/APs and Relays

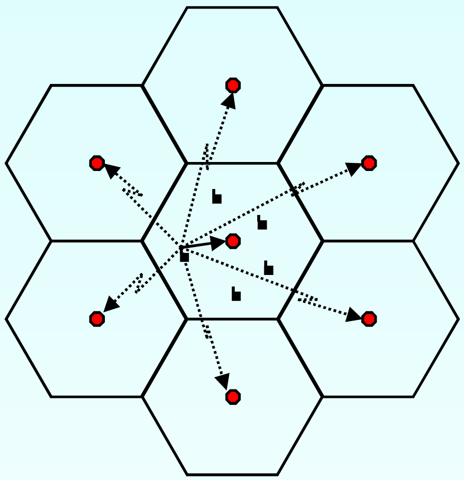
- Coordination among BSs
  - Scheduling
  - Interference management
  - Radio resource management
  - Admission control
  - …

- Rich literature
- Limited usage in practice in conventional cellular networks

- May be used in cellular relay networks

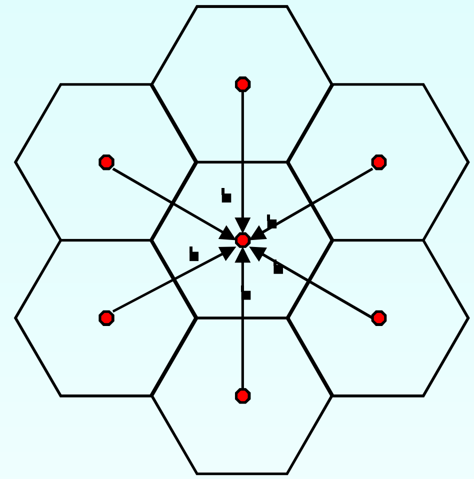
CLASSICAL DYNAMIC FREQUENCY HOPPING WITH NETWORK ASSISTED RESOURCE ALLOCATION (DFH with NARA) – [AT&T Bell Labs]

i.



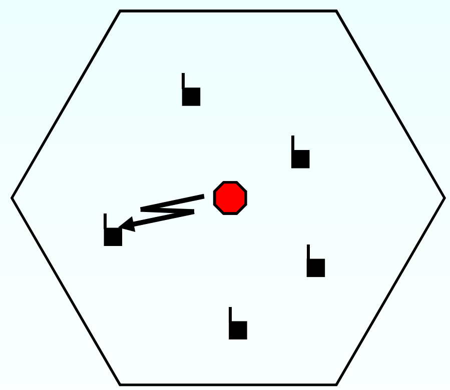
Each terminal measures path losses to the neighboring bases and transmits this information to its serving base on a regular basis.

ii.



Each base communicates to several tiers of its neighbors the information about its own resource utilization (i.e. time slots, frequency hopping patterns and current power levels).

iii.

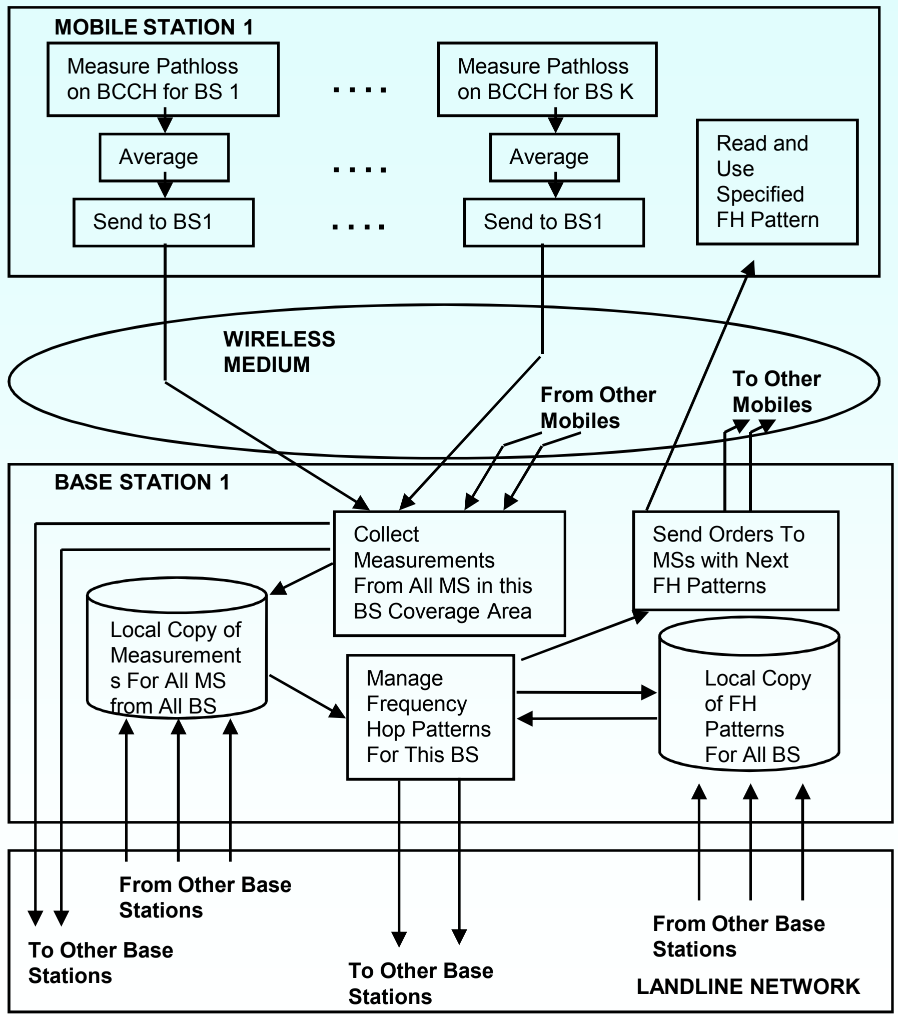


The serving base station calculates the interference level at each available resource, determines the least-interfered time slot and FH pattern pair, and assigns this to the terminal.

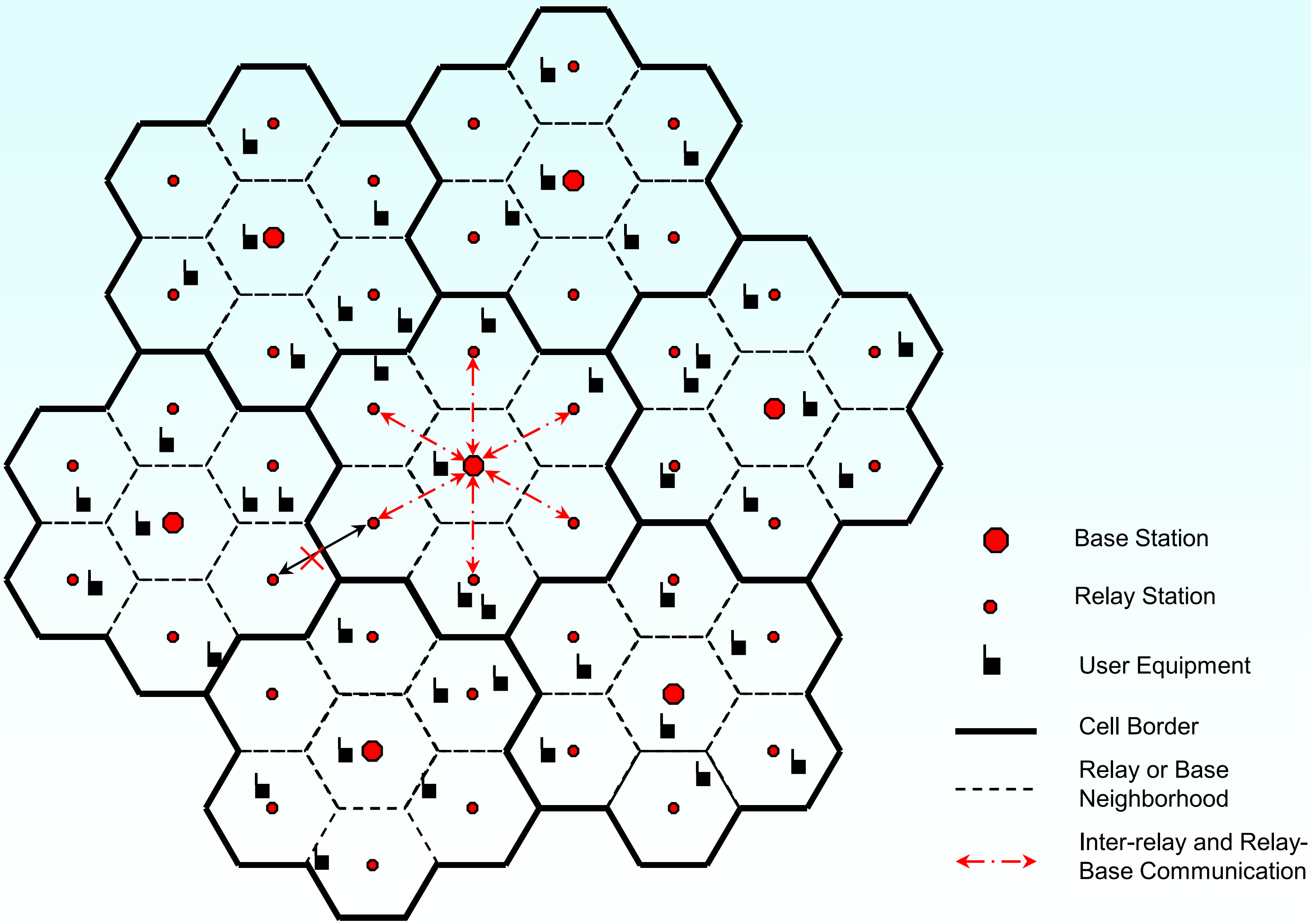
Base Station

Mobile terminal

BLOCK DIAGRAM OF A CELLULAR SYSTEM THAT SUPPORTS DFH WITH NARA FOR DOWNLINK

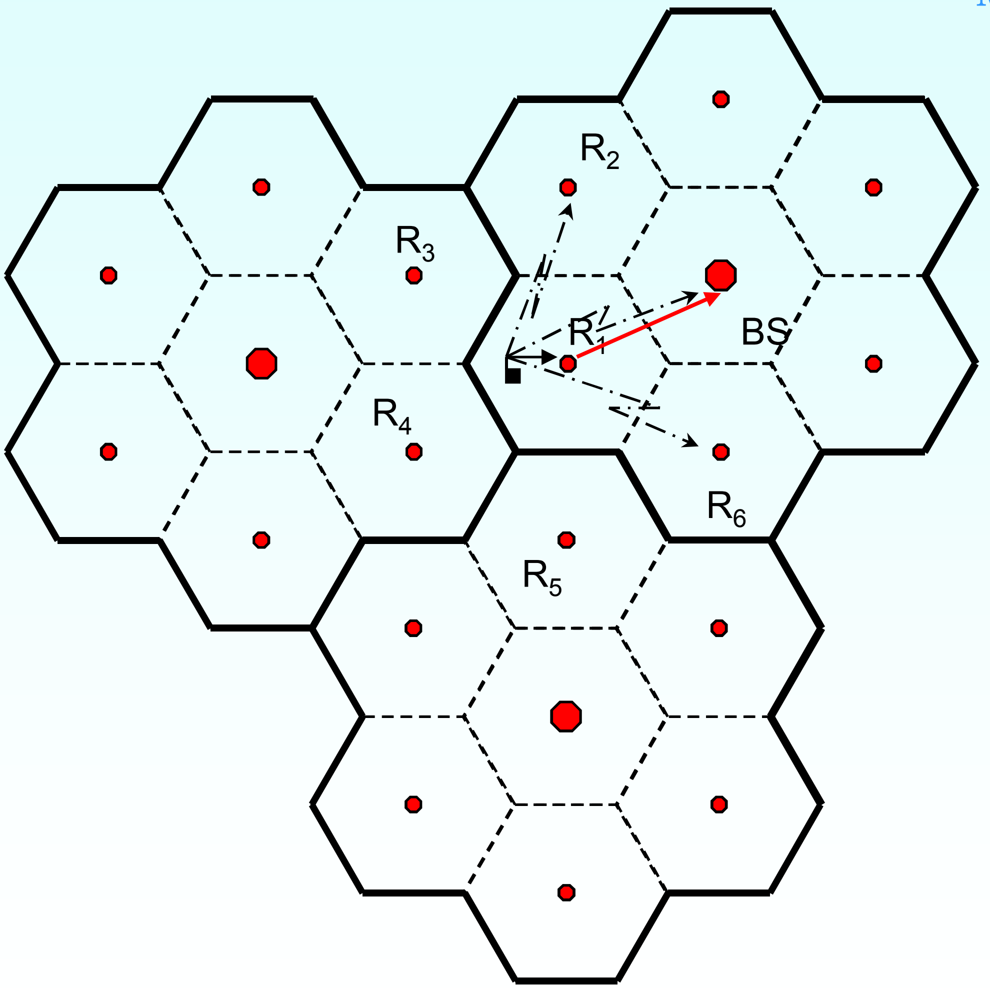


SYSTEM ARCHITECTURE FOR TWO-HOP COMMUNICATIONS



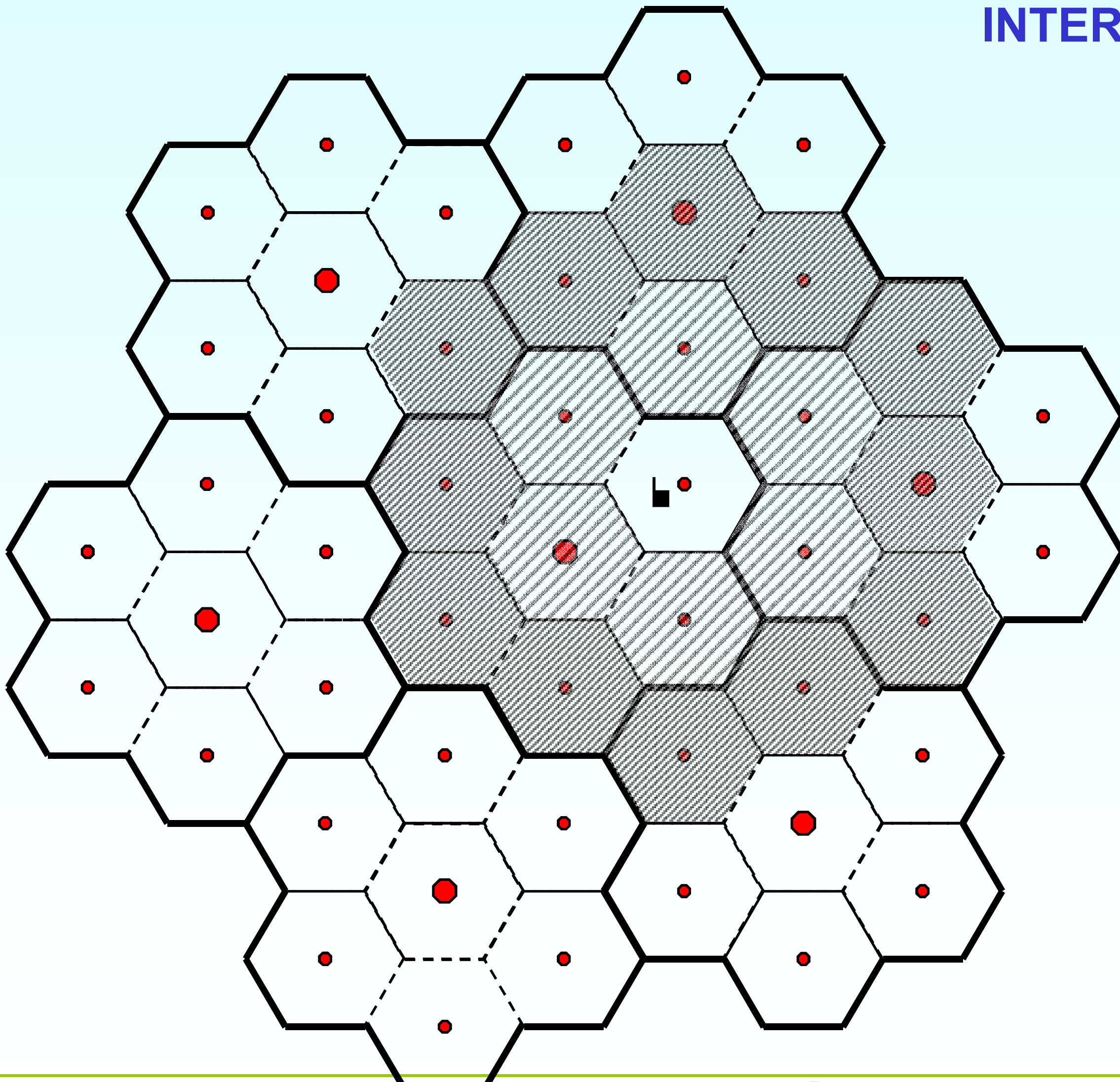
DFH with LIMITED INFORMATION (Time Slot 2)

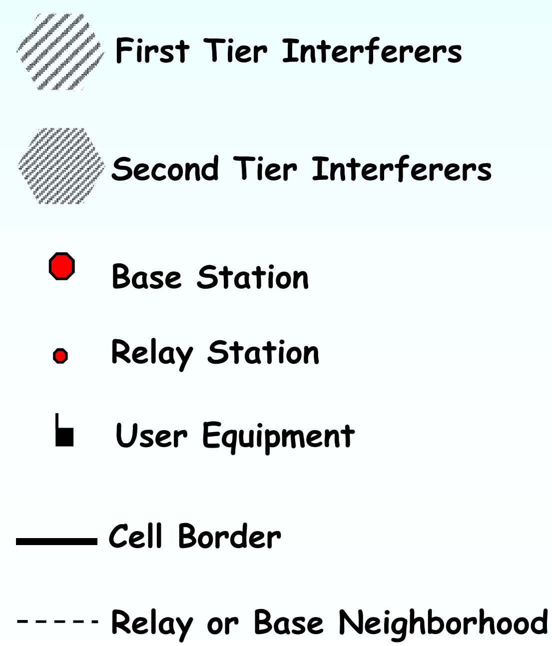
Mubarek, Yanikomeroglu, Periyalwar



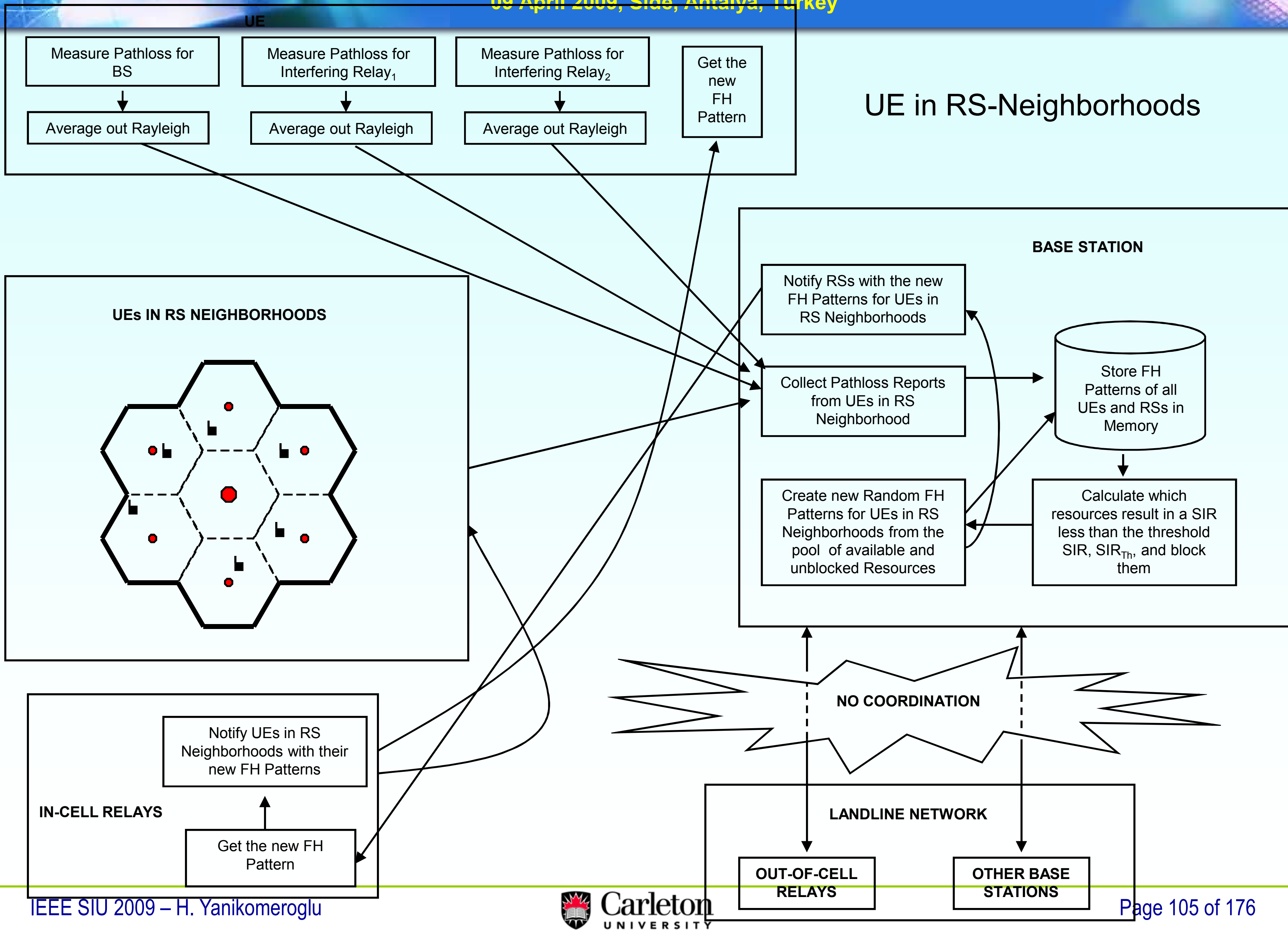
- R1: 3 in-cell interferers (R2,R6,BS) and 3 out-of-cell interferers (R3,R4,R5)
- UE pathloss info: R1→BS
- BS already has resource utilization information of the in-cell interferers of R1
- BS: decide on DFH pattern based on limited info
- BS→R1: DFH pattern

INTERFERING SUB-CELLS

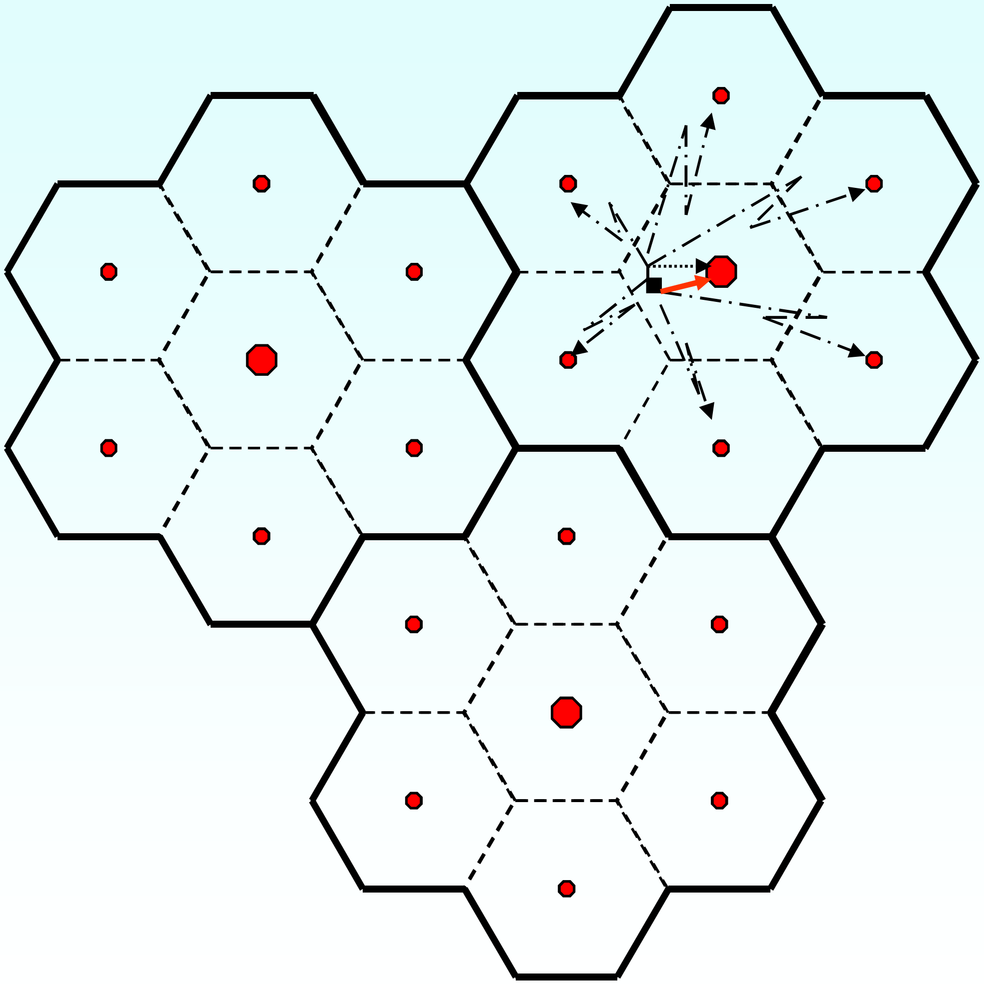




UE in RS-Neighborhoods

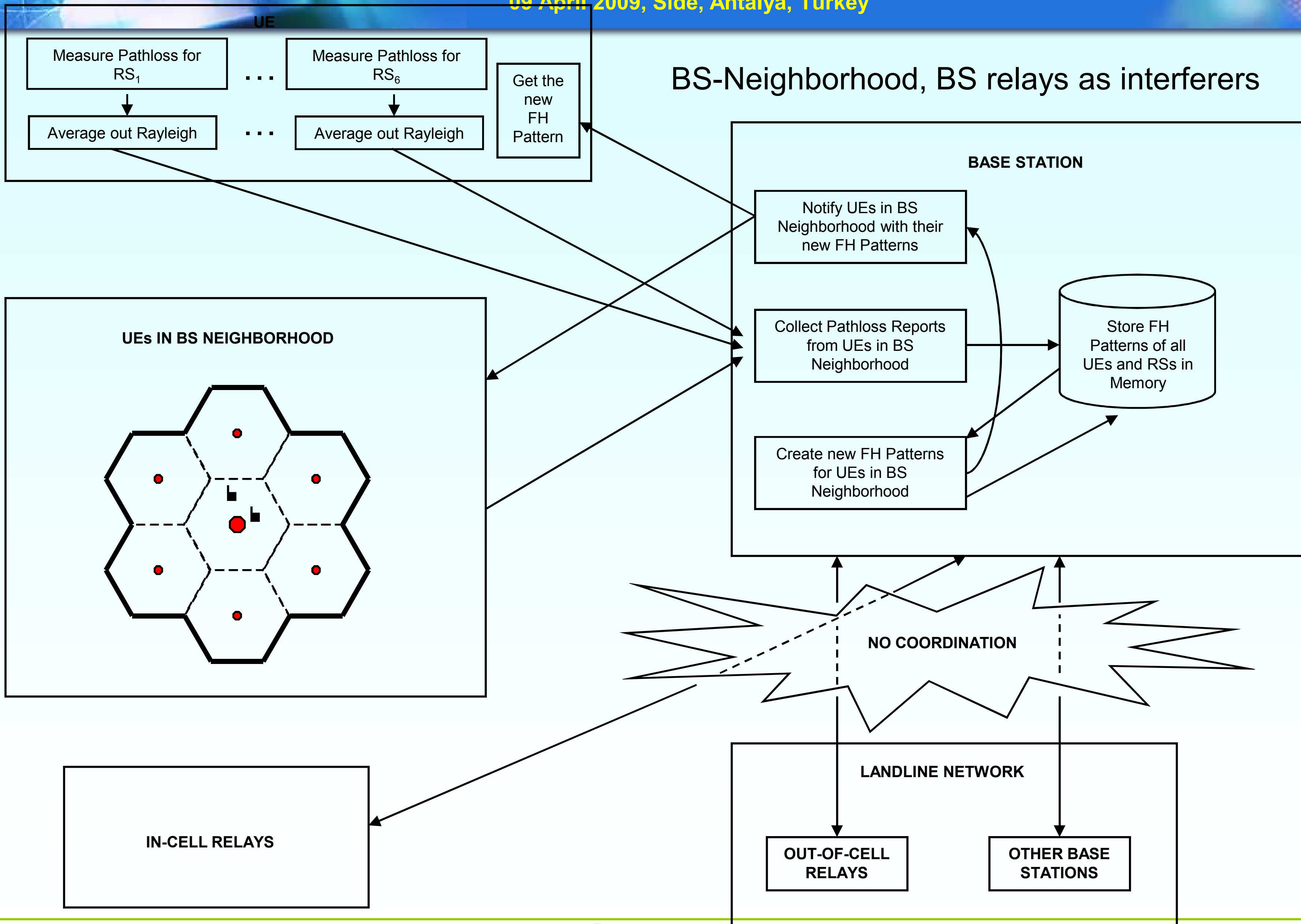


DFH with LIMITED INFORMATION (Time Slot 2)

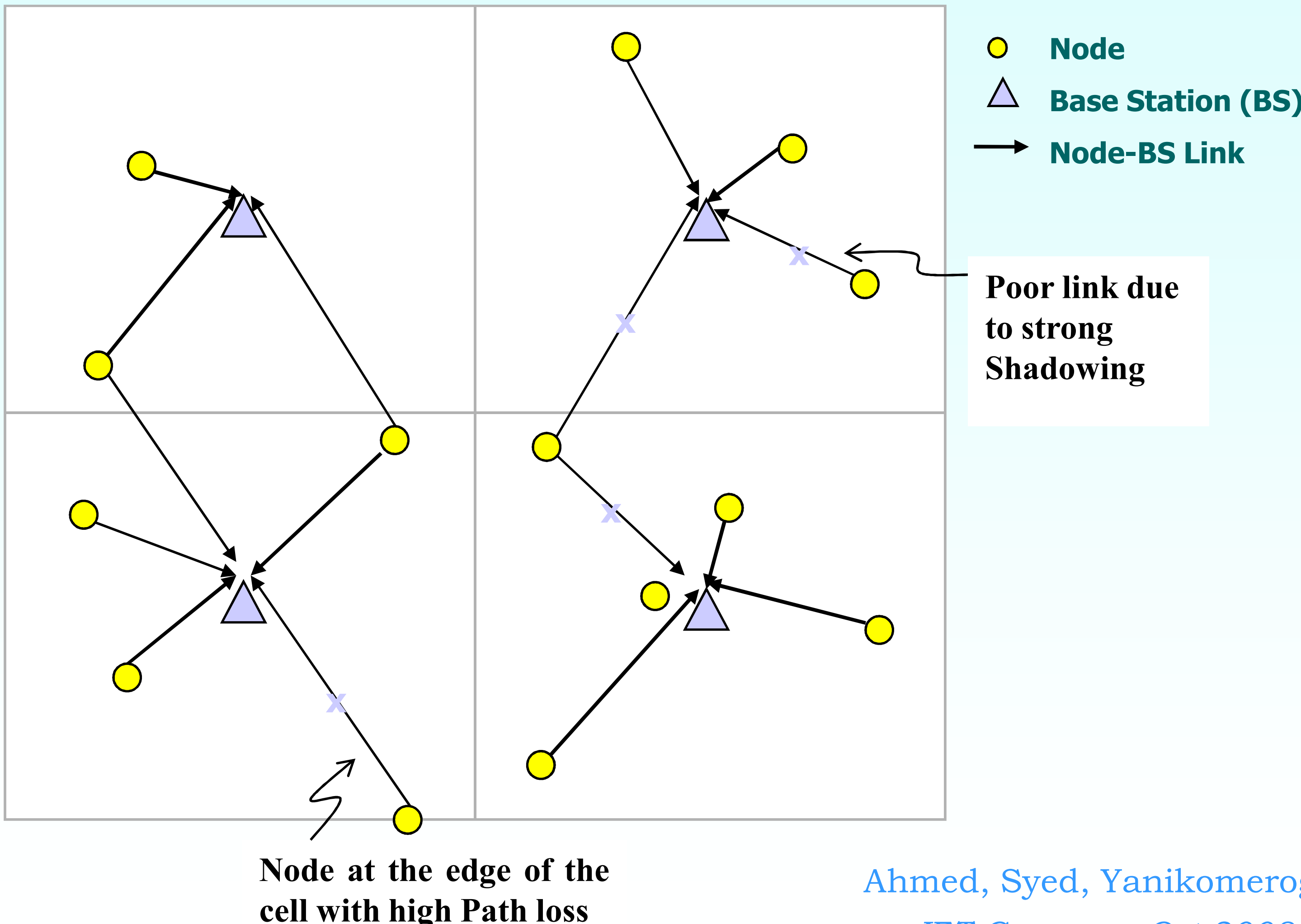


UE in BS service region:
DFH with full information

BS-Neighborhood, BS relays as interferers

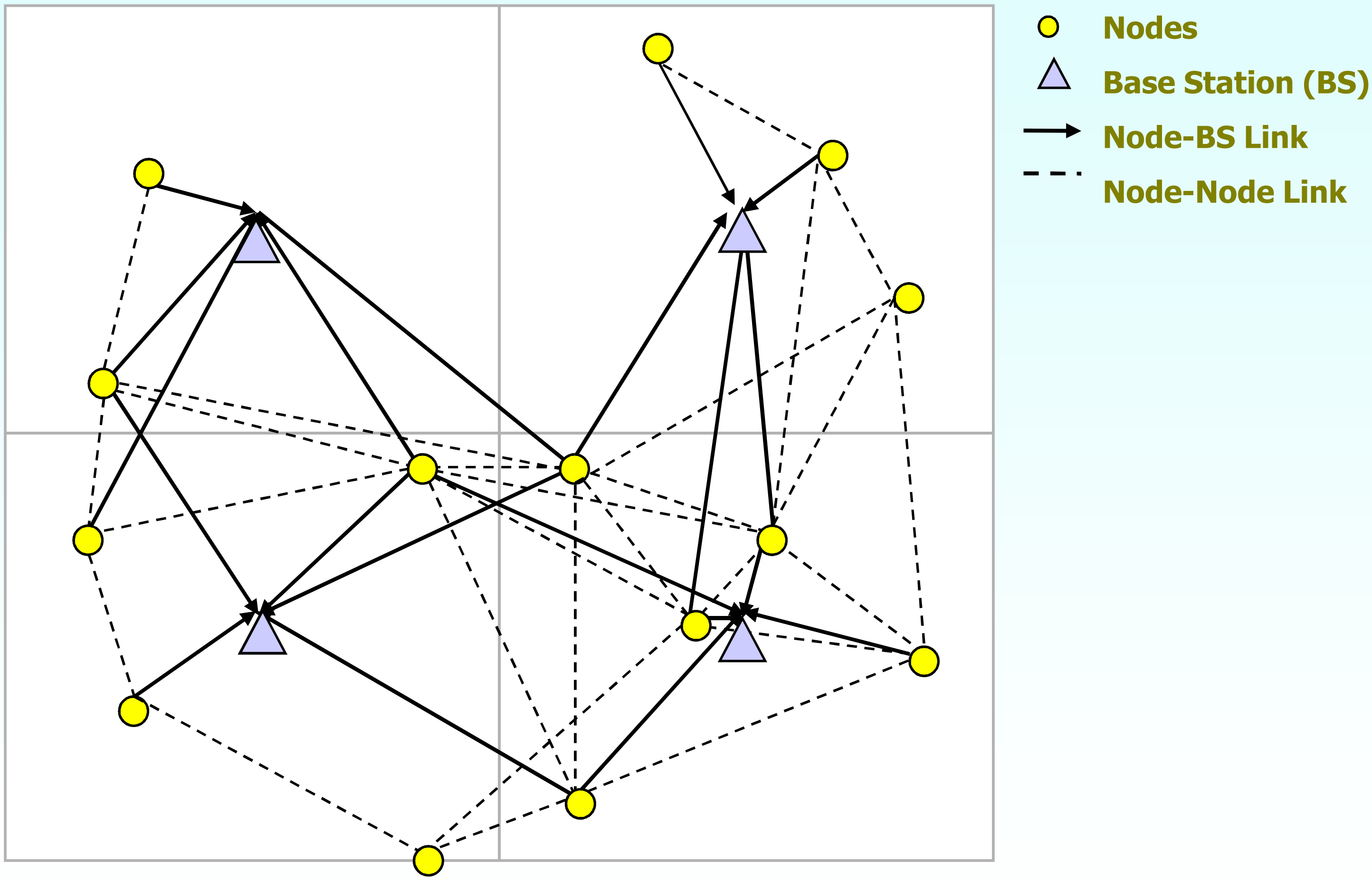


Example 4: Performance Improvements through the Mesh Architecture in TDMA based Broadband Fixed Cellular Network



Ahmed, Syed, Yanikomeroglu
IET Commun, Oct 2008

Cellular Mesh Network with Global Resource Allocation



Algorithm for Constructing Routing Table

Step 1

Reject all node-node & node-BS links with $PL > PL_{max}$

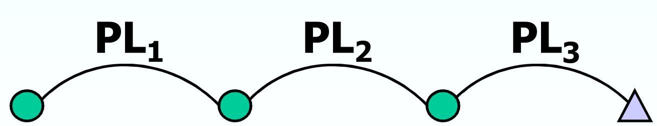
Step 2

List all 2-hop & 3-hop routes between source node and BS(s)

Step 3

Arrange in ascending order,the routes found in Step 2 using criterion

$\min\{ \max (PL_i)\}$ where i=1,2 or i=1,2,3



Step 4

If tie in $\max(PL_i)$, then $\min\{ \Sigma PL_i \}$ route on the top

Route Selection

Policy

Minimum Number of Hops Route First

Conditions

- Free slot(s) available on all hops
- $SINR_r \geq SINR_{th}$ on the free slot(s)

Salient Features

- Less spectral resources used (time slots)
- Viable SINR links used ($SINR_r \geq SINR_{th}$)
- Simple call admission policy
- Simple algorithm

Adaptive Modulation & Coding

SINR (dB)	Code & Mod.	Info. bps/hz
<4.65	-	0
4.65-7.45	½ QPSK	1
7.45-10.93	¾ QPSK	1.5
10.93-12.0	½ 16-QAM	2.0
12.0-14.02	2/3 16-QAM	2.67
14.02-15.0	¾ 16-QAM	3
15.0-17.7	7/8 16-QAM	3.5
17.70-19.0	2/3 64-QAM	4
19.0-21.94	¾ 16-QAM	4.5
21.94-26.0	7/8 64-QAM	5.25
>26.0	64-QAM	6

Main Simulation Parameters

System Parameter	Simulation Value
Network	Cellular, Noise limited, 200 Nodes, 4-Square Cells, Cell Size = 3x3 km^2
Multiple Access	TDMA / FDD, 10 slots/channel
Propagation Channel	$n_{n\text{-}BS}$= 3.8, $n_{n\text{-}n}$= 4, $\sigma_{n\text{-}BS}$= 6dB, $\sigma_{n\text{-}n}$= 4dB
Carriers & Bandwidth	Single Carrier @ 2.5GHz, BW= 5 MHzs No. of Channels = 2 to 6
Antenna Type	30^o, switched beam, G_{ml}= 7 dB, $G_{sl,bl}$= 0 dB, Rooftop (node end)
Transmit Power	Fixed, P_t= 2 watts
Noise	AWGN, Noise Power = - 130 dBW

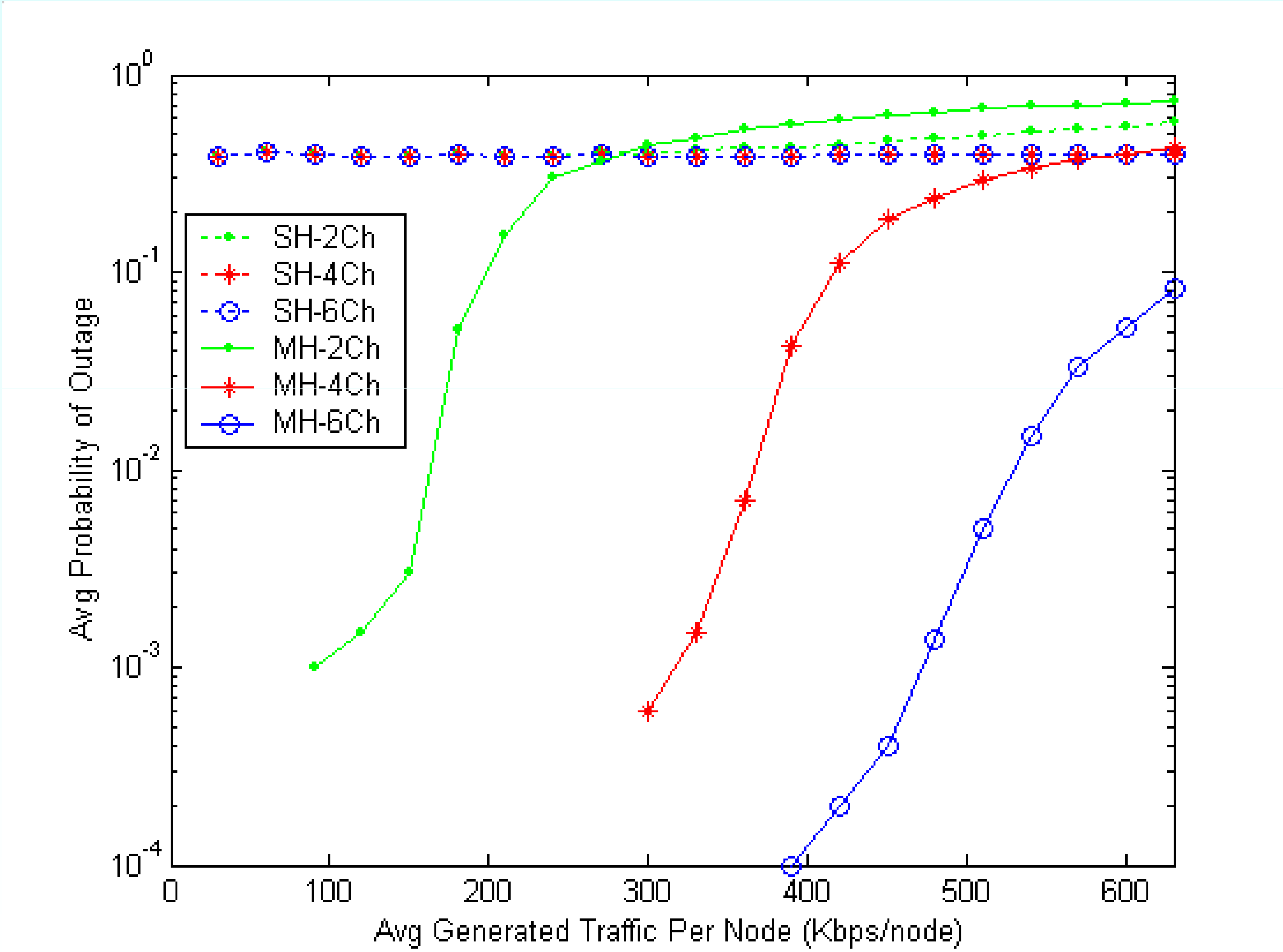
Simulation Parameters … Cont.

System Parameter	Simulation Value
Network Traffic	Traffic Arrival : Poisson, λ=400-8000 burst/sec Burst size : Exponential, μ=15 kbits
PL_{max} for Routing	126 dB
$SINR_{th}$	4.65 dB
Frame specification	T_f=10ms, 10 slots/frame
Slot allocated per hop	1
Upper limit on consecutive frame drop before retransmission	3

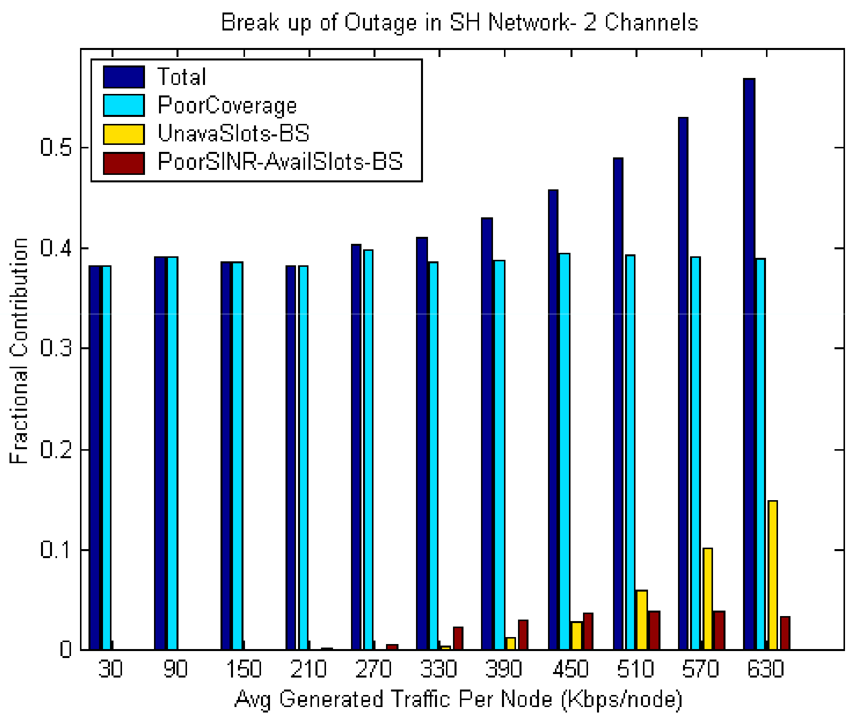
Simulation Assumptions

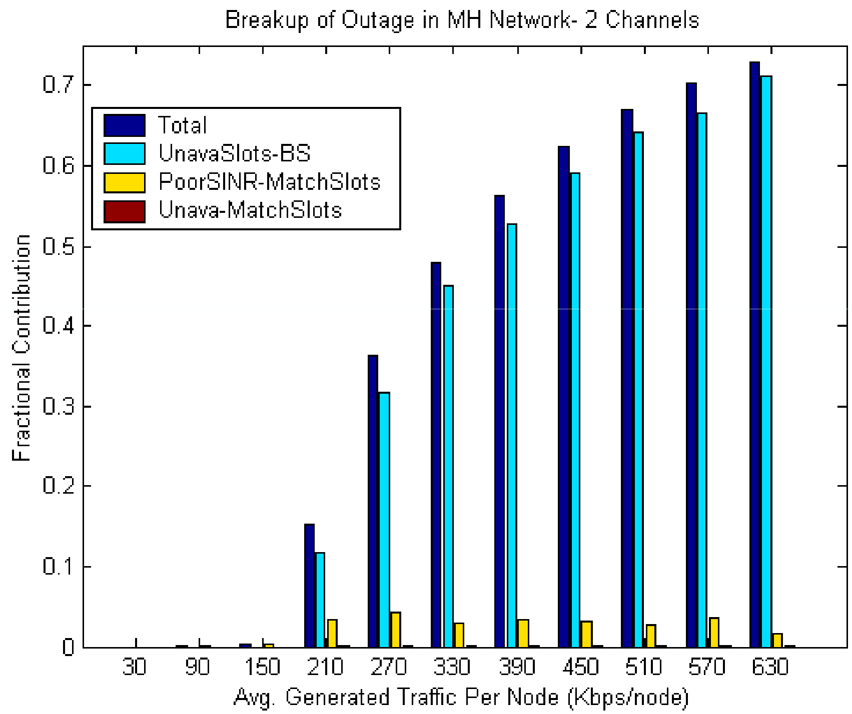
- Snap shot processing at frame level
- All transmissions are slot synchronized
- Independent & fixed shadowing on all links
- Doppler shift negligible
- Multipath fading handled by micro diversity
- Infinite buffer size on the node
- All user nodes are active
- Separate control channels are available
- Continuous ARQ Protocol

Outage Probability

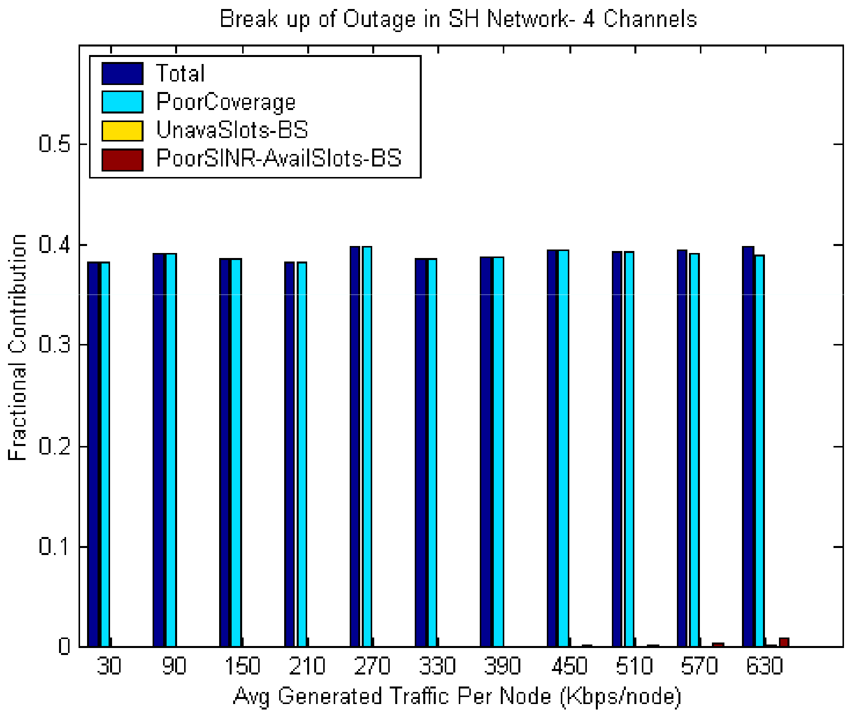


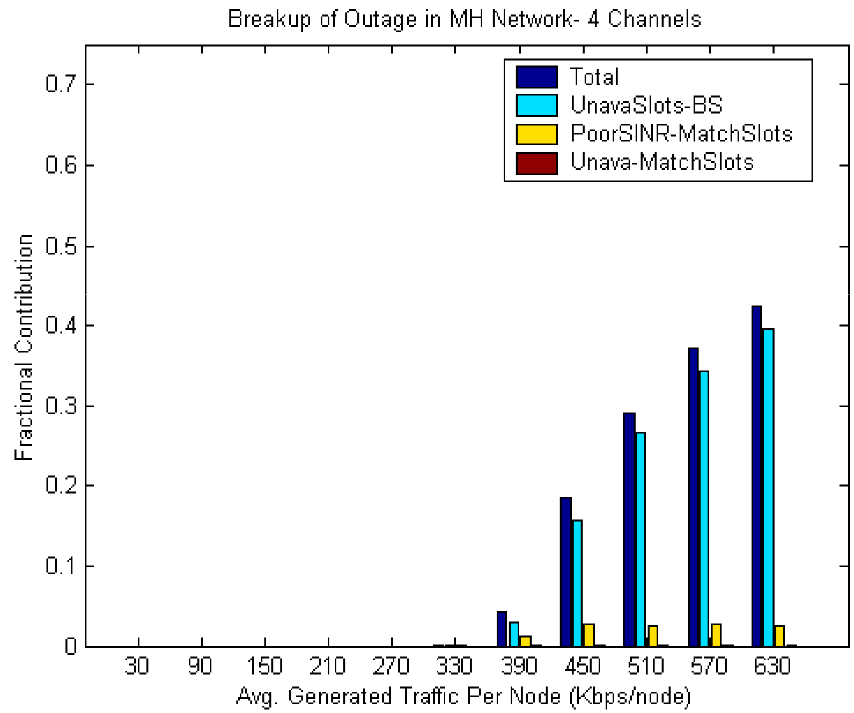
Outage Analysis of SH & MH Network, 2-Channels



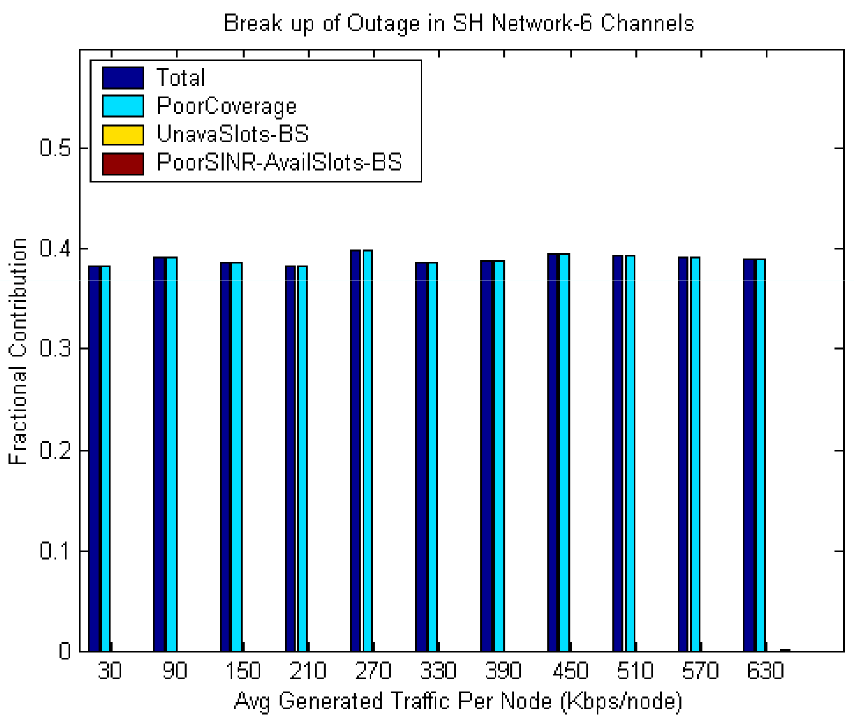


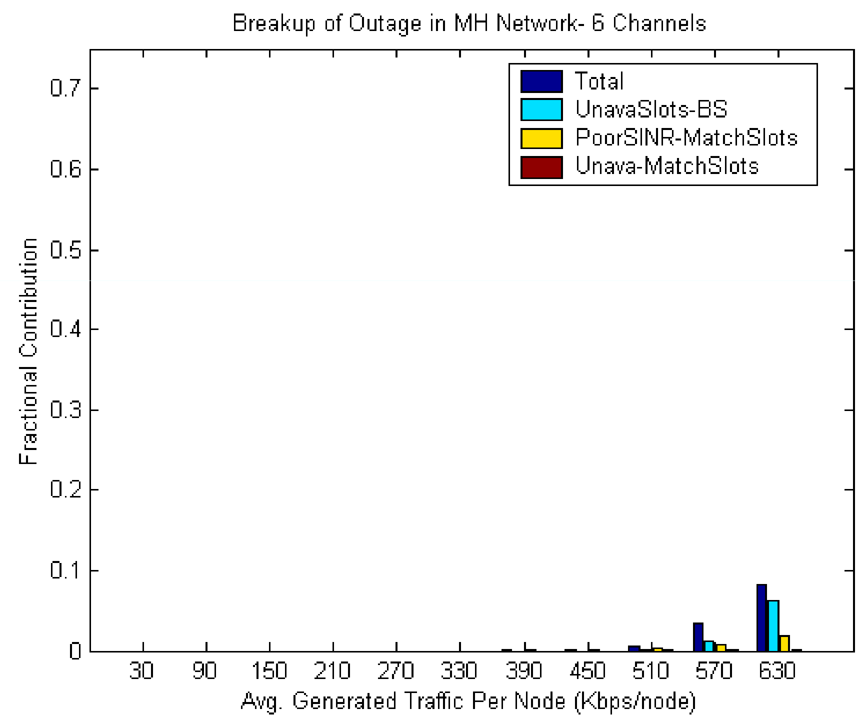
Outage Analysis of SH & MH Network, 4-Channels



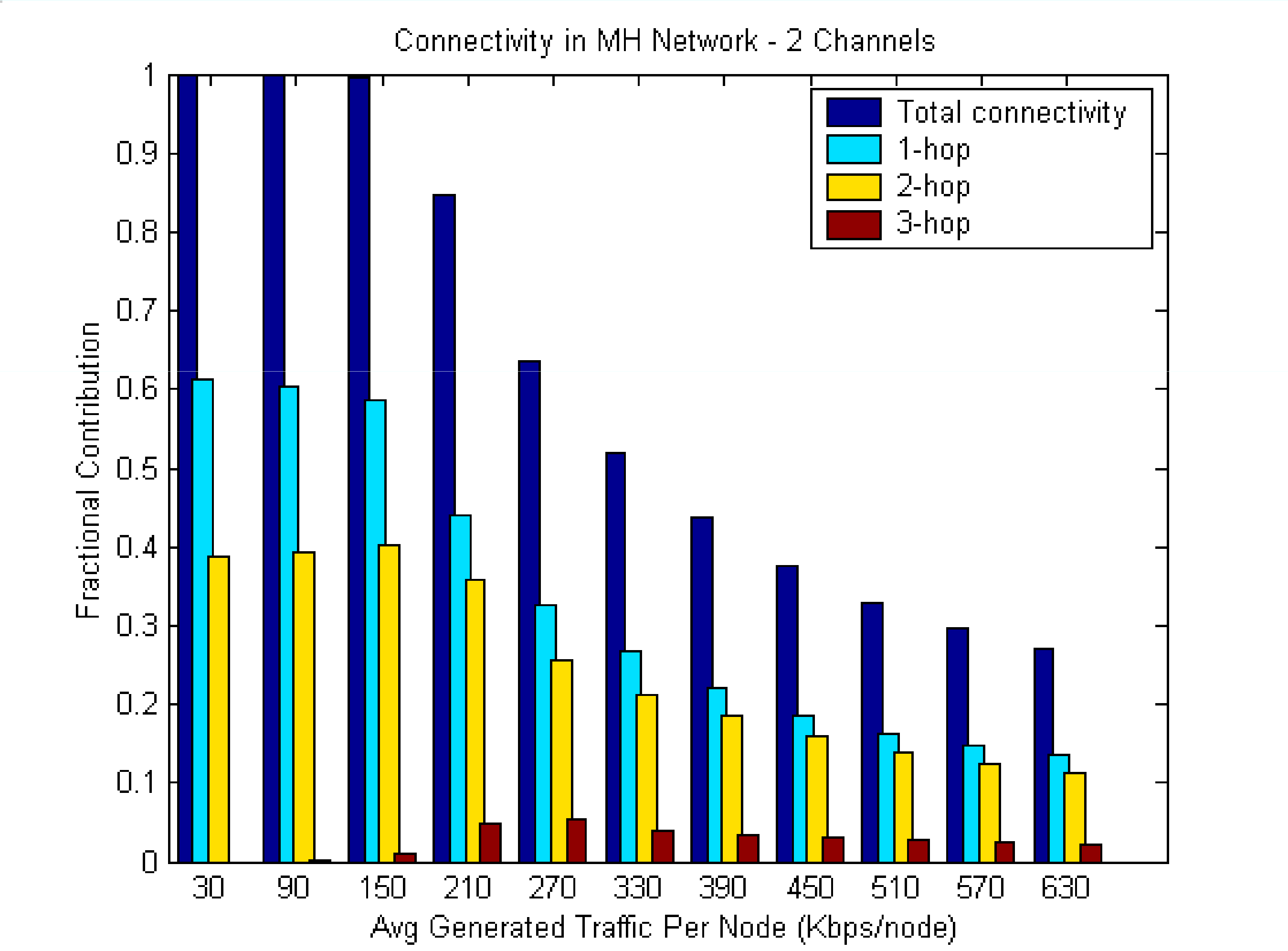


Outage Analysis of SH & MH Network, 6-Channels

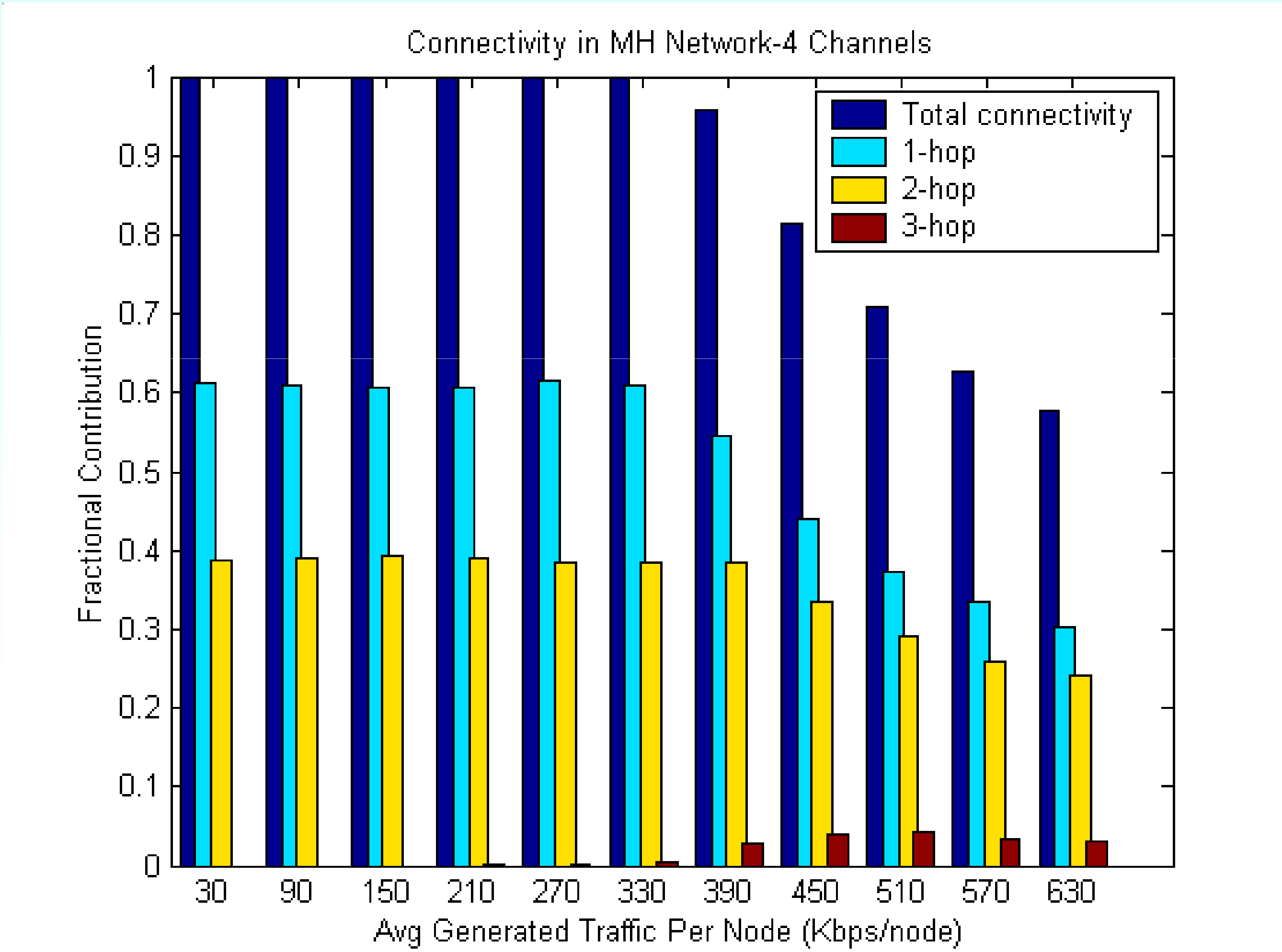




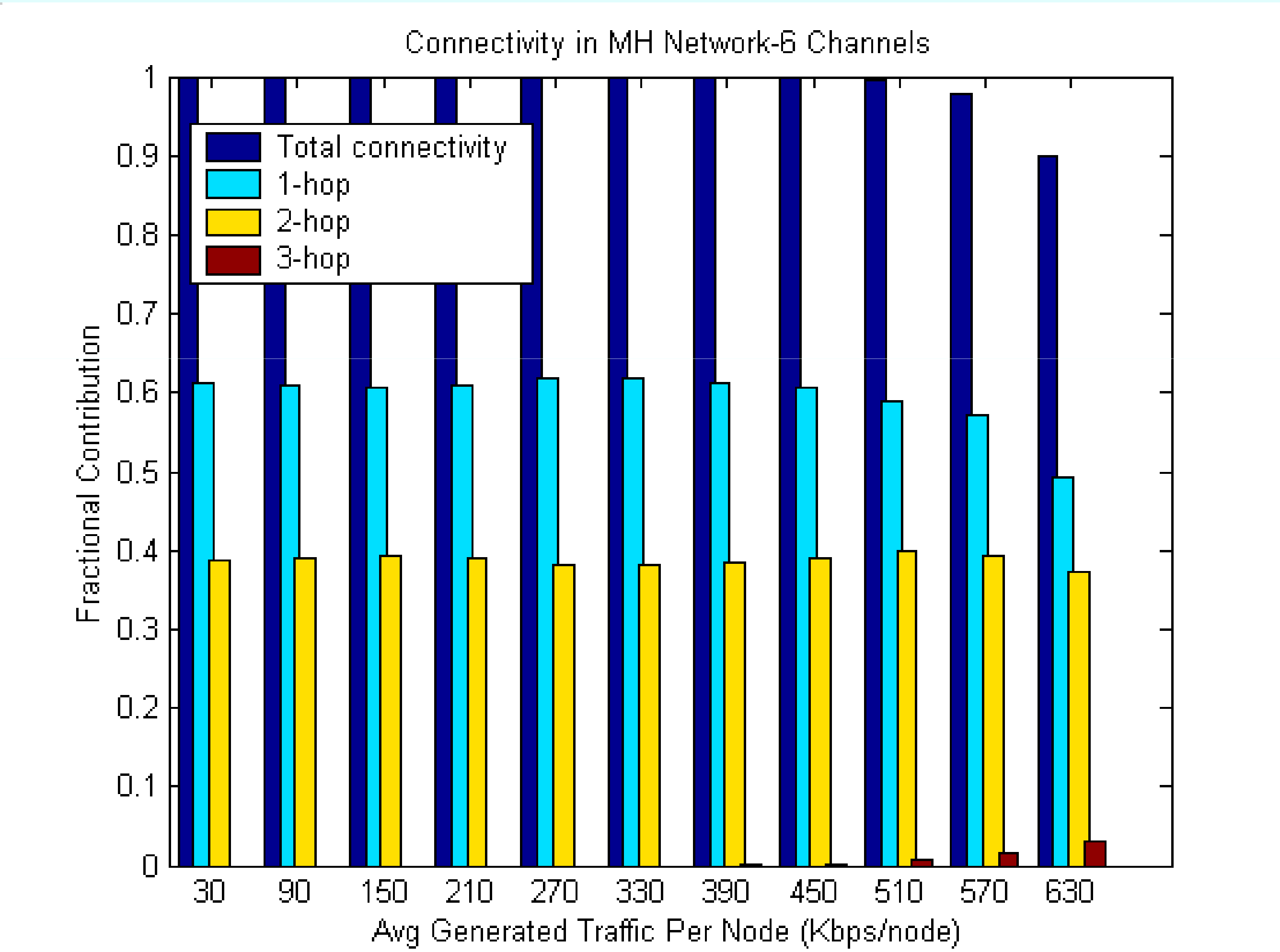
Connectivity Analysis: MH Network, 2-Channels



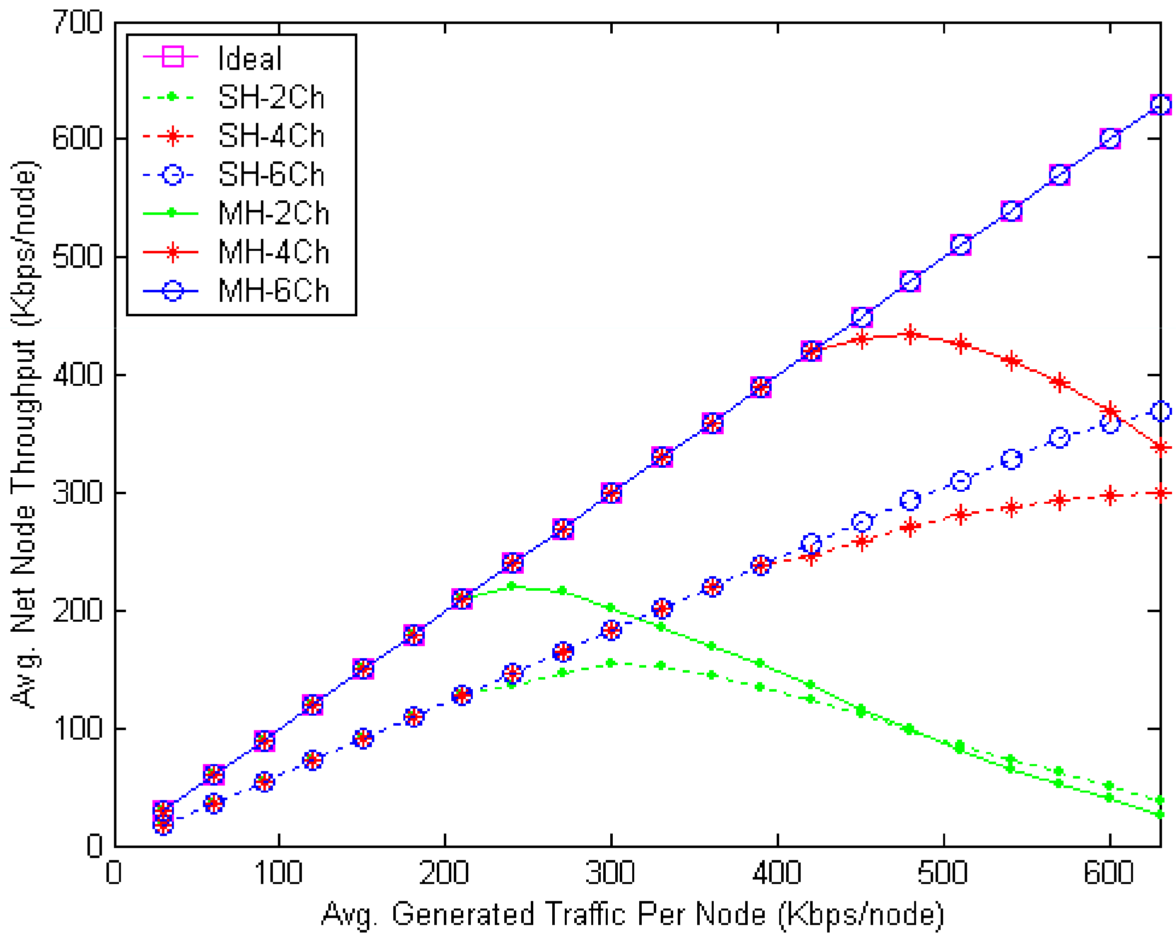
Connectivity Analysis: MH Network, 4-Channels



Connectivity Analysis: MH Network, 6-Channels

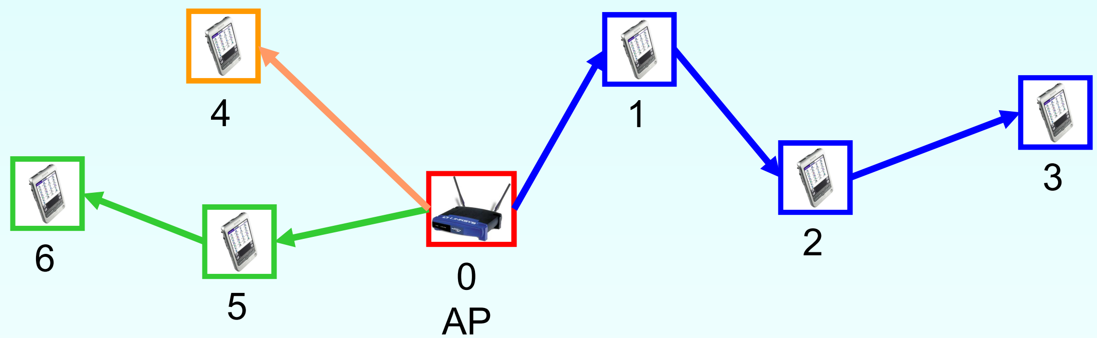


Net Node Throughput

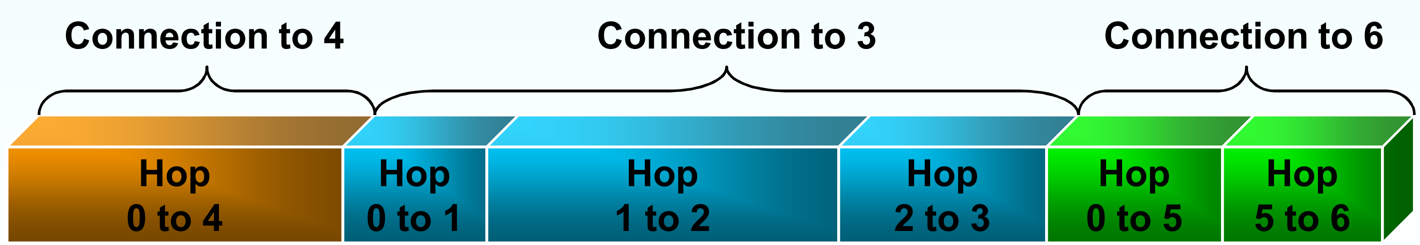


Example 5: Diversity- and AMC (Adaptive Modulation and Coding)-Aware Routing in Infrastructure-based Multihop Networks

Hares, Yanikomeroglu, Hashem
VTC'F03 & Globecom'03



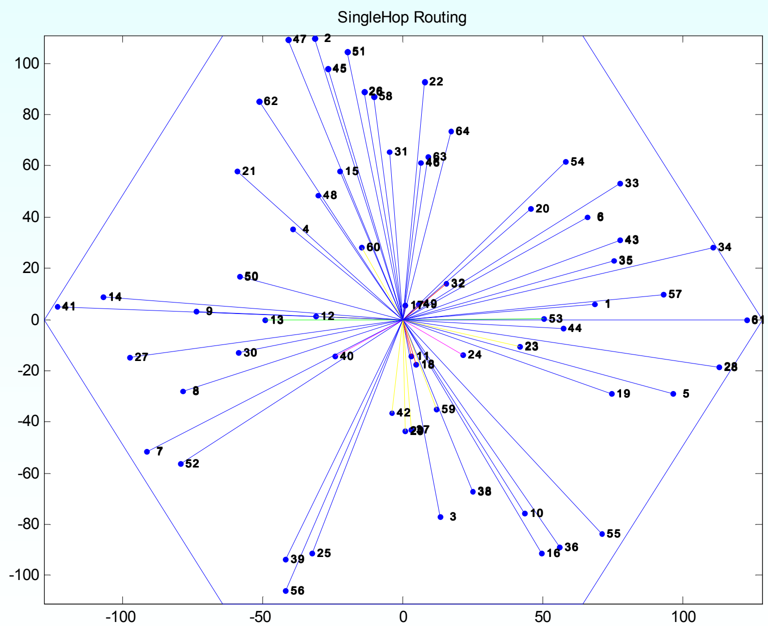
Time Domain – MAC Frame

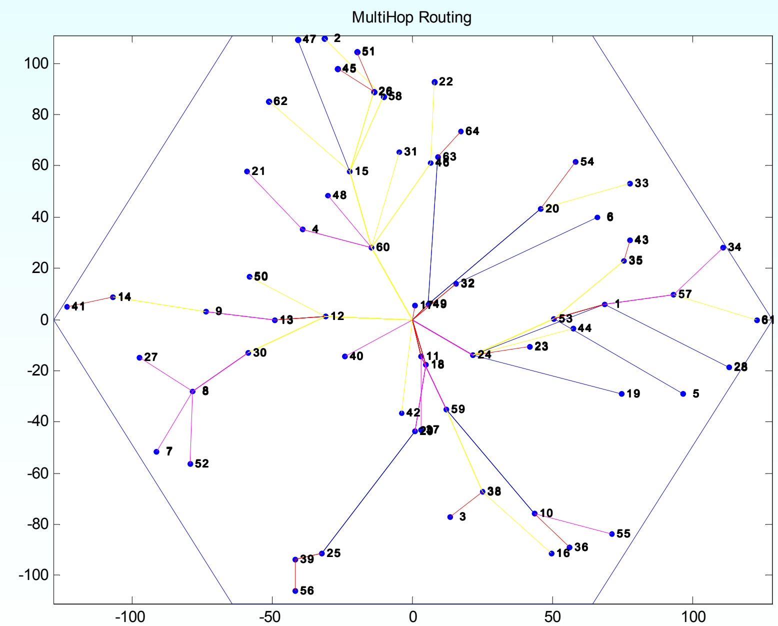


Extra channels are not used. Connections and hops are orthogonal in the time domain.

Routing

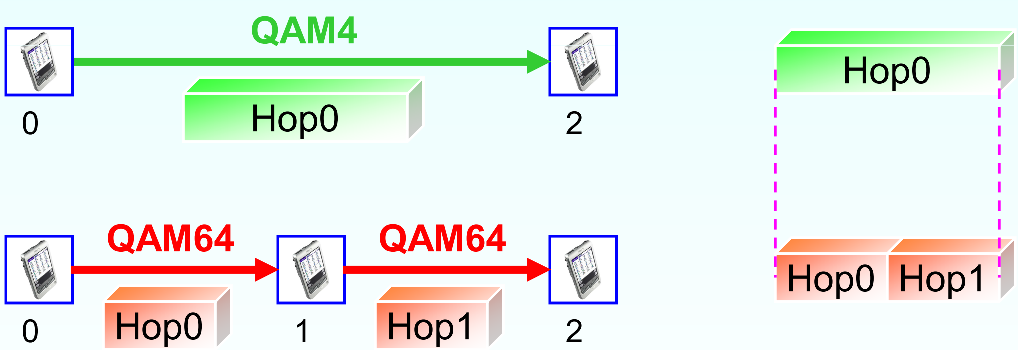
- Routing objective
  - Select relay nodes and hop modulation/coding (MC) to maximize throughput
    - Throughput = (Information Rate bits/sec)*(1 - Probability of error)
  - Increase Info. Rate or decrease end-to-end error rate to increase throughput. How?





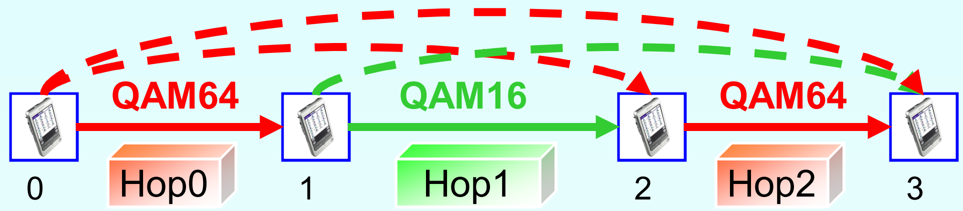
Frame Allocation for Relaying

- Adaptive modulation and coding (AMC)
- Different MC used on hops
- Amount of data entering and exiting relaying nodes are equal

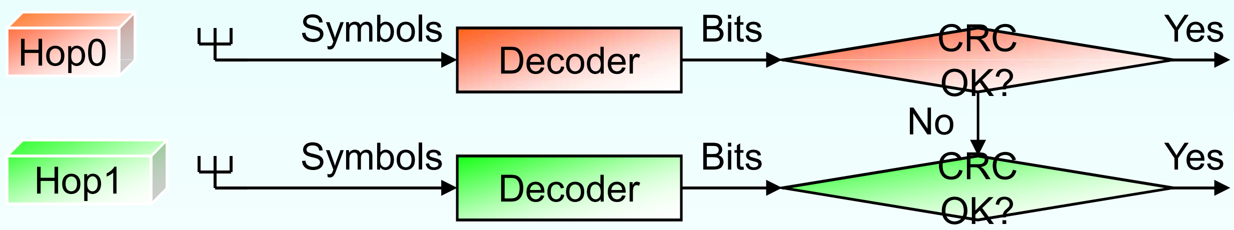


Multihop Diversity

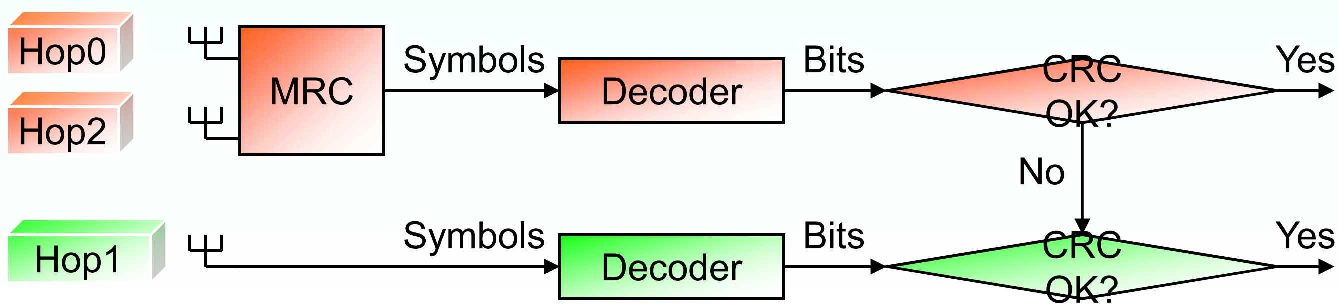
Time Domain



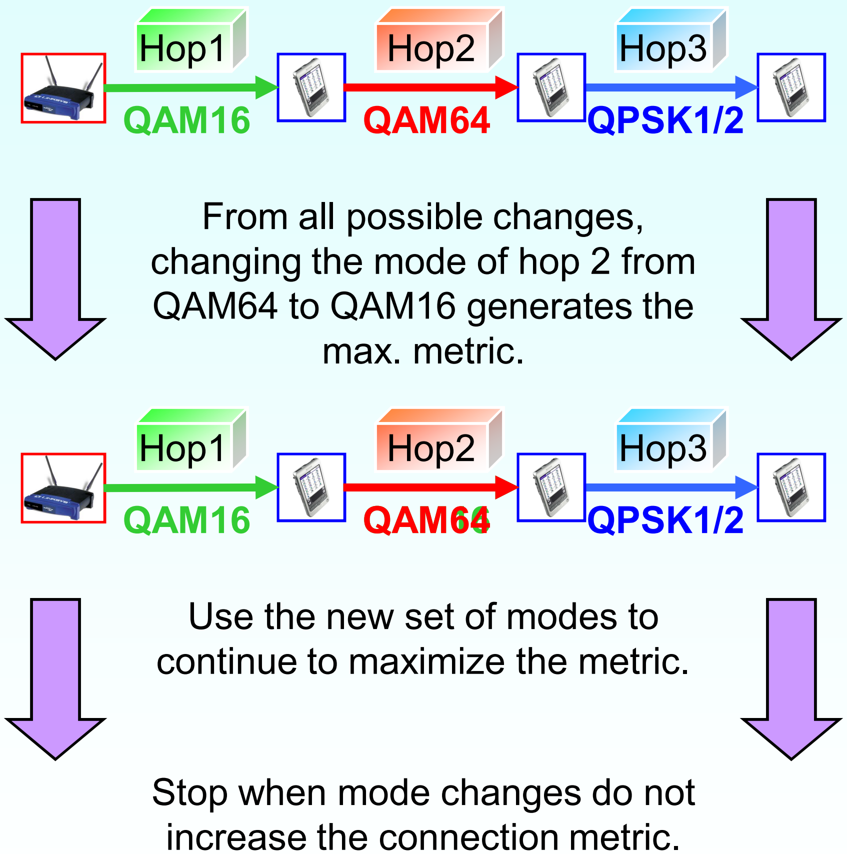
Node 2 Receiver Operation Equivalent



Node 3 Receiver Operation Equivalent



Adaptive Modulation & Coding Maximization (AMCM)

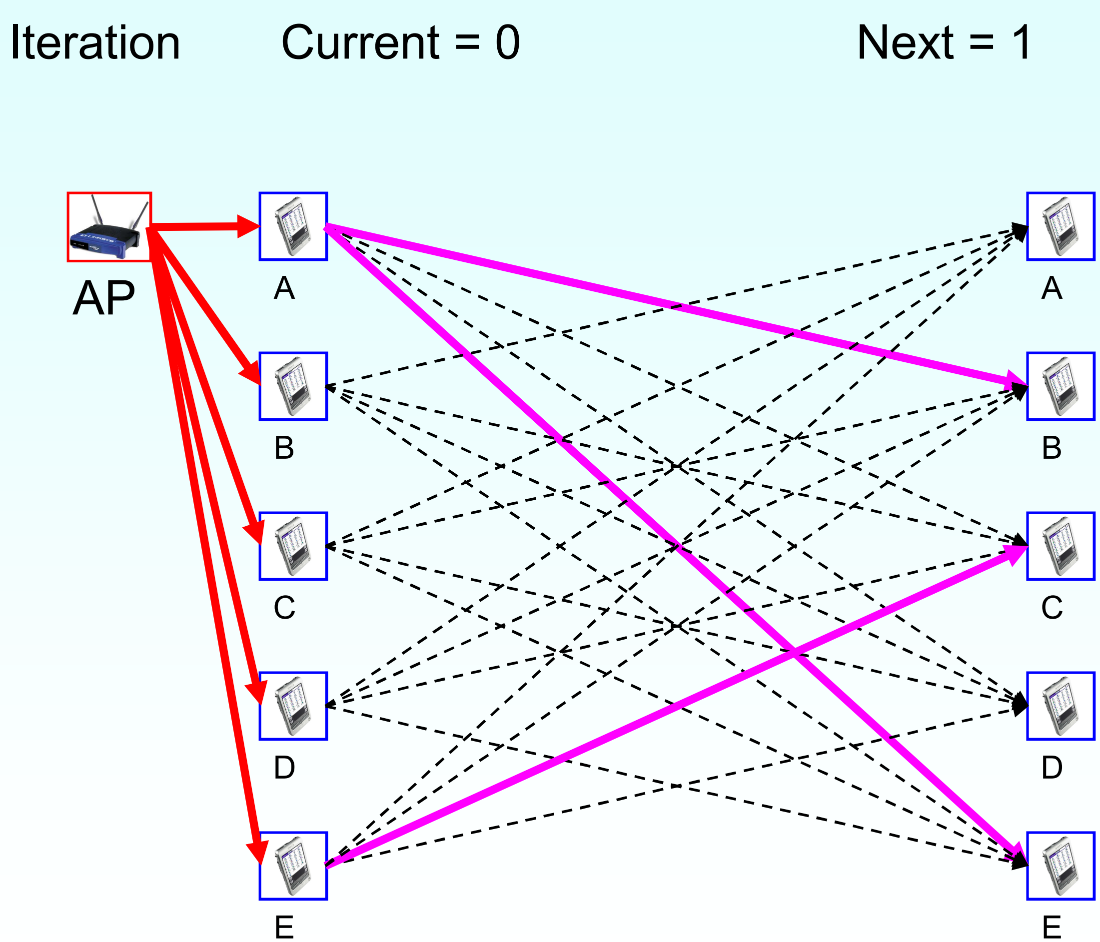


- Originally, hop modes were selected to maximize data rates on hops.
- AMCM adapts hop modes to maximize the connection throughput for systems using MRC diversity.
- Performed after route has been selected.
- Possible modes a hop can assume is limited to the set of modes used in the connection (i.e. QAM16, QAM64, QPSK1/2).
- For each iteration, examine all possible modes for all hops.
- Change a mode for a single hop that generates the maximum metric for the connection.
- Use the new set of modes for the subsequent iteration.
- Stop when a mode change does not increase the metric for the connection.

Routing Types

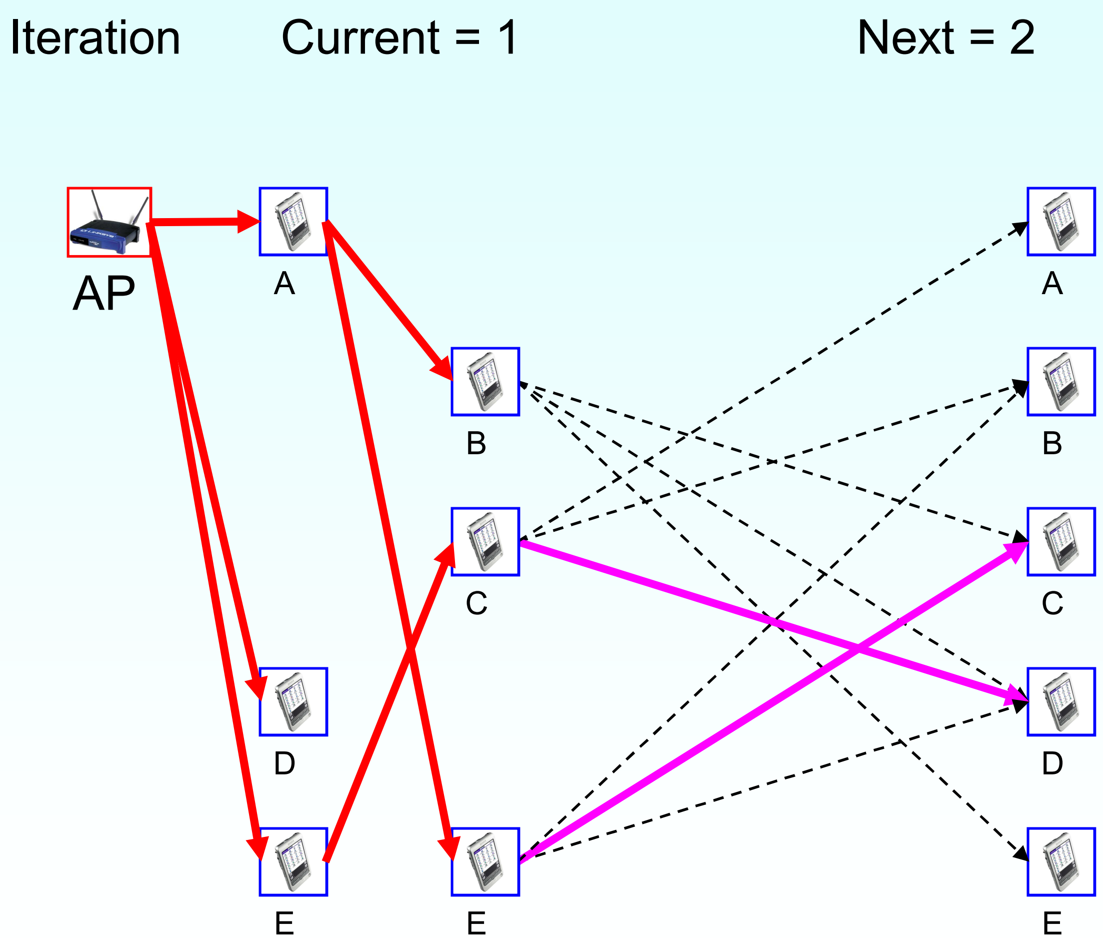
- Route Selection Strategies:
  - Single Hop (SH)
  - Multihop (MH)
  - Multihop Selection Combining Diversity (MHSC)
    - Routing metric factors selection combining diversity
  - Multihop MRC Diversity (MHMRC)
    - Routing metric factors MRC diversity
  - Multihop Adaptive Modulation MRC Diversity (MHAMMRC)
    - Routing metric factors MRC diversity
    - Uses AMCM
  - Hybrid Digital and Analog Relaying (HDAR)
    - Nodes relay incorrectly decoded signals as analog signals

Routing – Example (1)



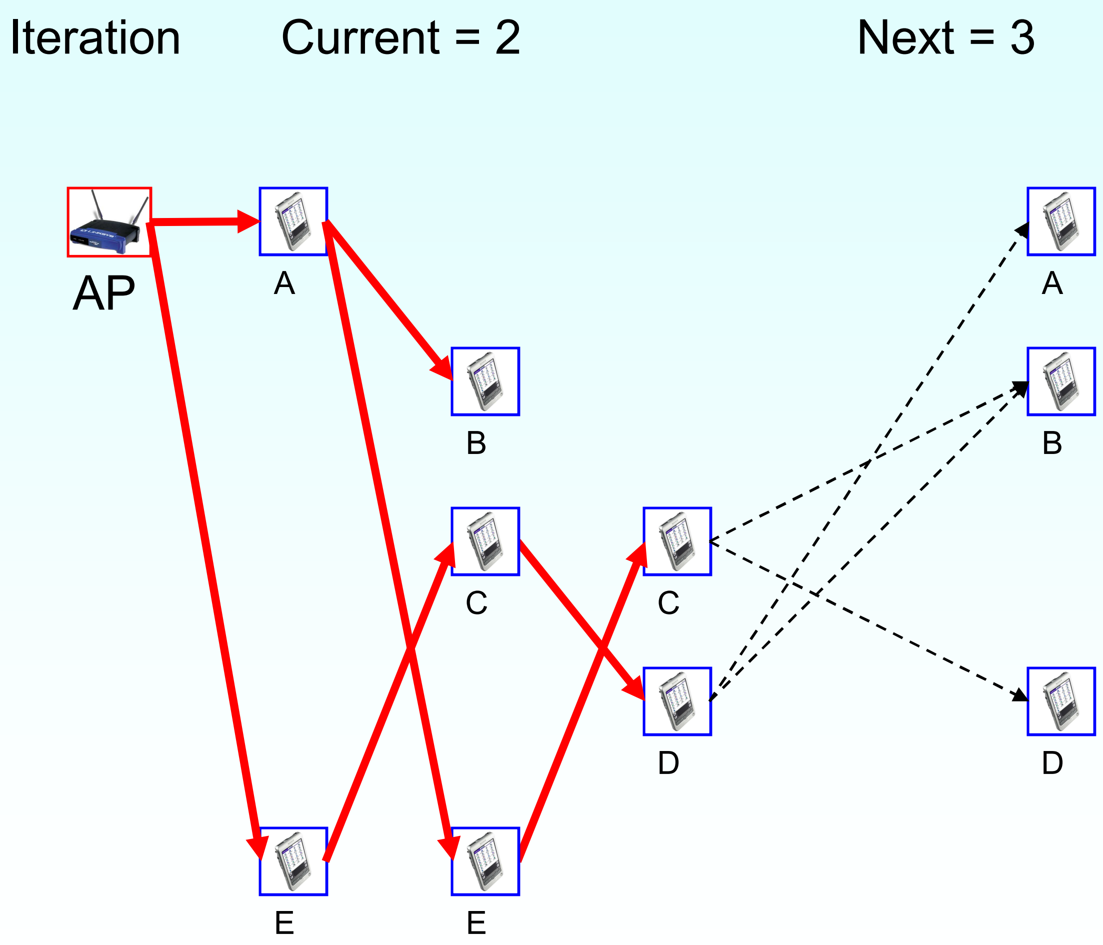
- Initially, routes only contain the AP and destination node.
- Examine all next routes.
- Next routes (black) built off current routes (red).
- Next routes generating max. metrics are in purple.
- If metric of next route > metric of current route, on next iteration, current route = next route.
- Next iteration routes:
  - B: AP-A-B
  - C: AP-E-C
  - E: AP-A-E

Routing – Example (2)



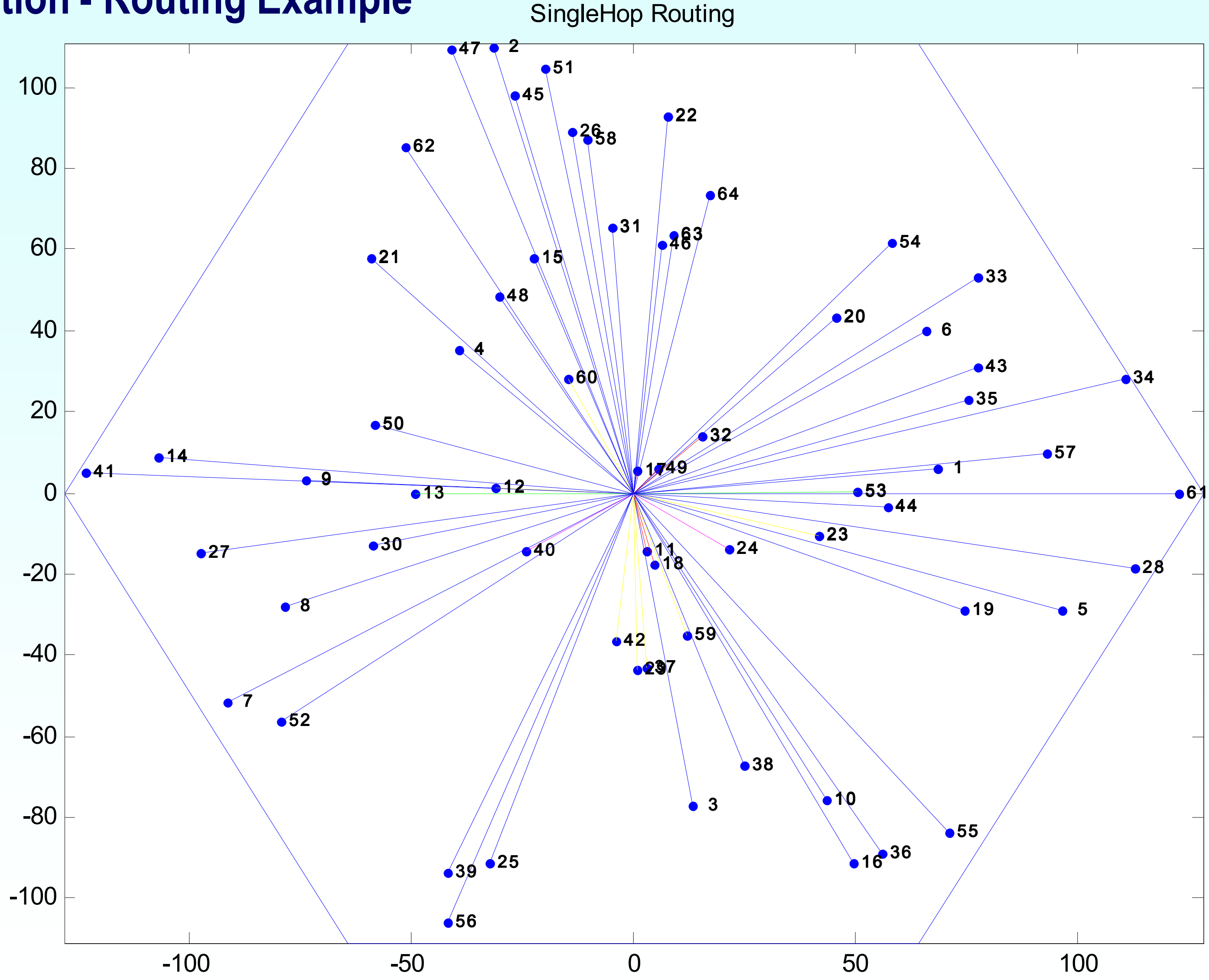
- Only check routes to nodes not included in current route.
- Next iteration routes:
  - C: AP-A-E-C
  - D: AP-E-C-D
- Need to only examine next routes built from routes which changed on previous iteration.

Routing – Example (3)

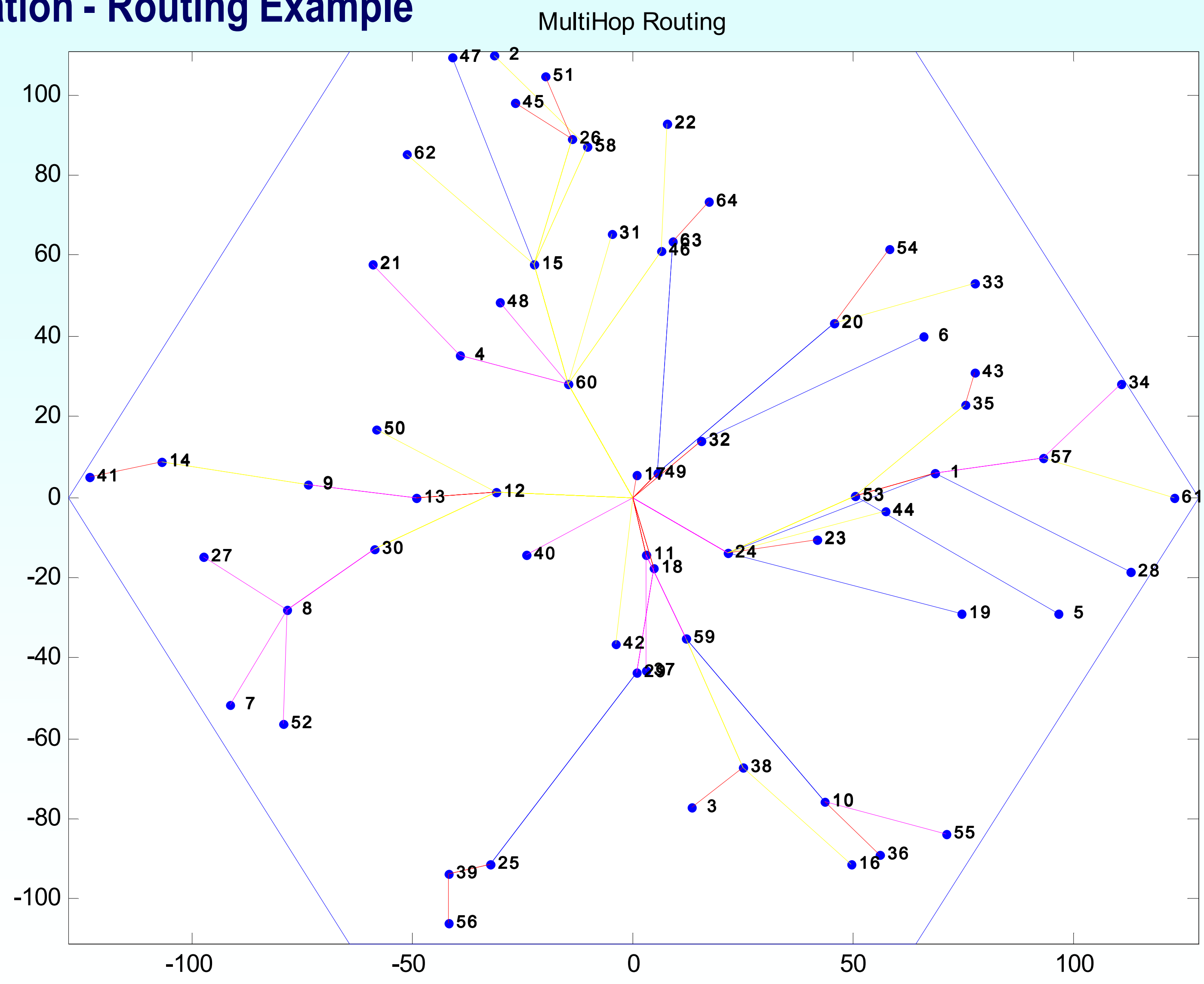


- Stop searching when next generation of routes do not yield higher metrics.
- Final connections:
  - A: AP-A
  - B: AP-A-B
  - C: AP-A-E-C
  - D: AP-E-C-D
  - E: AP-A-E

Simulation - Routing Example

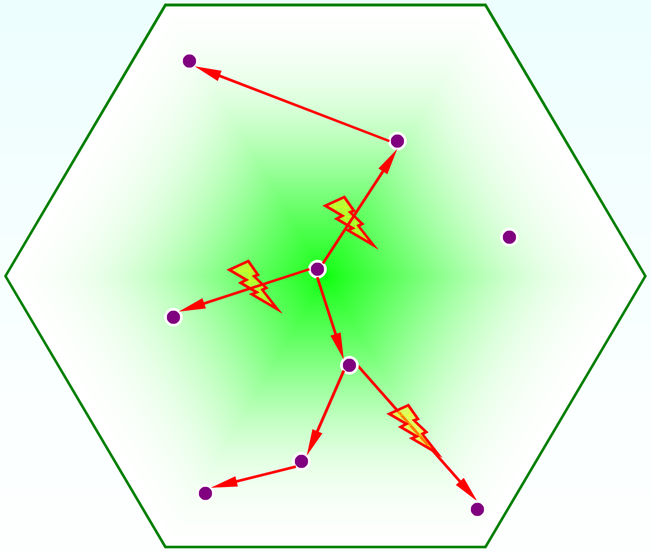


Simulation - Routing Example

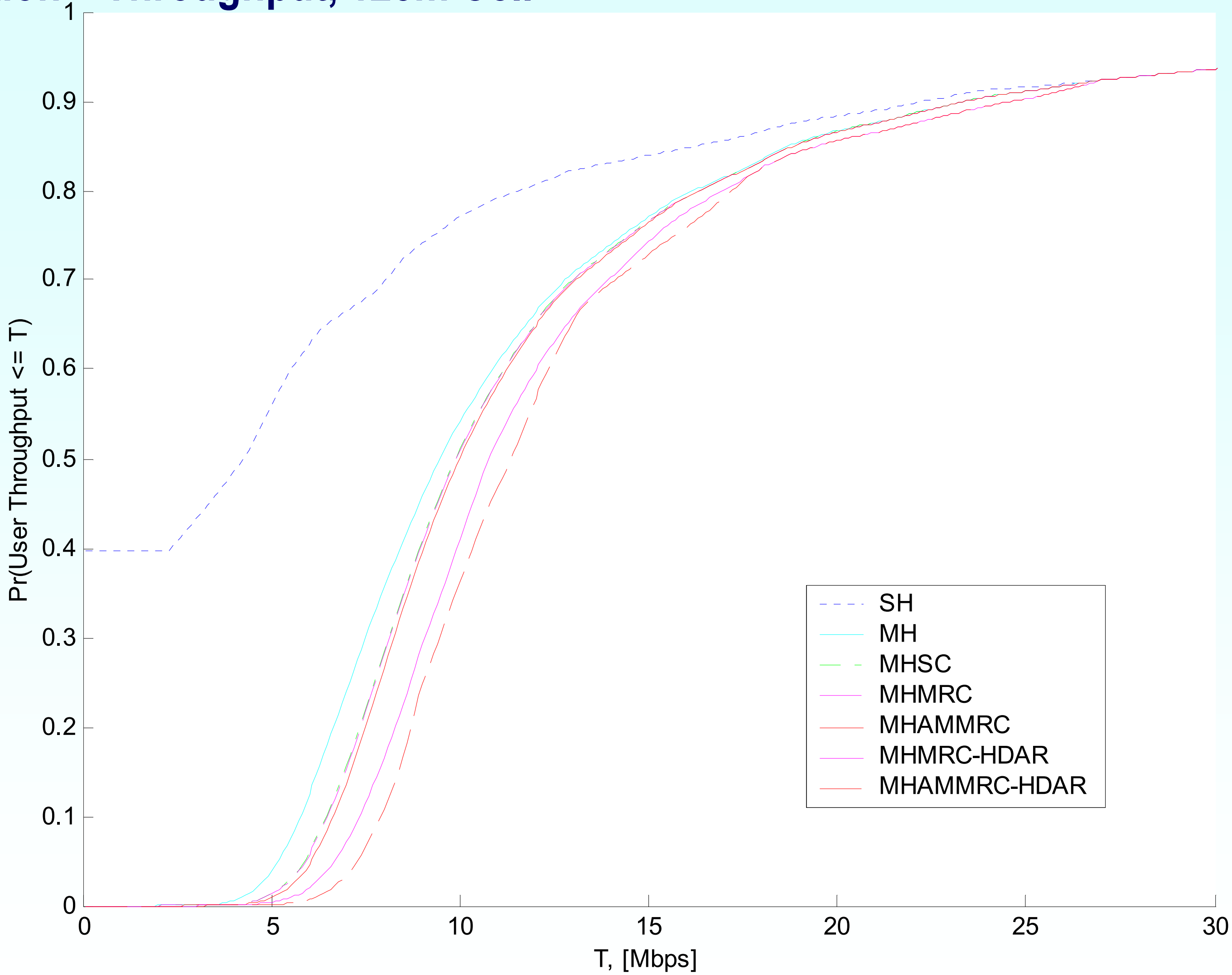


Simulation - Parameters

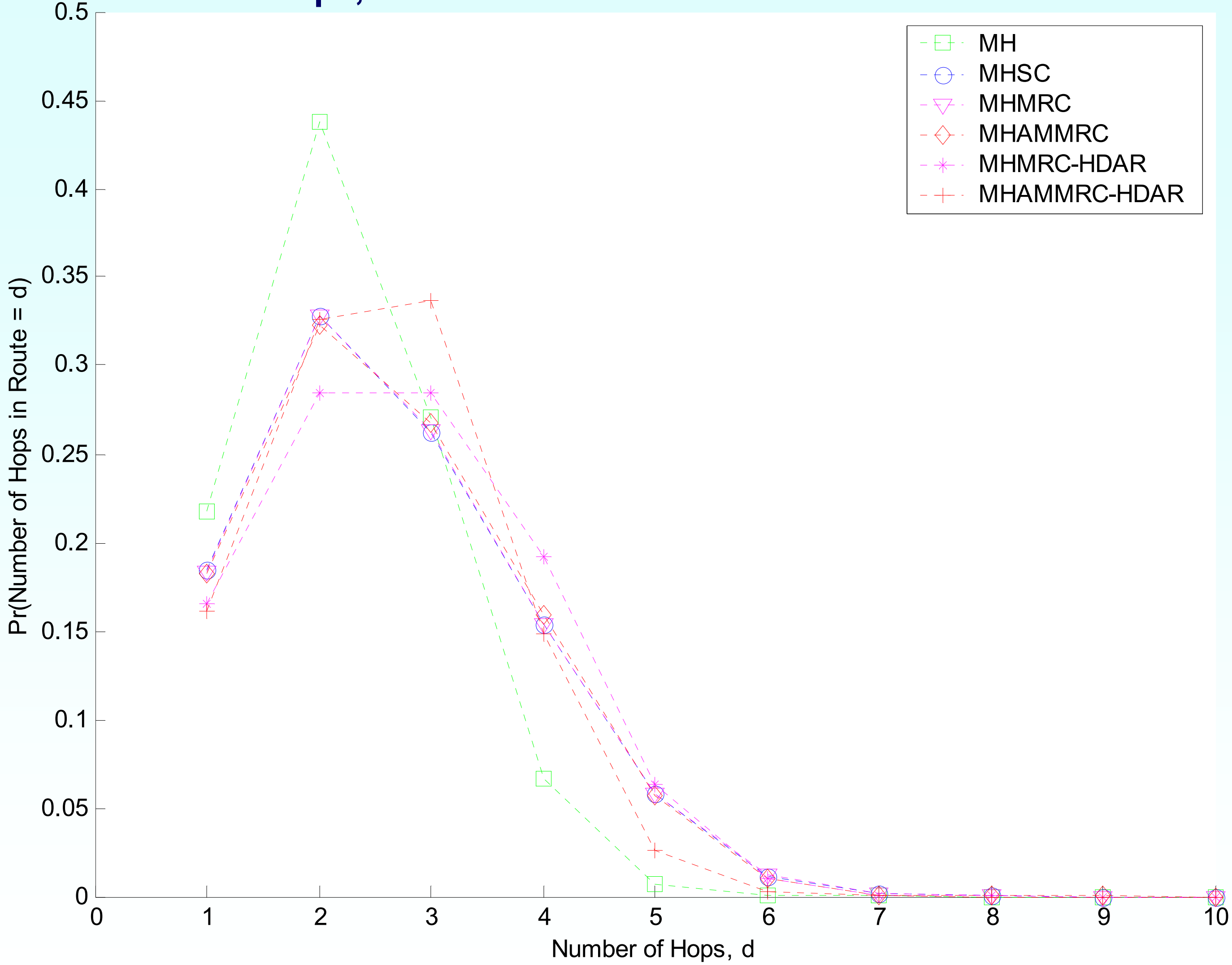
- NLOS office environment
- ETSI-A channel model
  - Rayleigh fading 50ns RMS delay spread
- Noise power, P_{N0} = -90dBm
- Propagation exponent, α = 3.4
- Carrier frequency, f_c = 5.3GHz
- Shadowing, σ = 5.1dB
- Omni-directional antennas
- Fixed transmit power, P_{tx} = 23dBm
- Adaptive modulation
- Constant interference
- Hexagonal radius, R = 128m
- Cluster size, N = 12
- No mobility



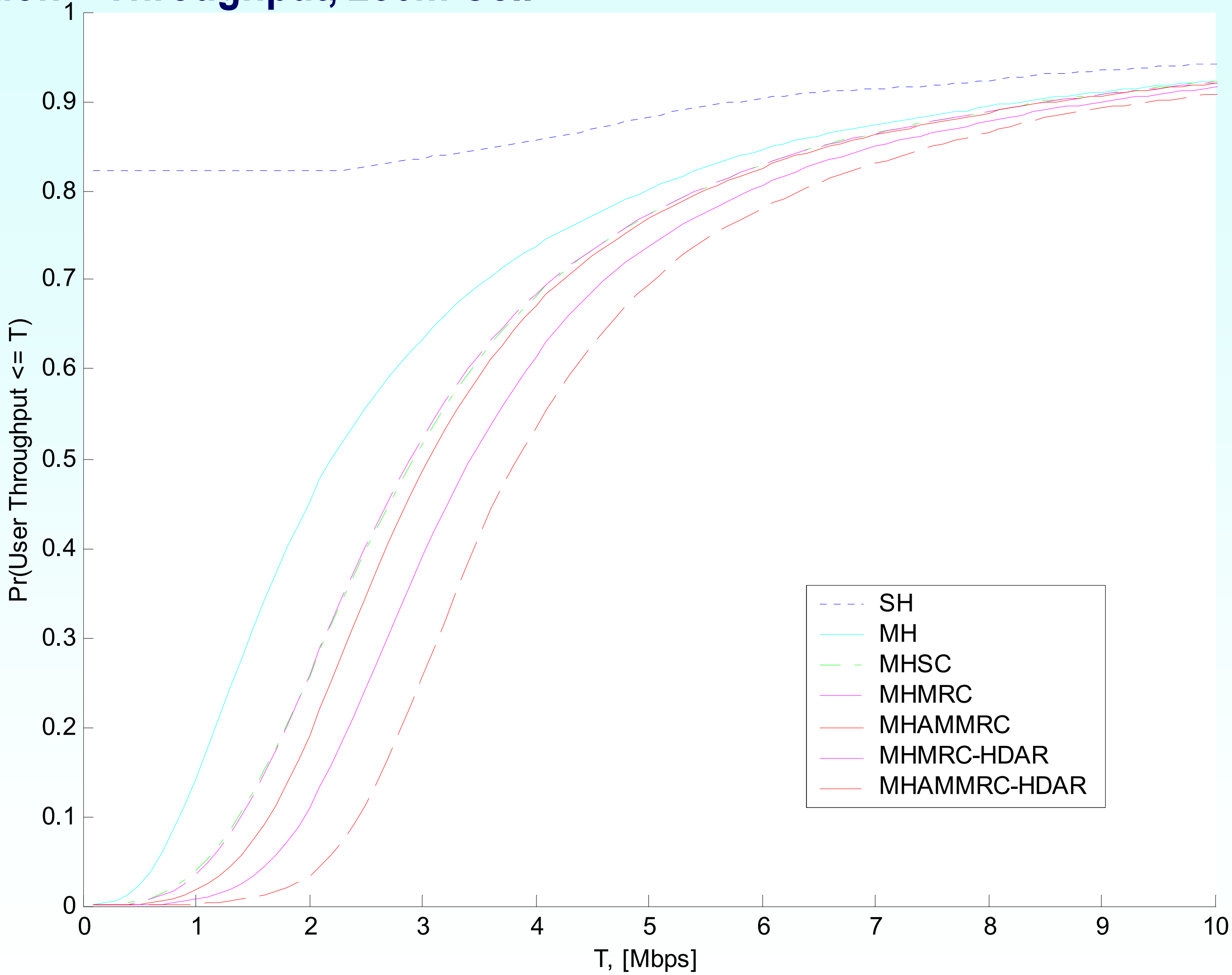
Simulation – Throughput, 128m Cell



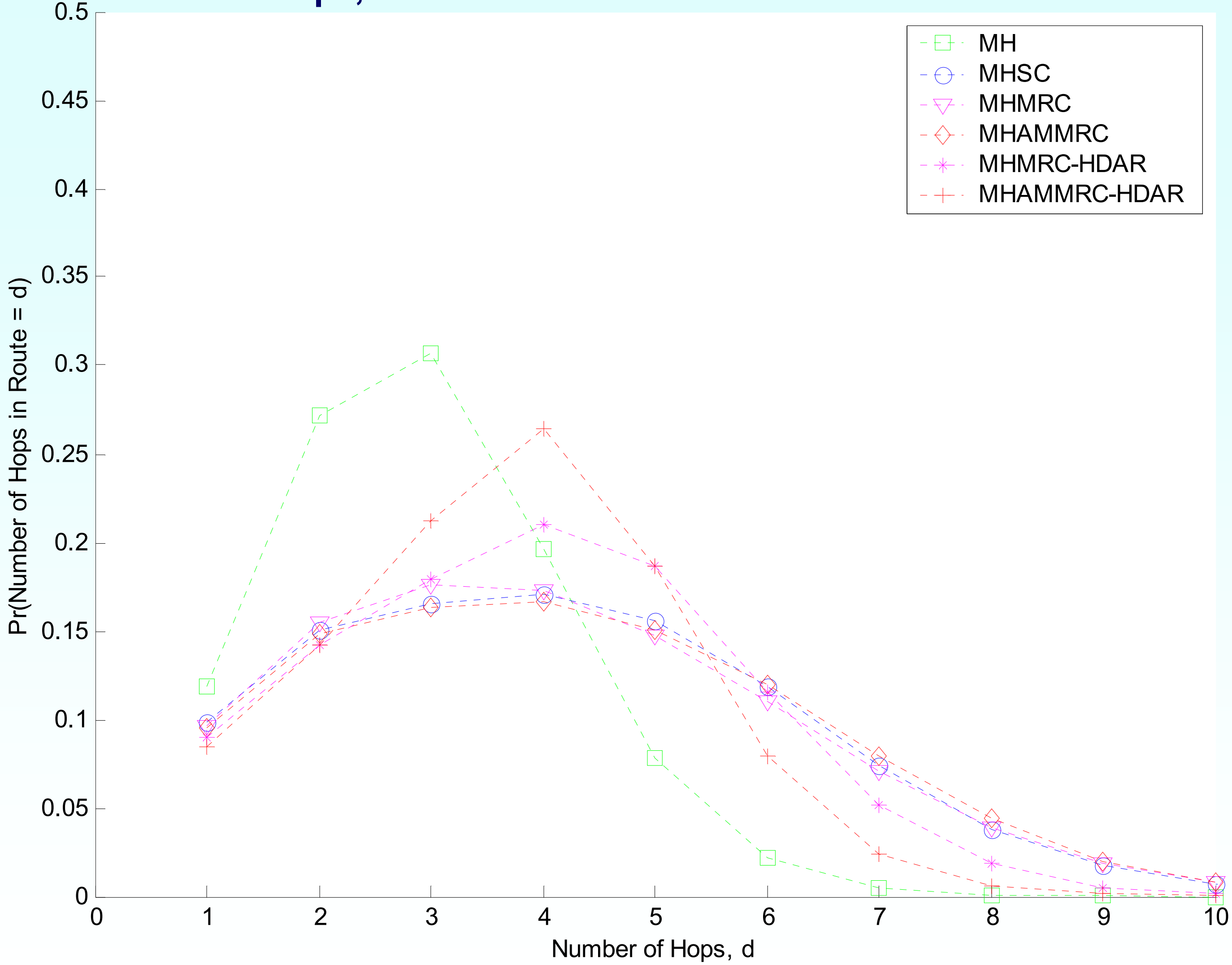
Simulation - Number of hops, 128m Cell



Simulation – Throughput, 256m Cell



Simulation - Number of hops, 256m Cell



Simulation Results

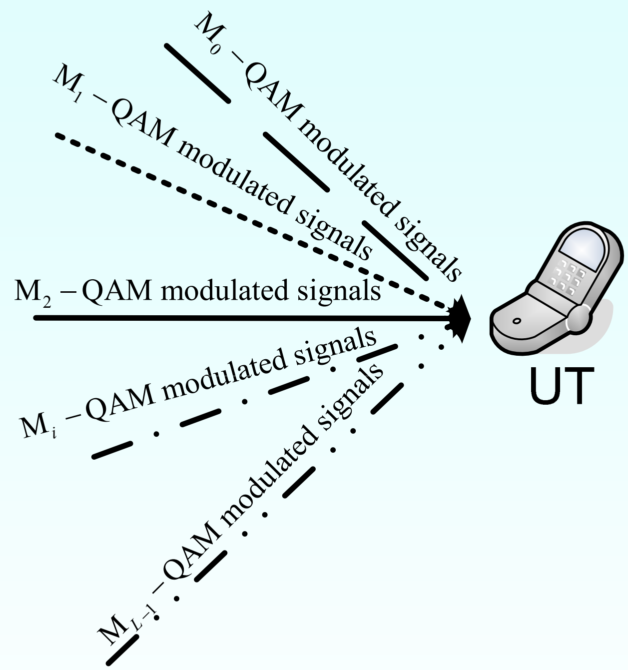
Routing Type	System Diversity	Avg. Network Throughput [Mbps]		Avg. Hops in Route	
		128m Cell	256m Cell	128m Cell	256m Cell
SH	None	7.75	2.07	1	1
MH	None	12.77	4.17	2.21	2.93
MHSC	SC	13.17	4.70	2.64	4.17
MHMRC	MRC	13.19	4.70	2.62	4.14
MHAMMRC	MRC	13.26	4.85	2.62	4.24
MHAMMRC-HDAR	MRC	14.32	5.62	2.56	3.70

- Routing Type – routing/metric type
- System Diversity – form of diversity used at nodes
- SH = singlehop, MH = multihop (routing algorithm)
- MHAM = multihop adaptive modulation (routing algorithm)

Observations

- Multihop routes → Optimal 2-hop routes
- Diversity techniques: very attractive -- they do not use additional radio resources (power or bandwidth)
- Routing: incorporates diversity benefits
- HDAR: increases diversity benefits
- Average aggregate throughput: increases 2-3X
- Outage: reduces very significantly (range extension: remarkable)
- Strategically placed fixed relayers: may be very attractive
- Can be used in any TDMA network, if
  - PER models are known & channel updates supported
- For more information:
  - Shoaev Hares, Halim Yanikomeroglu, and Bassam Hashem, "Diversity- and AMC (Adaptive Modulation and Coding)-Aware Routing in TDMA Multihop Networks", *IEEE GLOBECOM 2003*
  - Shoaev Hares, Halim Yanikomeroglu, and Bassam Hashem, "A relaying algorithm for multihop TDMA TDD networks using diversity", *IEEE VTC Fall 2003*

Example 6: Combining Signals with Different Modulation Levels



Selection Combining Schemes (1/5)

- Conventional Selection Combining (SC):
  Decodes the signal from the branch that has the Maximum SNR.
  Drawback:
  It doesn't account for the difference in reliabilities of different modulation levels.

- BER Selection Combining (BSC):
  Decodes the signal from the branch that has the Minimum BER.

Selection Combining Schemes (2/5)

BER performance analysis of SC and BSC

- Rich literature, but limited to similar modulation levels.
- Exact BER of SC:

$$BER=\frac{1}{2}c_{M_0}\left(1-\sqrt{\frac{d_{M_0}^2\bar{\gamma}_0}{1+d_{M_0}^2\bar{\gamma}_0}}\right)+\frac{1}{2}c_{M_1}\left(1-\sqrt{\frac{d_{M_1}^2\bar{\gamma}_1}{1+d_{M_1}^2\bar{\gamma}_1}}\right)-\frac{1}{2}c_{M_0}\frac{\bar{\gamma}_1}{\bar{\gamma}_0+\bar{\gamma}_1}\left(1-\sqrt{\frac{d_{M_0}^2\bar{\gamma}_2}{1+d_{M_0}^2\bar{\gamma}_2}}\right)-\frac{1}{2}c_{M_1}\frac{\bar{\gamma}_0}{\bar{\gamma}_0+\bar{\gamma}_1}\left(1-\sqrt{\frac{d_{M_1}^2\bar{\gamma}_2}{1+d_{M_1}^2\bar{\gamma}_2}}\right)$$

$$\bar{\gamma}_2 \triangleq \frac{\bar{\gamma}_0\bar{\gamma}_1}{\bar{\gamma}_0+\bar{\gamma}_1}$$

$$BER\approx\frac{1}{2}c_{M_0}\left(1-\sqrt{\frac{d_{M_0}^2\bar{\gamma}_0}{1+d_{M_0}^2\bar{\gamma}_0}}\right)+\frac{1}{2}c_{M_1}\left(1-c_{M_1}\sqrt{\frac{d_{M_1}^2\bar{\gamma}_1}{1+d_{M_1}^2\bar{\gamma}_1}}\right)-\frac{1}{2}\frac{c_{M_0}d_{M_1}^2\bar{\gamma}_1+c_{M_1}d_{M_0}^2\bar{\gamma}_0}{d_{M_0}^2\bar{\gamma}_0+d_{M_1}^2\bar{\gamma}_1}\left(1-\sqrt{\frac{\bar{\gamma}_2}{1+\bar{\gamma}_2}}\right)$$

$$\bar{\gamma}_2 \triangleq \frac{d_{M_0}^2\bar{\gamma}_0 d_{M_1}^2\bar{\gamma}_1}{d_{M_0}^2\bar{\gamma}_0+d_{M_1}^2\bar{\gamma}_1}$$

- Very good approximation of BER of BSC:

Selection Combining Schemes (3/5)

Asymptotic BER performance analysis of SC and BSC

- SC:

$$BER \approx \left(D^{SC}\mathbf{SNR}\right)^{-2}, \text{ as } \mathbf{SNR}\to\infty$$

$$\text{where } D^{SC} = \frac{4}{\sqrt{3}}\left(\frac{c_{M_0}d_{M_1}^4 + c_{M_1}d_{M_0}^4}{d_{M_0}^4 d_{M_1}^4}\right)^{-\frac{1}{2}}\sigma_0\sigma_1.$$

- BSC:

$$BER \approx \left(D^{BSC}\mathbf{SNR}\right)^{-2}, \text{ as } \mathbf{SNR}\to\infty$$

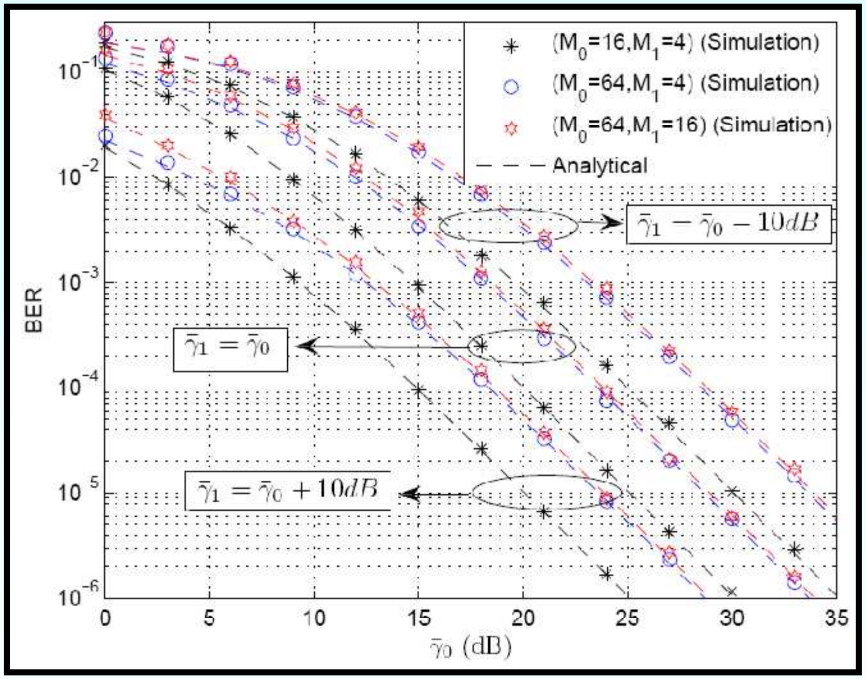
$$\text{where } D^{BSC} = \frac{4}{\sqrt{3}}\left(c_{M_0} + c_{M_1}\right)^{-\frac{1}{2}} d_{M_0} d_{M_1}\sigma_0\sigma_1.$$

- Asymptotic Gain (AG):

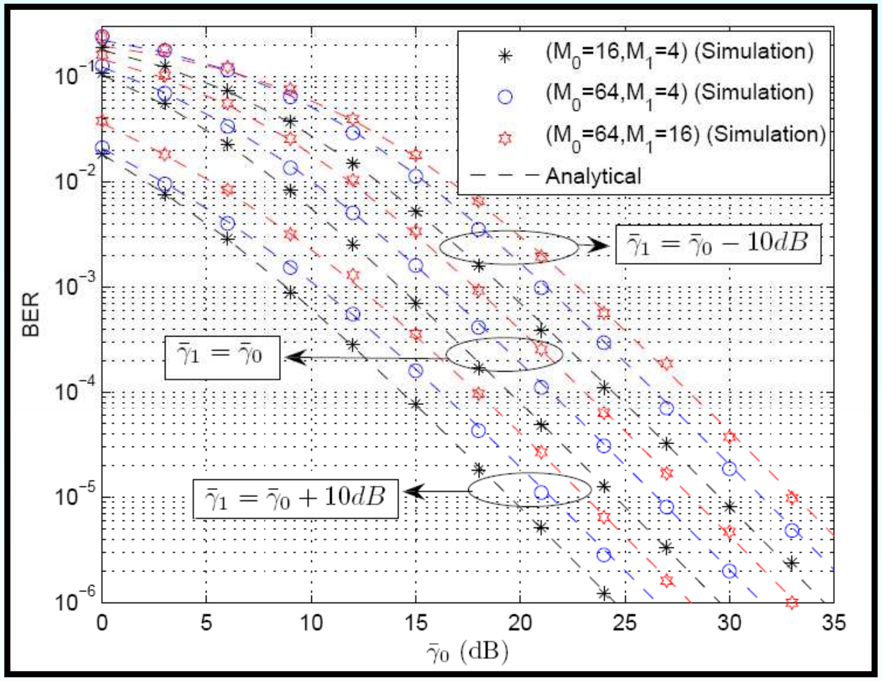
$$AG = 10\log_{10}\left(\frac{D^{BSC}}{D^{SC}}\right) = 5\log_{10}\left(\frac{c_{M_0}\dfrac{d_{M_1}^2}{d_{M_0}^2} + c_{M_1}\dfrac{d_{M_0}^2}{d_{M_1}^2}}{c_{M_0} + c_{M_1}}\right).$$

$$AG = \begin{cases} 0.57\text{dB}, & \text{combining QPSK and 16-QAM} \\ 2.13\text{dB}, & \text{combining QPSK and 64-QAM} \\ 0.77\text{dB}, & \text{combining 16-QAM and 64-QAM} \end{cases}.$$

Selection Combining Schemes (4/5)



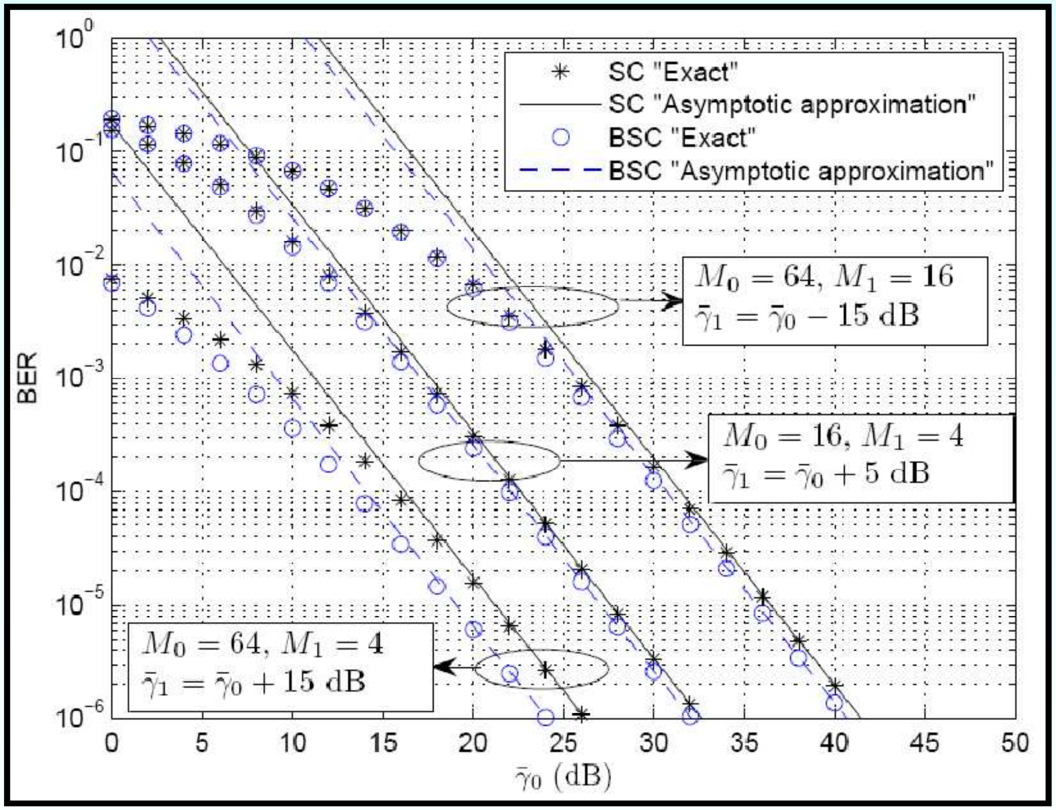
SC



BSC

Excellent agreement between theory and simulation.

Selection Combining Schemes (5/5)



$$AG = \begin{cases} 0.57\text{dB}, & \text{combining QPSK and 16-QAM} \\ 2.13\text{dB}, & \text{combining QPSK and 64-QAM} \\ 0.77\text{dB}, & \text{combining 16-QAM and 64-QAM} \end{cases}.$$

Comparison between SC and BSC.

Optimal Detector

- Maximum Likelihood Detector (MLD):
  The MLD performs joint detection and utilizes all the branches according to following criterion:

$$[\hat{s}_1,\ldots,\hat{s}_C] = \arg\min_{s_1,\ldots,s_C} \sum_{i=0}^{L-1}\sum_{j=0}^{T_i-1} | r_{i,j}^{M_i} - \alpha_i S_{i,j}^{M_i}(s_{jK_i+1}, s_{jK_i+2}, \ldots, s_{(j+1)K_i}) |^2$$

- It achieves Optimum performance.

Drawback:

It has excessive computational complexity!

For example, for the case of combining 16-QAM and 64-QAM, the MLD decodes *C*=LCM*({4,6})=12* bits jointly.

This requires 2^{12} computations!

Soft-bit maximal ratio combining (SBMRC) (1/4)

- In the MLD: different modulation schemes carry different number of bits per symbol →
  bit by bit (or symbol by symbol) decoding is not possible!

- To overcome this problem, the received M_i-QAM soft symbol is mapped into K_i soft bits.

- Decoding can be preformed on the soft bits, which leads to bit by bit detection, rather than detecting a sequence of bits jointly.

Soft-bit maximal ratio combining (SBMRC) (2/4)

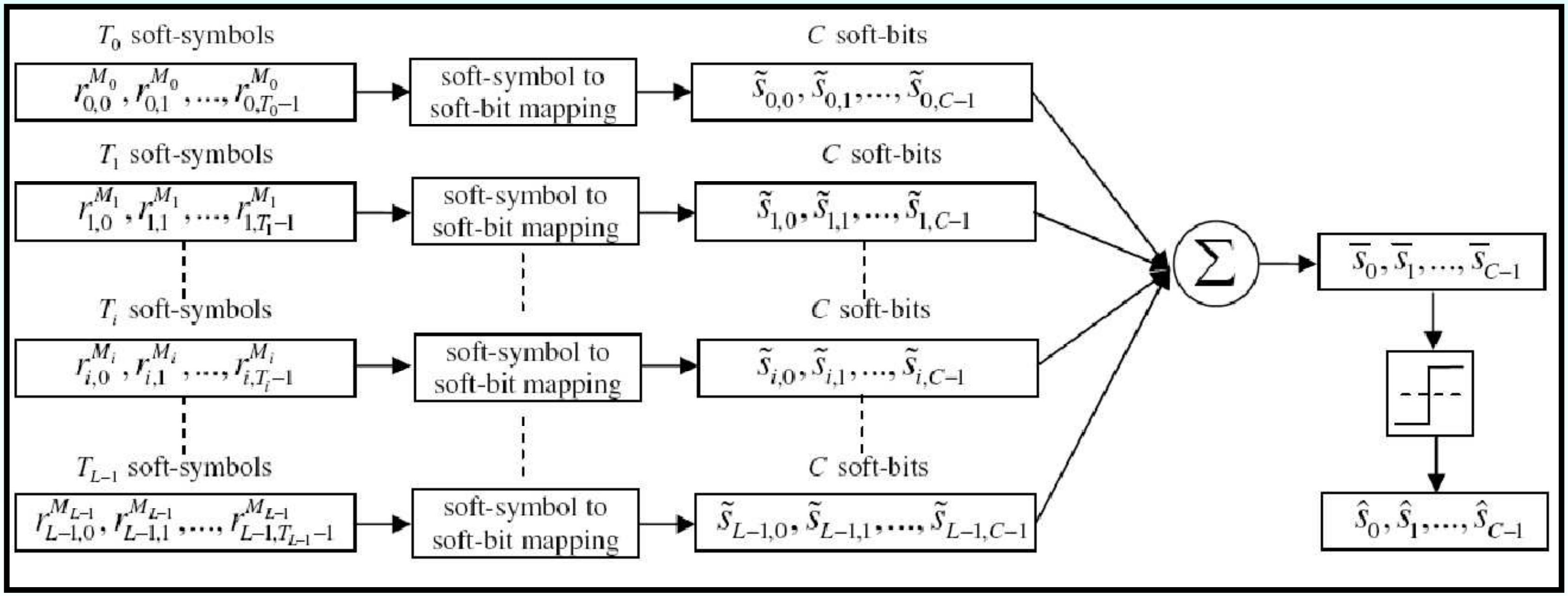
- Log-Likelihood ratio (LLR) can be used as soft-bit metric.
- Adding LLRs will result in the minimum BER (MAP receiver).
- However, calculating LLRs can be pricey!
- Use approximate LLR

$$\tilde{s}_{i,jK_i+k} = \begin{cases} d_{M_i}\,\mathrm{R}\,\{\alpha_i^{*} r_{i,j}^{M_i}\}, & k = 0 \\ 2^{\frac{K_i}{2}-k} d_{M_i}^{2}\,|\alpha_i|^2 - |\tilde{s}_{i,jK_i+k-1}|, & 0 < k \le \frac{K_i}{2} - 1 \\ -d_{M_i}\,\mathrm{I}\,\{\alpha_i^{*} r_{i,j}^{M_i}\}, & k = \frac{K_i}{2} \\ 2^{K_i-k} d_{M_i}^{2}\,|\alpha_i|^2 - |\tilde{s}_{i,jK_i+k-1}|, & \frac{K_i}{2} < k \le K_i - 1 \end{cases}$$

One simple calculation per bit

Goff, Glavieux, and Berrou (1994)
Aue & Nuessgen (2004)

Soft-bit maximal ratio combining (SBMRC) (3/4)



Soft-bit maximal ratio combining (SBMRC) (4/4)

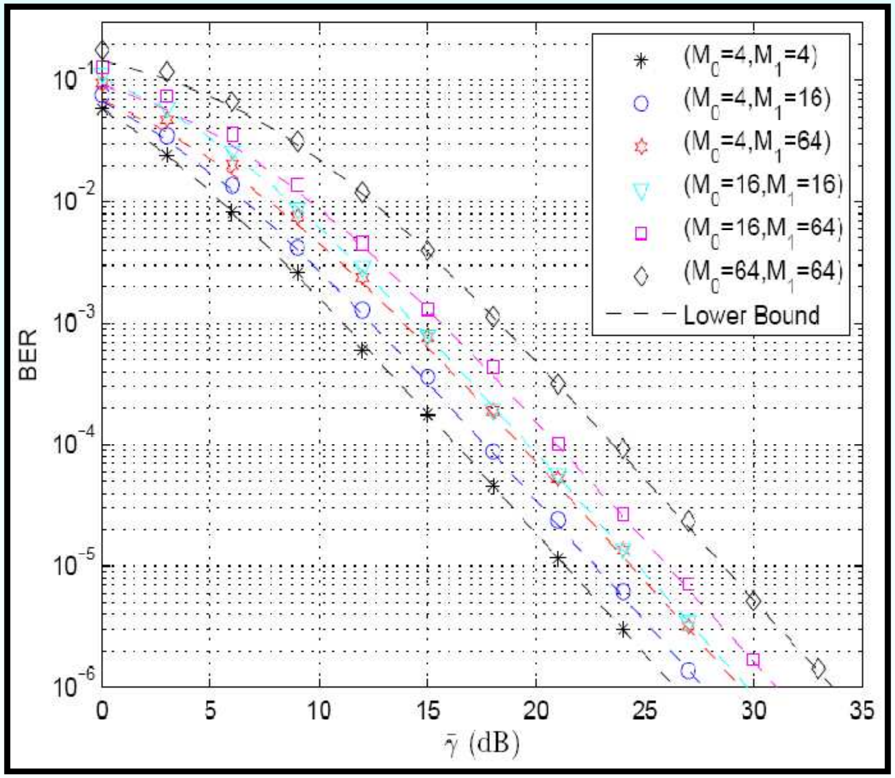
BER performance analysis of SBMRC

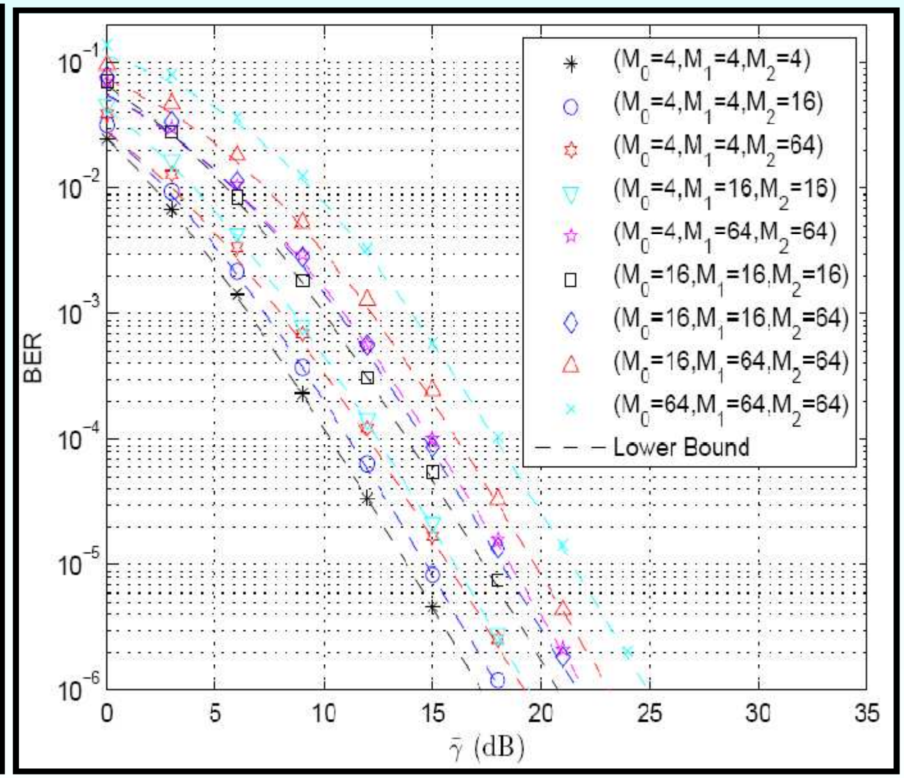
- Very tight lower bound on the BER performance of SBMRC:

$$BER > \frac{1}{2}\left(\frac{1}{C}\sum_{l=0}^{C-1}\frac{1}{N_{\bar{s}_l}}\right)\sum_{i=0}^{L-1}\pi_i\left(1-\sqrt{\frac{d_{M_i}^2\bar{\gamma}_i}{1+d_{M_i}^2\bar{\gamma}_i}}\right) \qquad \pi_i = \prod_{j=0,j\neq i}^{L-1}\frac{d_{M_i}^2\bar{\gamma}_i}{d_{M_i}^2\bar{\gamma}_i - d_{M_j}^2\bar{\gamma}_i}$$

A. Bin Sediq and H. Yanikomeroglu, "Performance analysis of soft-bit maximal ratio combining in cooperative relay networks", submitted to IEEE Transaction on Wireless Communications.

BER of SBMRC





- Excellent agreement between theory and simulation.
- Full diversity regardless of the combination.

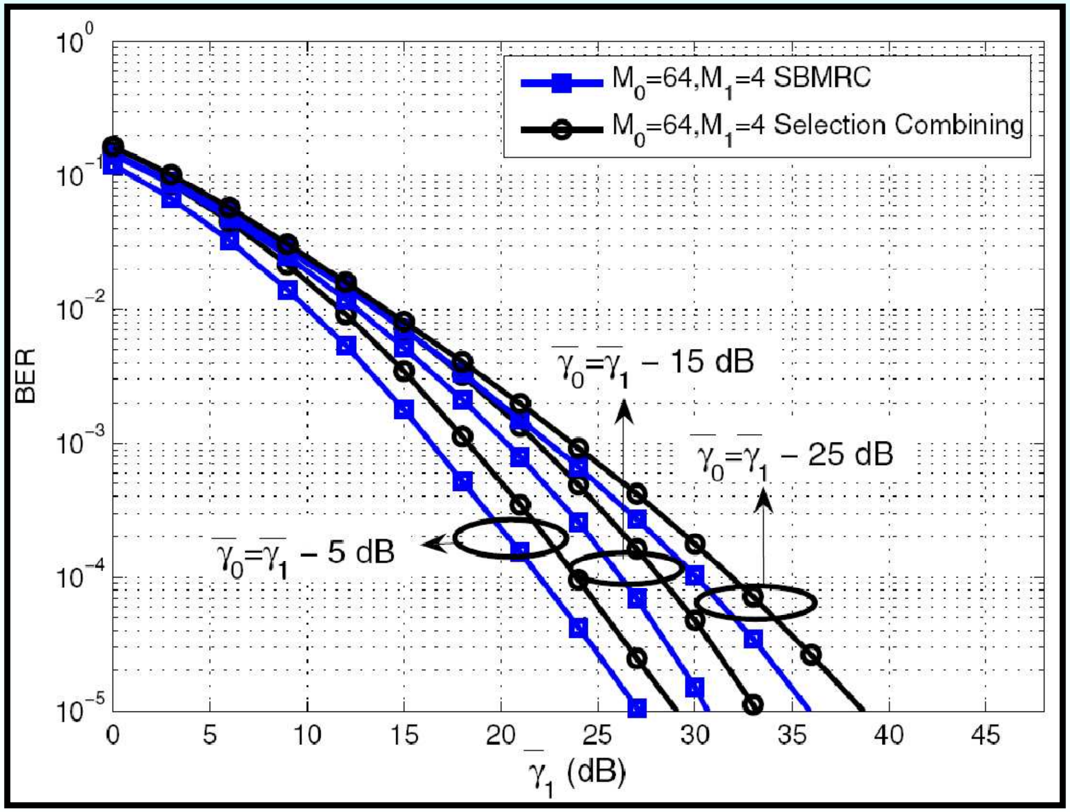
Comparing SC, BSC, and SBMRC with the optimal MLD

Loss in SNR (dB) at BER=10^{-3} of SC, BSC, and SBMRC compared to the optimum MLD.

Scheme / Scenario	SC	BSC	SBMRC
$M_0=4, M_1=16$	2.30	1.62	0.02
$M_0=4, M_1=64$	4.10	1.94	0.09
$M_0=16, M_1=64$	2.73	1.95	0.08
$M_0=4, M_1=4, M_2=16$	3.49	2.70	0.07
$M_0=4, M_1=4, M_2=64$	6.48	3.10	0.27
$M_0=4, M_1=16, M_2=16$	3.36	2.71	0.09
$M_0=16, M_1=16, M_2=64$	3.93	3.12	0.13
$M_0=16, M_1=64, M_2=64$	3.63	2.95	0.09

SBMRC has loss that is less than 0.3 dB!

Comparing selection combining and SBMRC

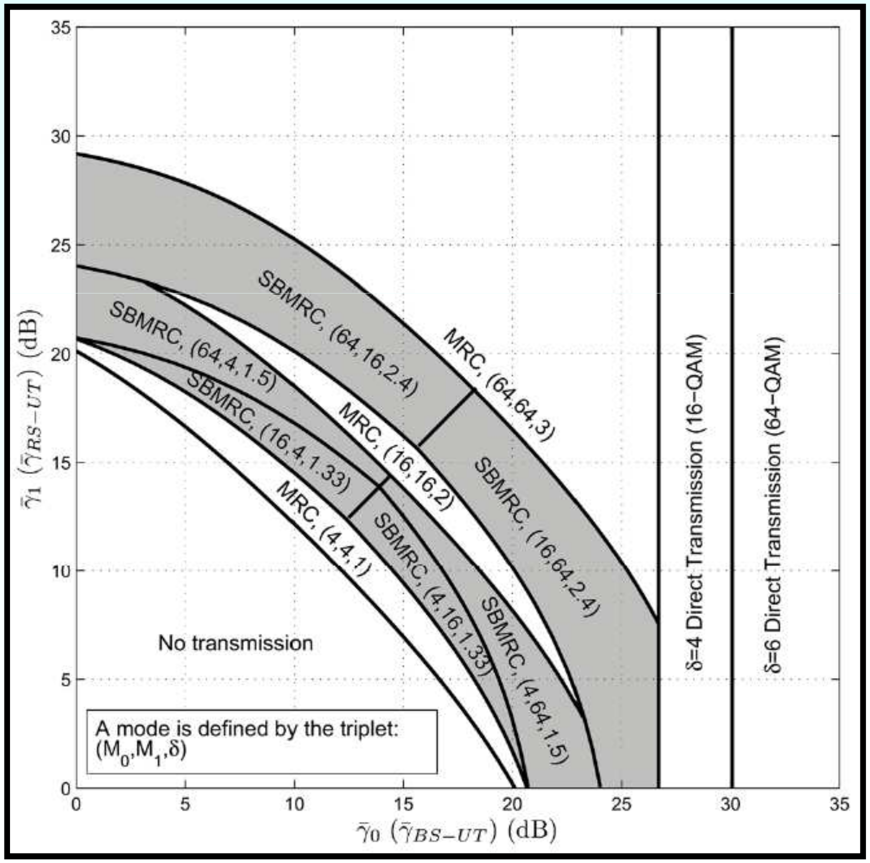


SBMRC provides a gain of ~ 2 dB!

Ongoing Work (1/2)

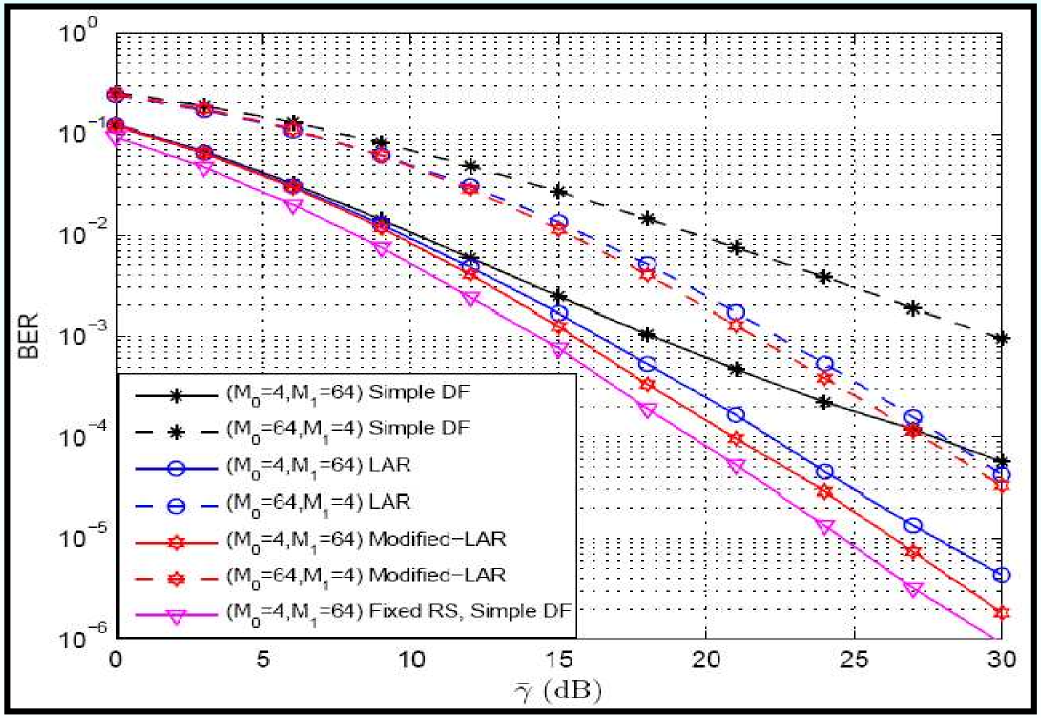
Quantifying the Gain in spectral efficiency achieved by using SBMRC

- Assuming *average* SNRs are available at BS.



Ongoing Work (2/2)

- Combining signals with different modulation levels in the presence of error propagation.



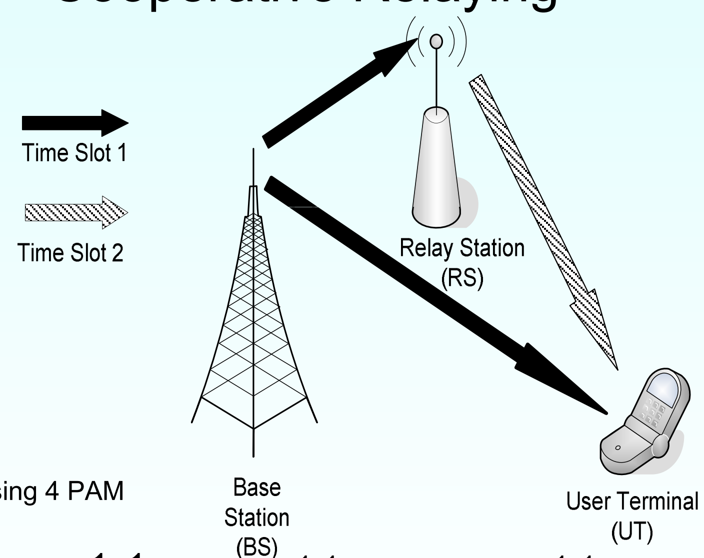
- **Full diversity still can be achieved.**
- **BS should be assigned lower (or equal) modulation level than that of RS.**

Summary of Combining Signals with Different Modulation Levels

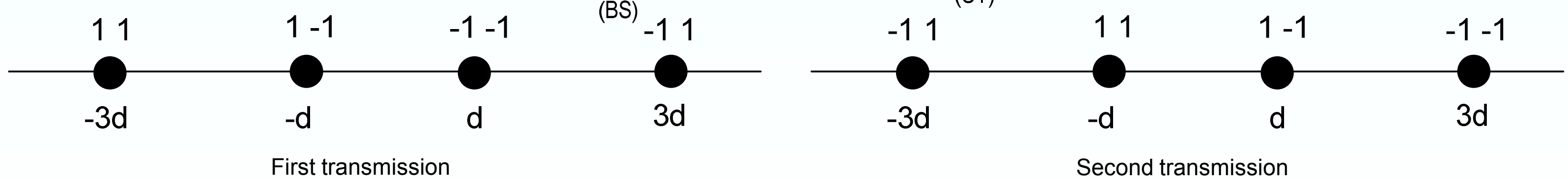
- We have investigated different diversity combining schemes for combining signals with different modulation levels.
- Introduced BSC which significantly outperforms SC. However, its performance is still worse than the optimal MLD.
- The SBMRC is a simple bit by bit detector and slightly inferior to the optimal MLD in performance.
- Comparing the BER performance results of different diversity combining schemes for different scenarios using both simulation and analytical results.
- The SBMRC significantly outperforms both SC and BSC.
- Closed-form BER expressions for SC, BSC, and SBMRC have been developed.
- Introducing modified LAR which significantly outperforms LAR.
- BER performance analysis for LAR and modified LAR.

Example 7: Constellation Rearrangement

Cooperative Relaying



Example: Two transmissions, using 4 PAM



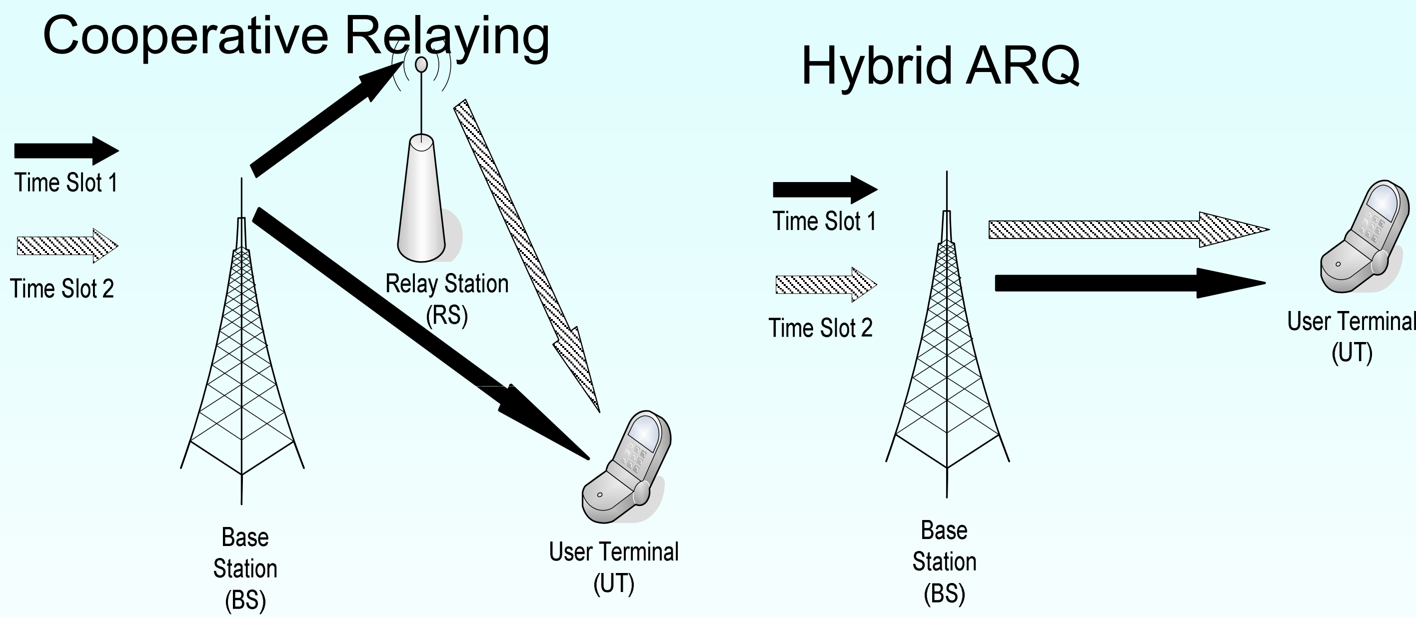
Relevant Work

- CoRe is originally proposed for HARQ where multiple transmission are needed for the same bits.

- CoRe 1:
  - Introduced by Wengerter et al. (VTC 2002).
  - The key idea is to average the variations in bit reliabilities inherited in Gray coded multilevel modulation schemes (such as PAM, QAM) .
  - All the transmissions are Gray coded.
  - Yamazaki et al. applied the previous scheme in Cooperative Relaying, for 16-QAM and 64-QAM (VTC 2007).

- CoRe 2:
  - Introduced by Gidlund et al. (ISCIT 2004).
  - The first transmission is Gray coded, while the rest are not.
  - It maximizes the minimum distance between the symbols in the augmented signal space.

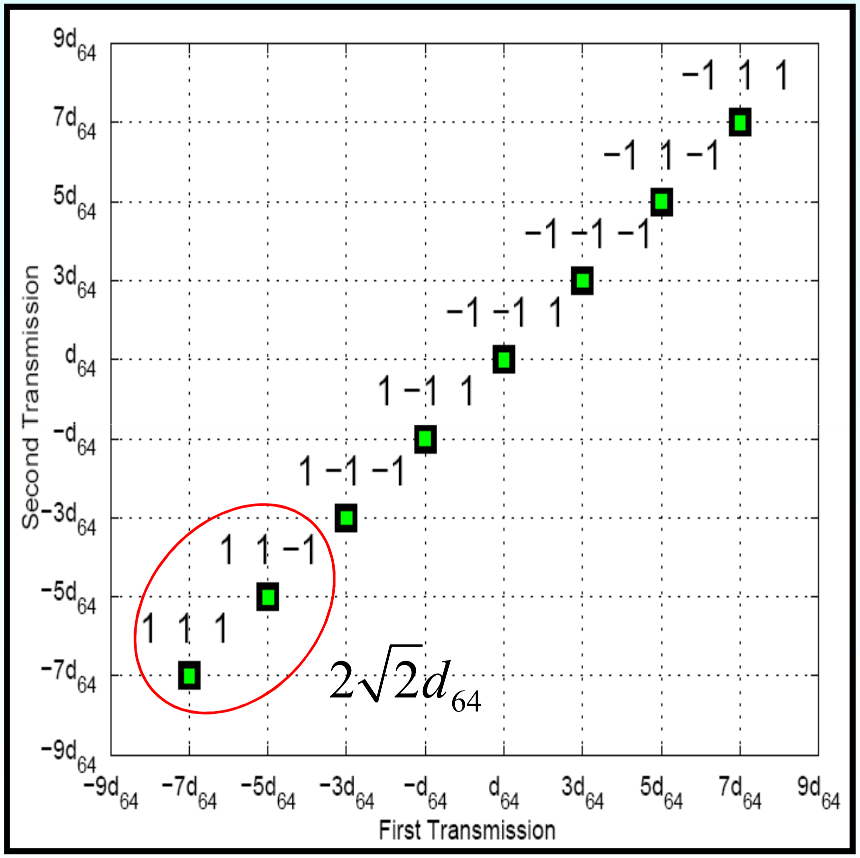
Differences between HARQ and Cooperative Relaying



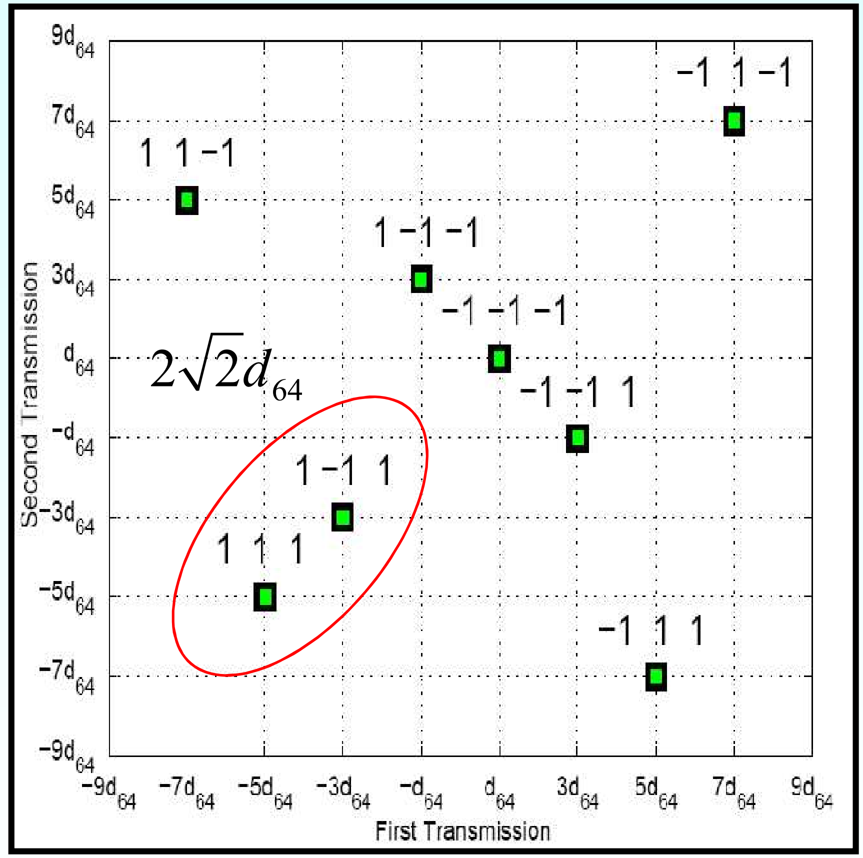
1. In HARQ, the source doesn't know the number of retransmissions, unlike the case of cooperative relaying.
   No need for Gray-Coding in the first transmission!

2. Error propagation in cooperative relaying in nomadic relays scenario
   Will CoRe benefit or harm the performance in this case?

Augmented Signal Space (1/2)

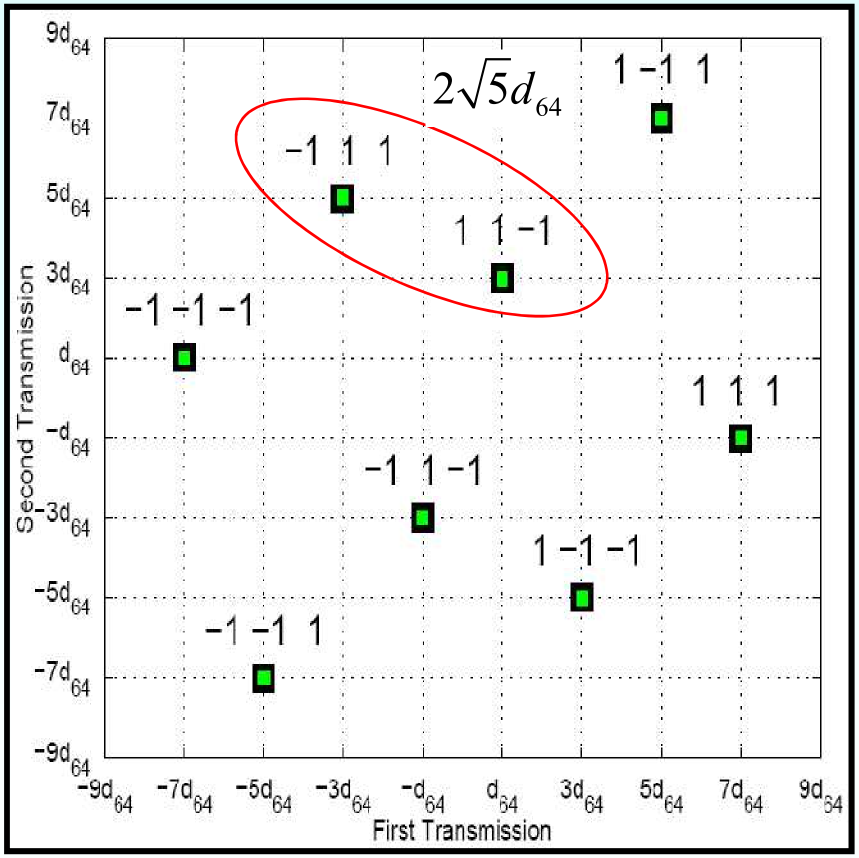


Conventional scheme

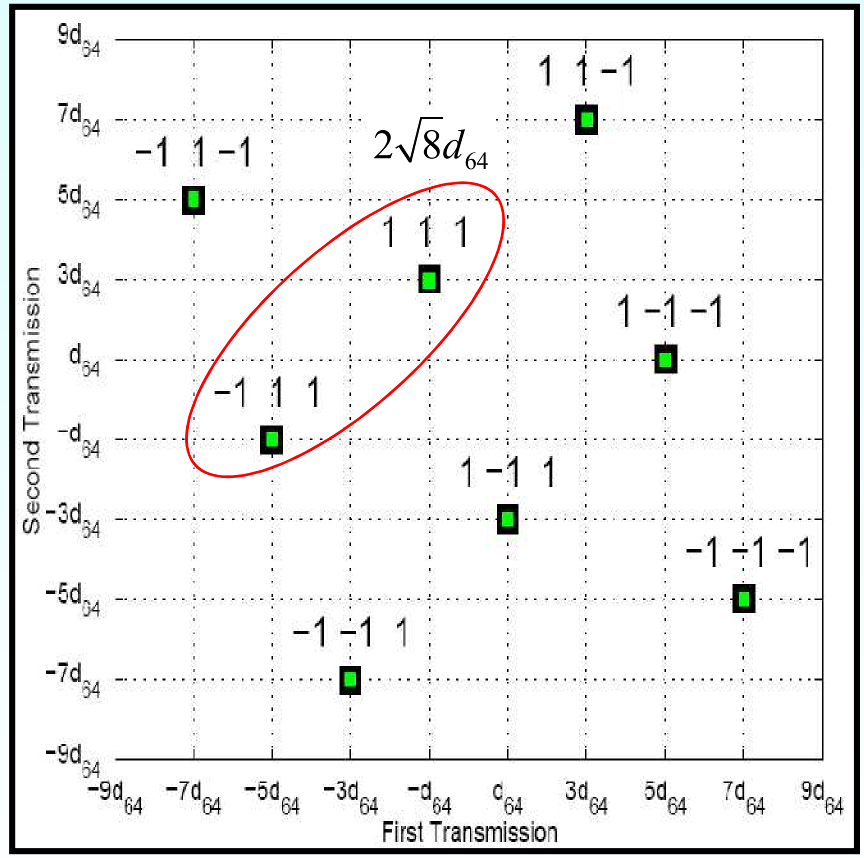


CoRe 1

Augmented Signal Space (2/2)



CoRe 2

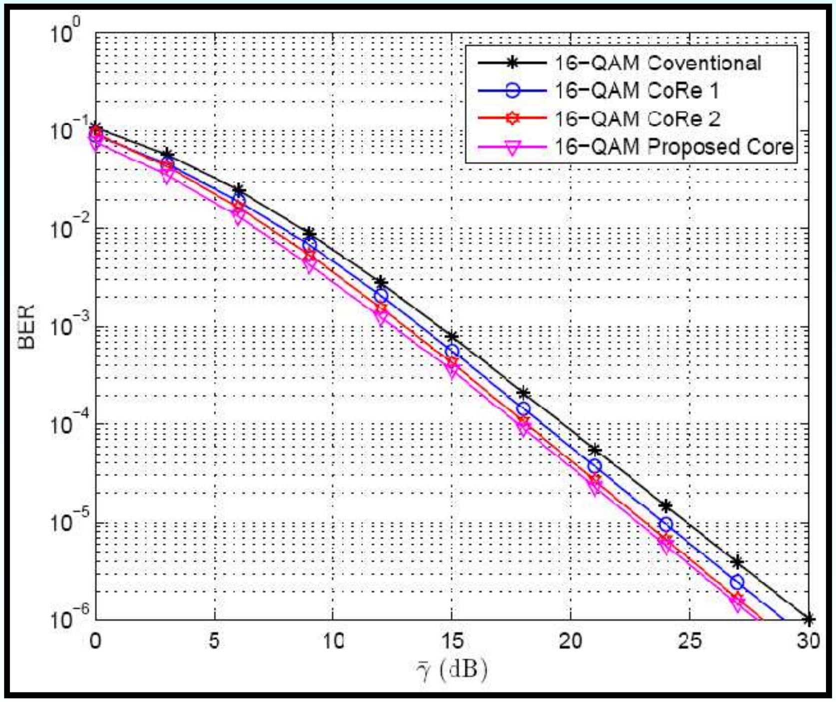


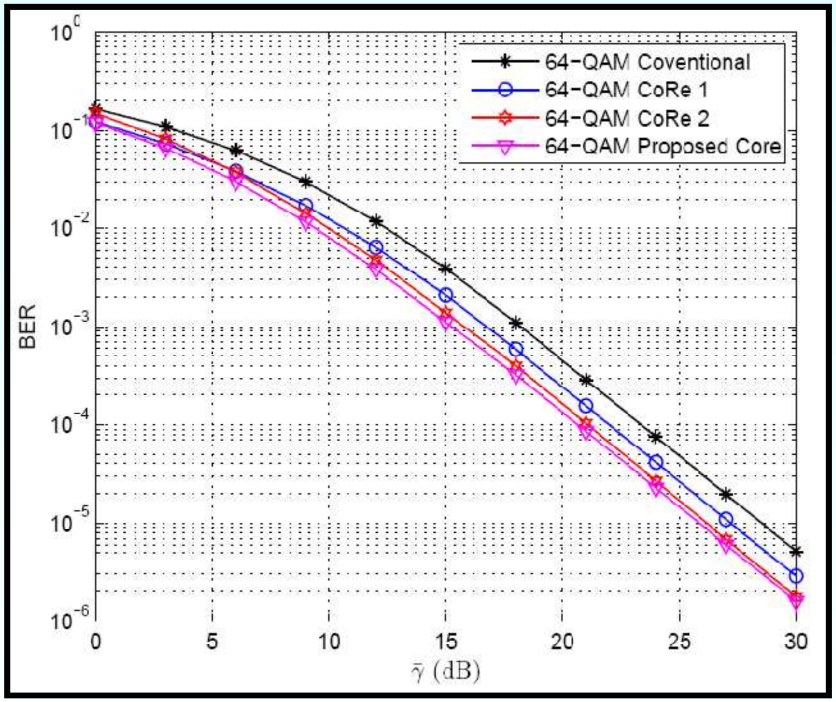
Proposed CoRe

Results (1/2)

Error Free transmission from BS to RS (Fixed RS)

$$\bar{\gamma}_{BS-UT} = \bar{\gamma}_{RS-UT} = \bar{\gamma}$$



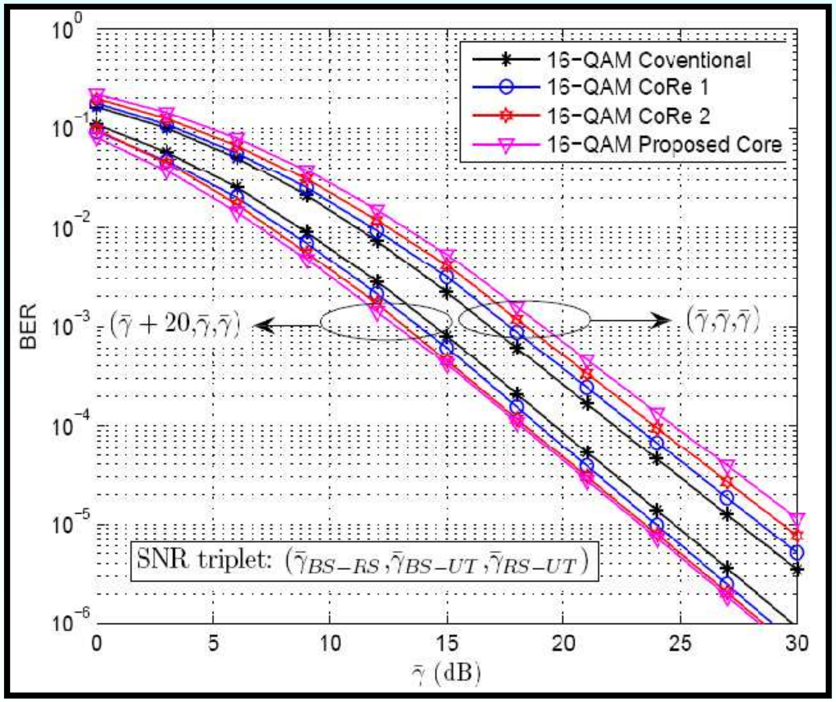


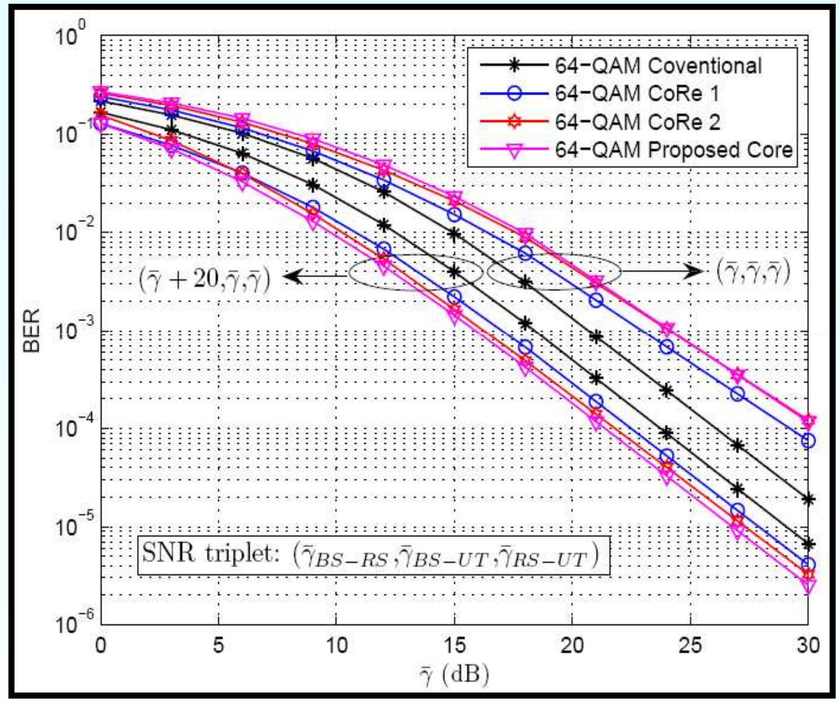
Gain over Conventional scheme ~ 1.9 dB
Gain over CoRe 1 ~ 1.0 dB
Gain over CoRe 2 ~ 0.5 dB

Gain over Conventional scheme ~ 2.6 dB
Gain over CoRe 1 ~ 1.3 dB
Gain over CoRe 2 ~ 0.5 dB

Results (1/2)

Error Propagation (Nomadic RS)

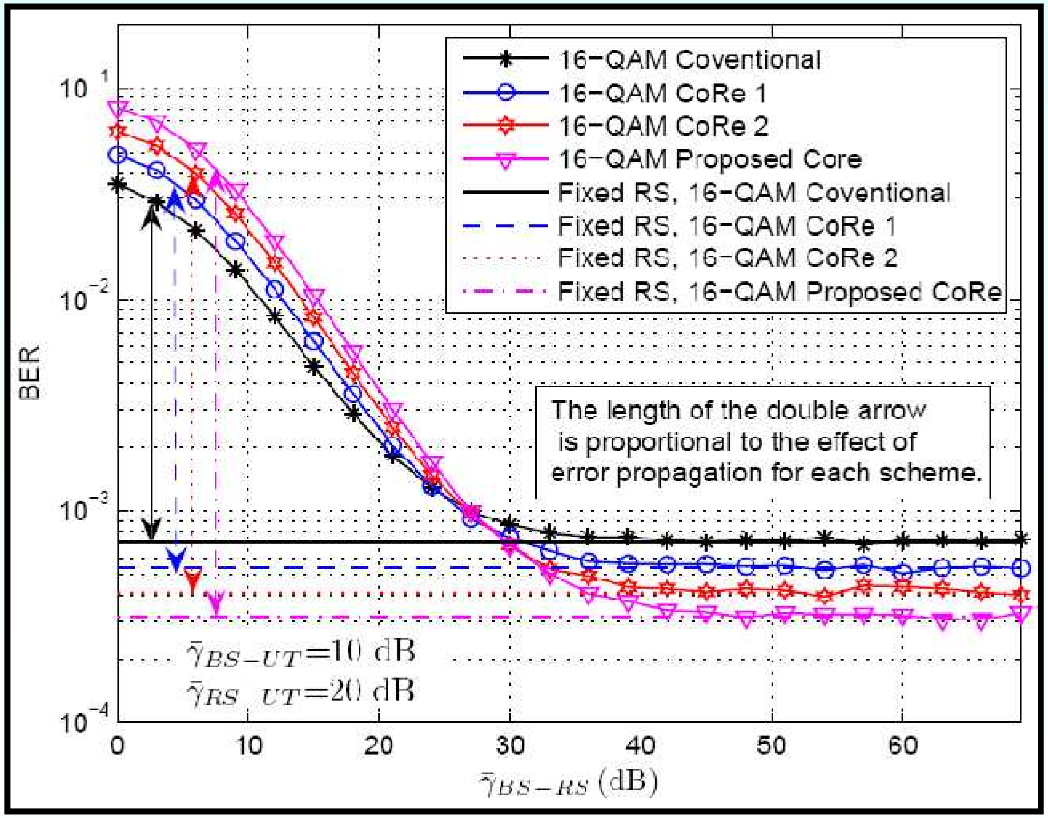




Results (2/2)

Error Propagation (Nomadic RS)

$$\bar{\gamma}_{RS-UT} = 10\ \text{dB},\ \bar{\gamma}_{BS-UT} = 20\ \text{dB}$$



Summary of Constellation Rearrangements

1. Unlike most of the existing CoRe schemes, the proposed CoRe does not use Gray-coding for any transmitting node.

2. In the context of fixed relays, the proposed CoRe shows significant gain compared to the conventional scheme and it outperforms the existing CoRe techniques.

3. If the BS-RS link is not reliable enough, all CoRe techniques perform worse than conventional scheme.

4. In the context of nomadic relays, the proposed CoRe outperforms the existing CoRe techniques, if and only if the BS-RS link is reliable enough.

Current Interest in Relay/Mesh/Multihop Networks (1)

Previous Standardization Efforts

- Opportunity-driven multiple access (ODMA) – 1999, 3GPP
- HiperLAN/2 (non-contention based multiple access)

Current Interest in Relay/Mesh/Multihop Networks (2)

- IEEE 802.11s – WLAN (Wireless Local Area Network) ESS Mesh Networking
- IEEE 802.15.5 – WPAN (Wireless Personal Area Network) Mesh Networking
  - Aims at determining the necessary mechanisms that must be present in the PHY and MAC layers of WPANs to enable mesh networking.
- IEEE 802.16 – WMAN (Wireless Metropolitan Area Network)
  - 802.16j
  - 802.16 m
- IEEE 802.20 – MBWA (Mobile Broadband Wireless Access)
  - Aims at developing the specification of PHY and MAC layers of an air interface for interoperable mobile broadband wireless access systems, operating in licensed bands below 3.5 GHz, optimized for IP-data transport, with peak data rates per user in excess of 1 Mbps.
  - Expected to support the mesh architecture.

http://grouper.ieee.org/groups/802/11/index.html
http://www.802wirelessworld.com

- Cellular 4G Networks
  - LTE-Advanced
  - WINNER+
- Propriety solutions by industry
  - Start-ups

WINNER – Wireless World Initiative New Radio

- Integrated Project funded by European Union under the 6th Framework Program (FP6)
- Objective: "to develop a ubiquitous radio system concept based on global requirements for mobile communication systems beyond 3G. The project covers a full scope from short-range to wide-area scenarios and will provide significant improvement to current systems in terms of performance, efficiency, coverage and flexibility."

Caution in Interpreting the Literature!

Literature on cooperative mesh networks: growing very fast
significant portion: on physical layer → limitation
some literature: (implicit) assumption → may be misleading!

- Infrastructure-less (ad hoc) networks
- Terminal relaying
- Diversity benefits

Future Directions (I)

Infrastructure-based Wireless Relay Networks:

cost-effective ubiquitous high data rate coverage

- Becoming a reality! (LTE-A, .16j/m, WiMAX 2.0, .11s, .20, .15.5, WINNER, FuTURE,…)
- Can we do more than mere coverage extension?

Future Directions (II)

- Cooperative communications in sensor networks
- Relaying in heterogeneous networks
- Relaying in MIMO OFDM and MIMO SC/FDE
- Above-PHY cooperation
- Behavior of large wireless networks

Future Directions (III)

- 4G wireless networks (1G mesh networks)
  systems level (above PHY or cross-layer) cooperation of fixed relays through
  "BS to relay" & "relay to relay" coordination
  → great benefits can be achieved
  - Subcarrier assignment in OFDMA
  - Dynamic channel allocation
  - Interference management
  - RRM
  - Intelligent routing and load balancing

Collaboration opportunities?...