Cooperative Strategies for Future Wireless Communication Systems: A Critical View

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Evolution of Wireless Communications

I. wired channel/link (point-to-point) [PHY]
communications = communication & information theory

II. wireless channel/link (point-to-point) [PHY]
wireless communications = communication & information theory for wireless channel

III. wireless system (many terminals + one AP) [PHY+MAC+RRM]

IV. wireless network (many terminals + many APs)
[PHY+MAC+RRM+scheduling+routing; cross-layer optimization]

V. wireless mesh network (many terminals + many relays + many APs; multihop)

VI. wireless cooperative mesh network

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
- Analog relaying
- Symbol-by-symbol digital relaying
- Homogeneous relaying
- Scalability
- Multiplexing loss (vs diversity benefits)
- Carrier phase control (synchronization)
- Signaling overhead
- Latency

Infrastructure-based vs Infrastructure-less Mesh Networks

mesh architecture in infrastructure-based networks

- cellular
- WiMax
- WLAN
- sensor

$\left.\right\}$ a subset of nodes are wire-connected to internet

mesh architecture in infrastructure-less networks

- ad hoc → limited applications (tactical, rescue, emergency,…) X

Terminal/Mobile Relaying

- Rich theoretical area, full of potentials

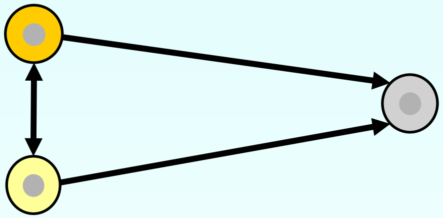
- But, many technical challenges
  - No service guarantee
  - Increased energy consumption (fast battery draining)
  - Increased transmit power (in CDMA)
  - Additional hardware and functionality (higher terminal cost)
  - Frequent hand-offs (especially in the presence of mobility)
  - Security issues

- Terminal relaying: any incentives?
  - Special applications: single team (law-enforcement, military, rescue)
  - Non-battery powered fixed user terminals (802.16)
  - Cooperative relaying with simultaneous mutual benefits (symmetric cooperation)
  - Personal area networks
  - Commercial applications: incentives?

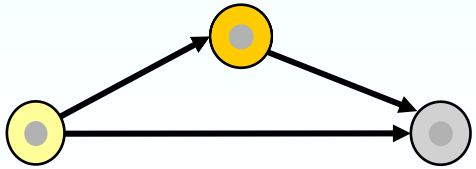
- Fixed relays: easier to realize and manage

Diversity Benefits

- Symmetric Cooperation: a pair of nearby terminals cooperate
  - Immediate benefit for both terminals
  - But no pathloss gain
  - Great diversity benefits



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



Analog Relaying

Non-regenerative relaying
Amplify-and-forward relaying

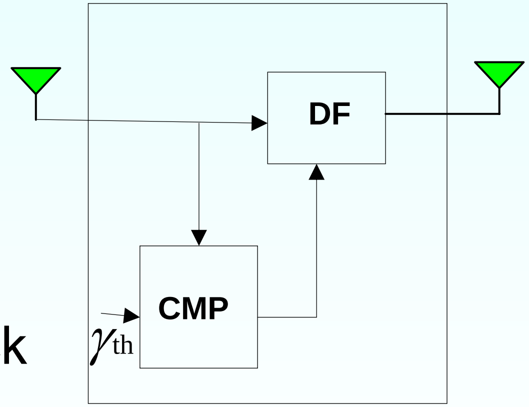
- Rationale: simplicity (was the case 20 years ago)
- Interest in the literature: because easier to analyze!
- Not suitable for exploitation above the physical layer
- Digital relaying: better option

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

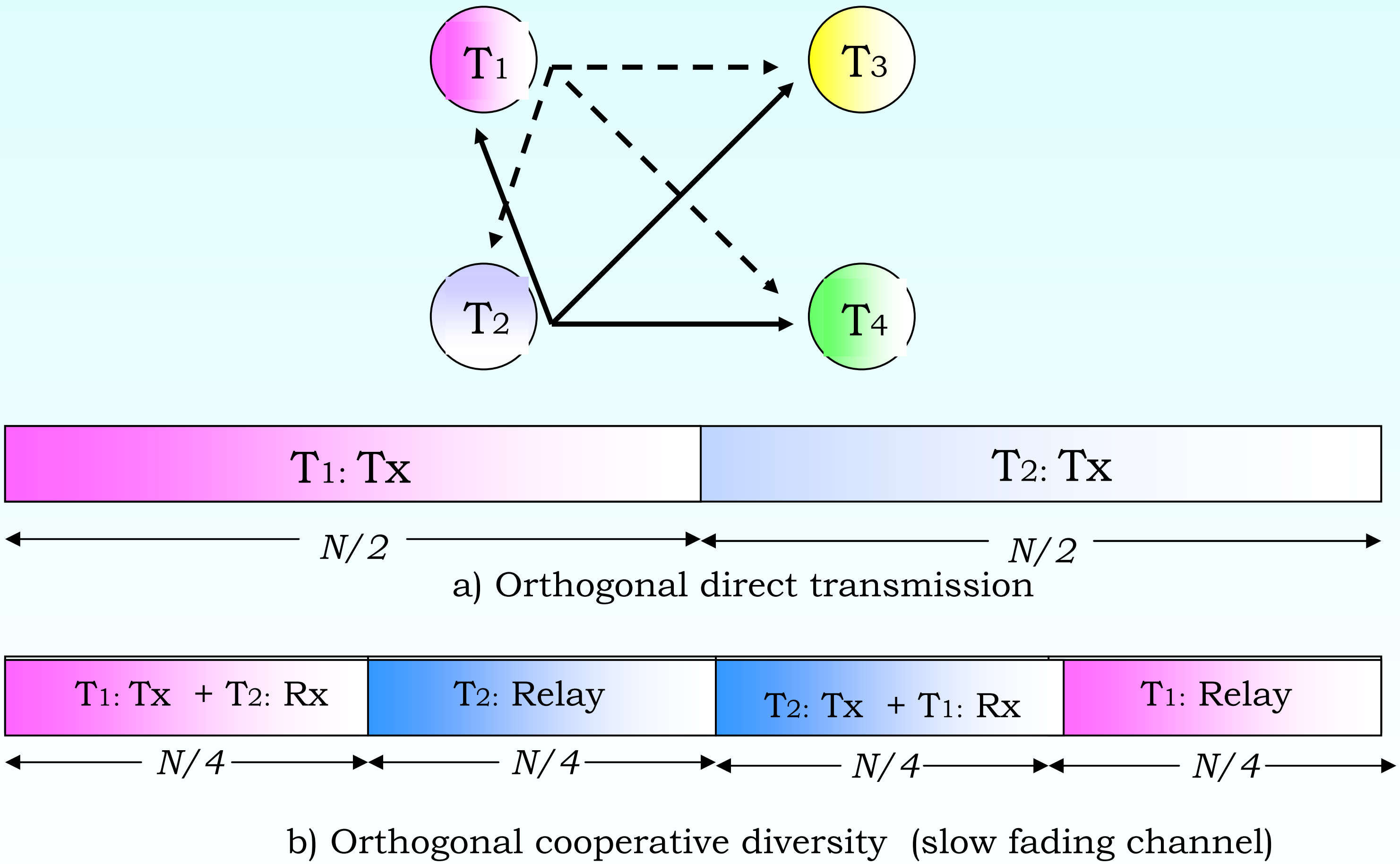


threshold-based selective digital relay

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
- Homogeneous relaying: suitable for diversity reception
  Heterogeneous relaying: more practical

Scalability

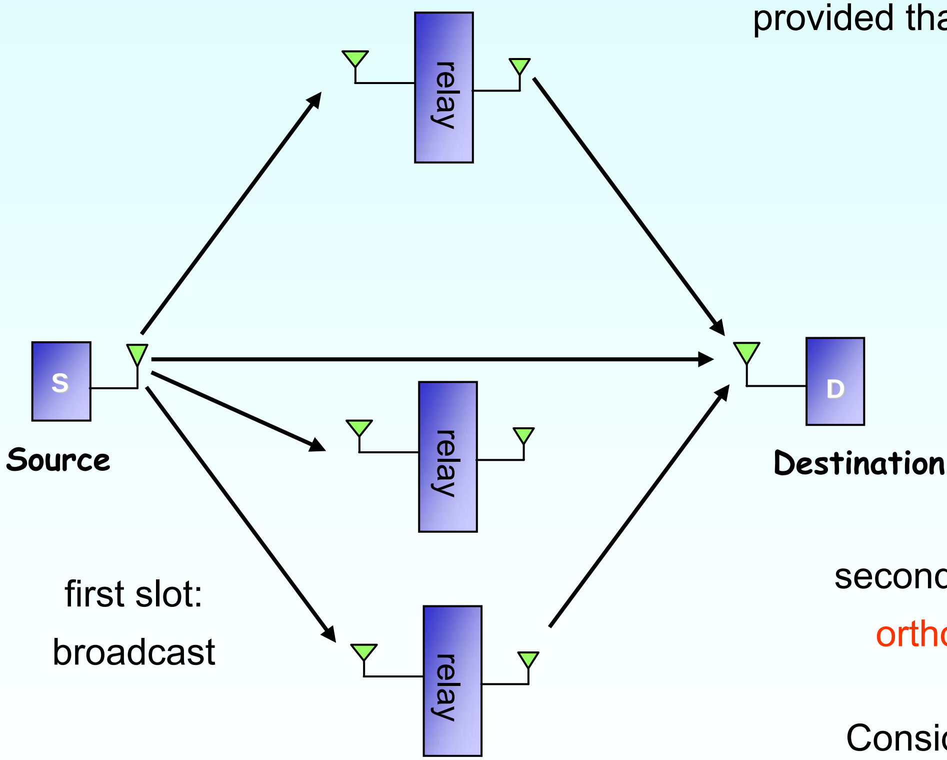


Scaling: difficult

Multiplexing Loss

diversity order: up to R+1

provided that error propagation is prevented



first slot:

broadcast

second slot: multiple access

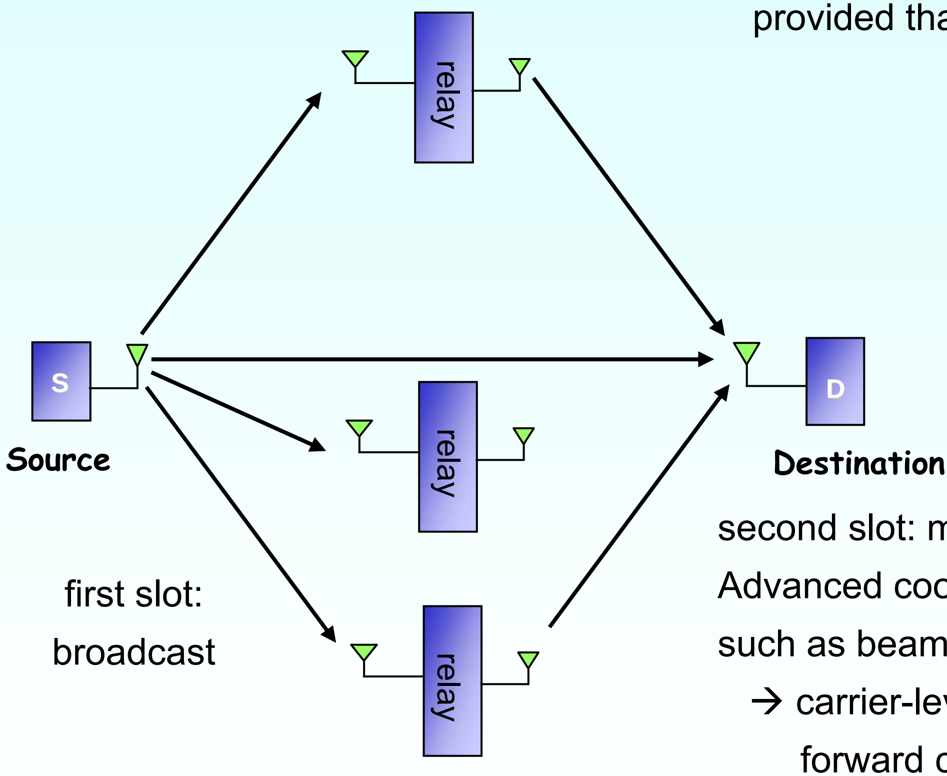
orthogonal → multiplexing loss

Consider distributed transmit diversity and distributed space-time coding

Carrier Level Synchronization

diversity order: up to R+1

provided that error propagation is prevented



first slot:

broadcast

second slot: multiple access

Advanced cooperative schemes,

such as beamforming, virtual antenna array

→ carrier-level phase adjustment with forward channel information (significant overhead)

→ difficult to realize

Contemporary Interest in Mesh Networks

Mesh architecture in the near future

- 802.16j
- 802.11s
- European Union 4G WINNER Project
- (Chinese FuTURE Project)
- Existing non-standardized mesh networks
- Fixed relays for coverage extension

Fixed relays for coverage extension

Concluding Remarks

Wireless Mesh Networks: becoming a reality

- 4G wireless networks (1G mesh networks)
  systems level cooperation of fixed relays through
  "BS to relay" & "relay to relay" coordination
  → great benefits can be achieved

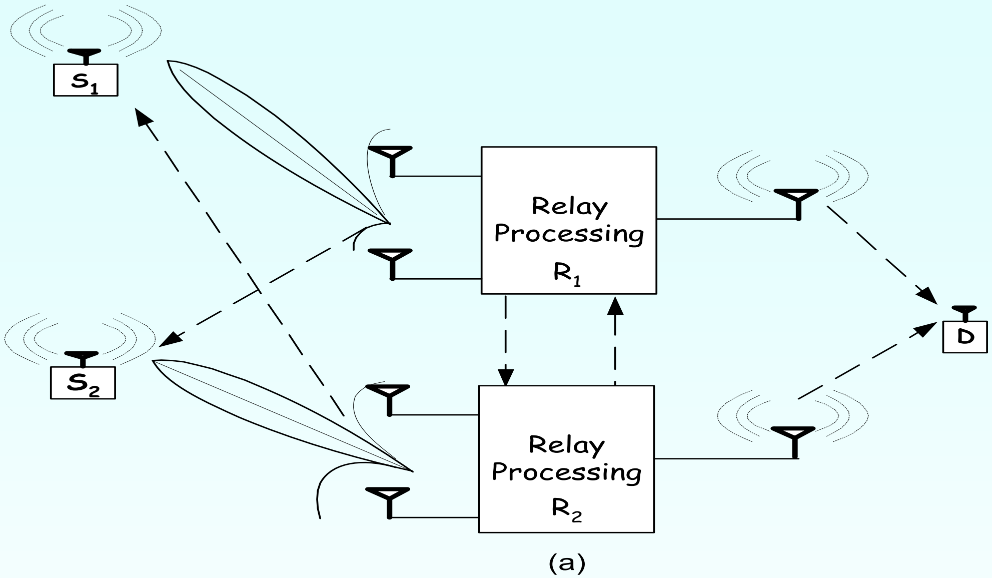
  - Dynamic channel allocation
  - Interference management
  - RRM
  - Intelligent routing and load balancing
  - Intelligent scheduling
  - Dynamic frequency hopping
  - …

- 4G+/5G wireless networks (1G+/2G mesh networks)
  cooperative diversity (as perceived in literature): add on
  → further opportunistic benefits
  - Cooperative diversity
  - Virtual antenna arrays
  - Distributed coding
  - Distributed MIMO
  - …

Practical Cooperative Communication Schemes Through Fixed Relays

Adinoyi, Yanikomeroglu

WWRF15, VTC'S06



(a)

S_1 (d_1) ---> R_1 S_2 (d_2) ---> R_2	R_1 (d_1) ---> D and R_2 R_2 (d_2) ---> D and R_1	R_1(d_2) ---> D R_2 (d_1) ---> D

(b)

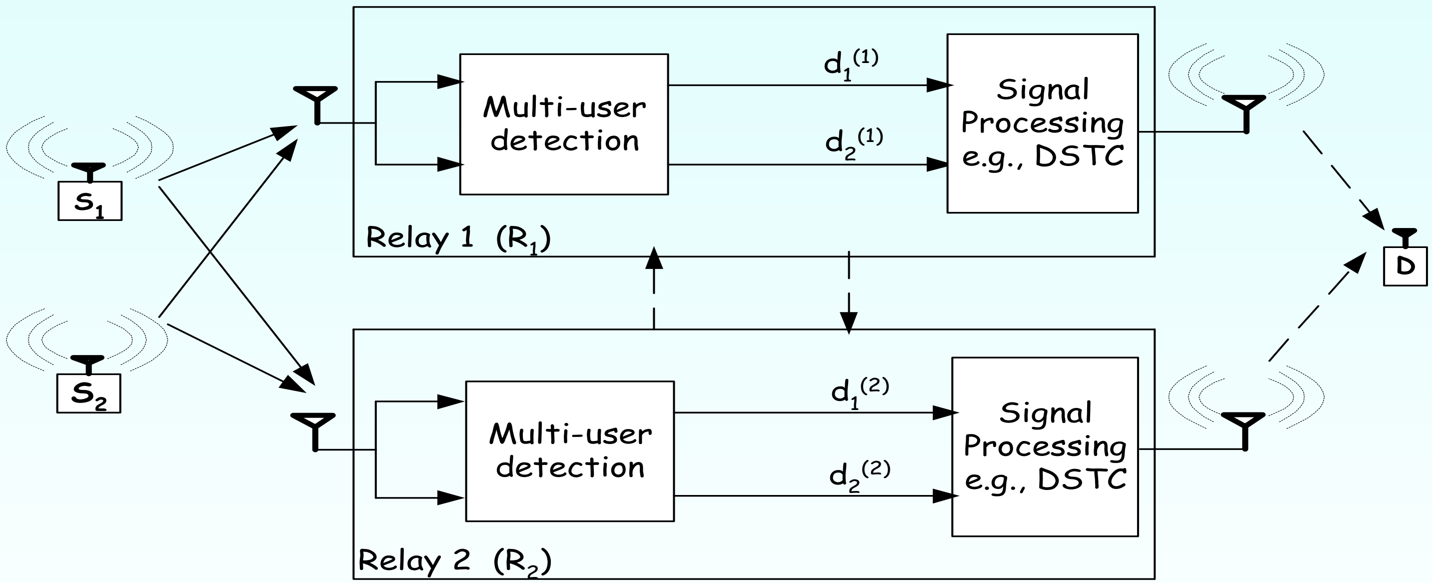
no need for incentives for cooperation

no security risk

no complexity incurred in terminals

complexity: moved to network

Practical Cooperative Communication Schemes Through Fixed Relays

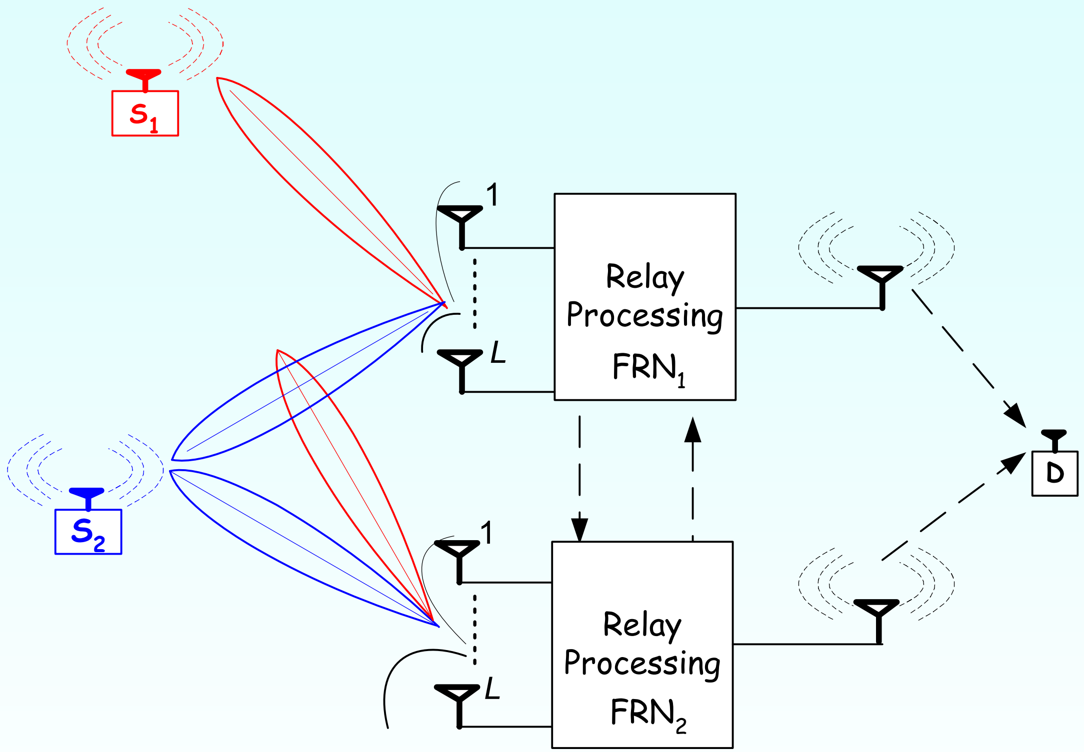


(a)

$S_1\ (d_1)$ ---> R_1 , R_2 $S_2\ (d_2)$ ---> R_1 , R_2	$R_1\ (d_1^{(1)})$ ---> D $R_2\ (d_2^{(2)})$ ---> D	$R_1(d_2^{(1)})$ ---> D $R_2\ (d_1^{(2)})$ ---> D

(b)

Practical Cooperative Communication Schemes Through Fixed Relays



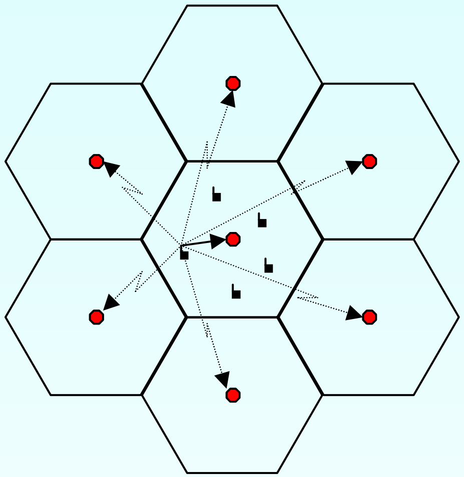
S_1 (d_1) ---> FRN_1, FRN_2 S_2(d_2) ---> FRN_1, FRN_2	FRN_1 (d_1) ---> D FRN_2 (d_2) ---> D	FRN_1(d_2) ---> D FRN_2 (d_1) ---> D

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

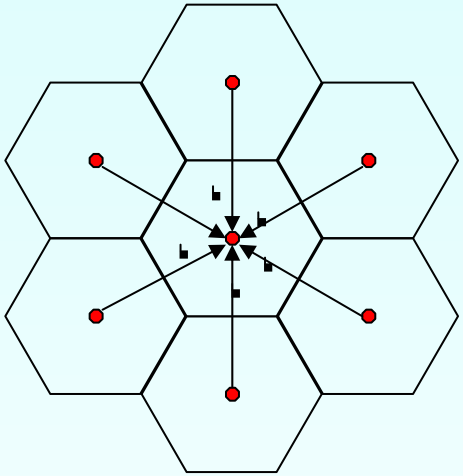
CLASSICAL DYNAMIC FREQUENCY HOPPING WITH NETWORK ASSISTED RESOURCE ALLOCATION (DFH with NARA) – [AT&T Bell Labs]

i.



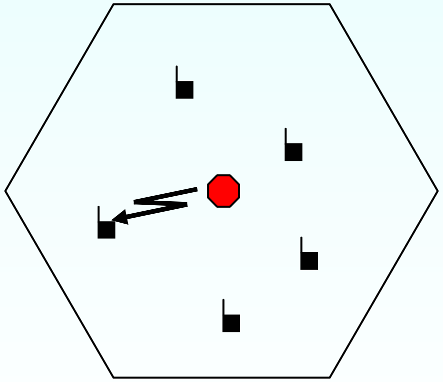
Each terminal measures path losses to the neighboring bases and transmits this information to its serving base on a regular basis.

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.

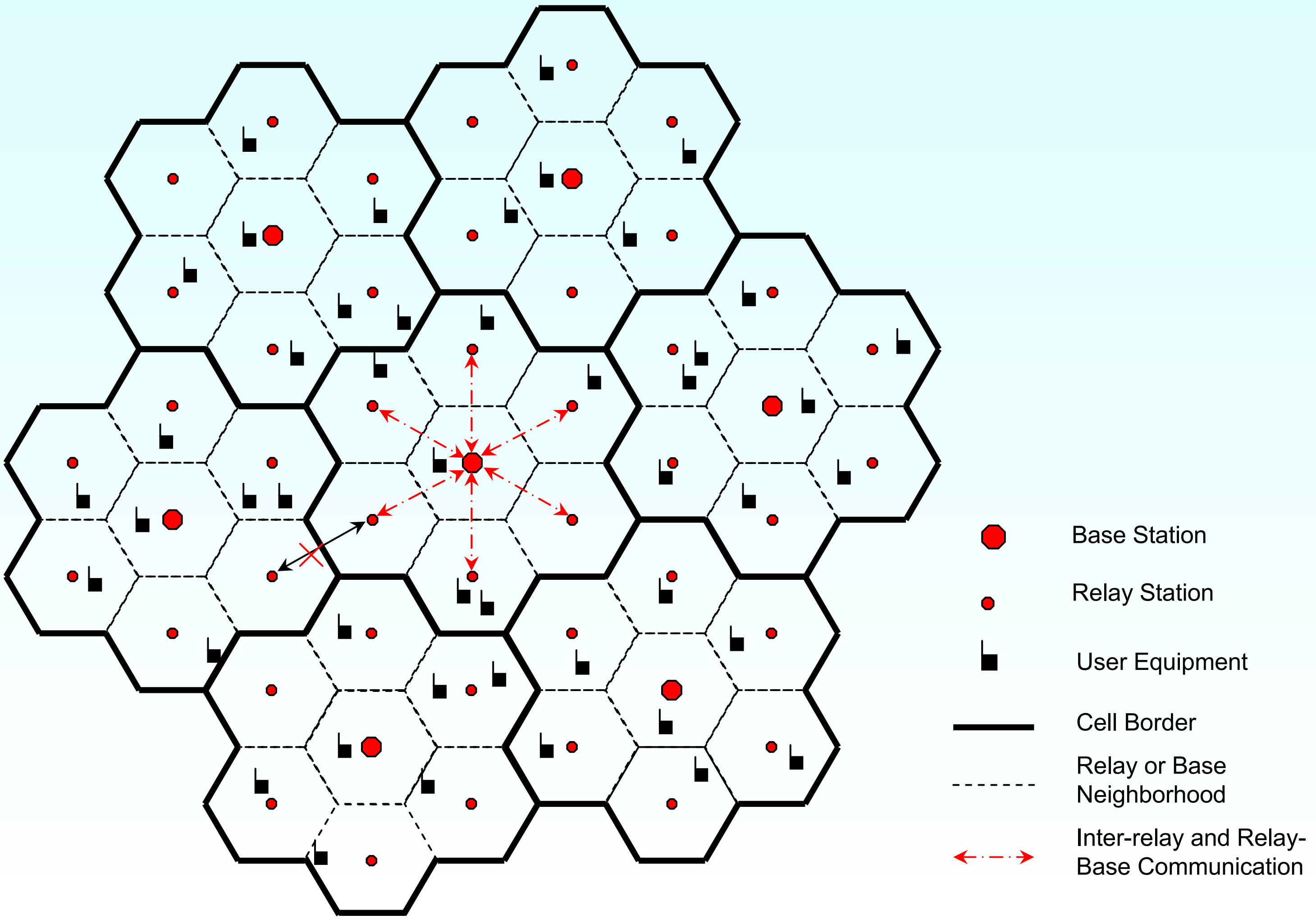


The serving base station calculates the interference level at each available resource, determines the least-interfered time slot and FH pattern pair, and assigns this to the terminal.

Base Station

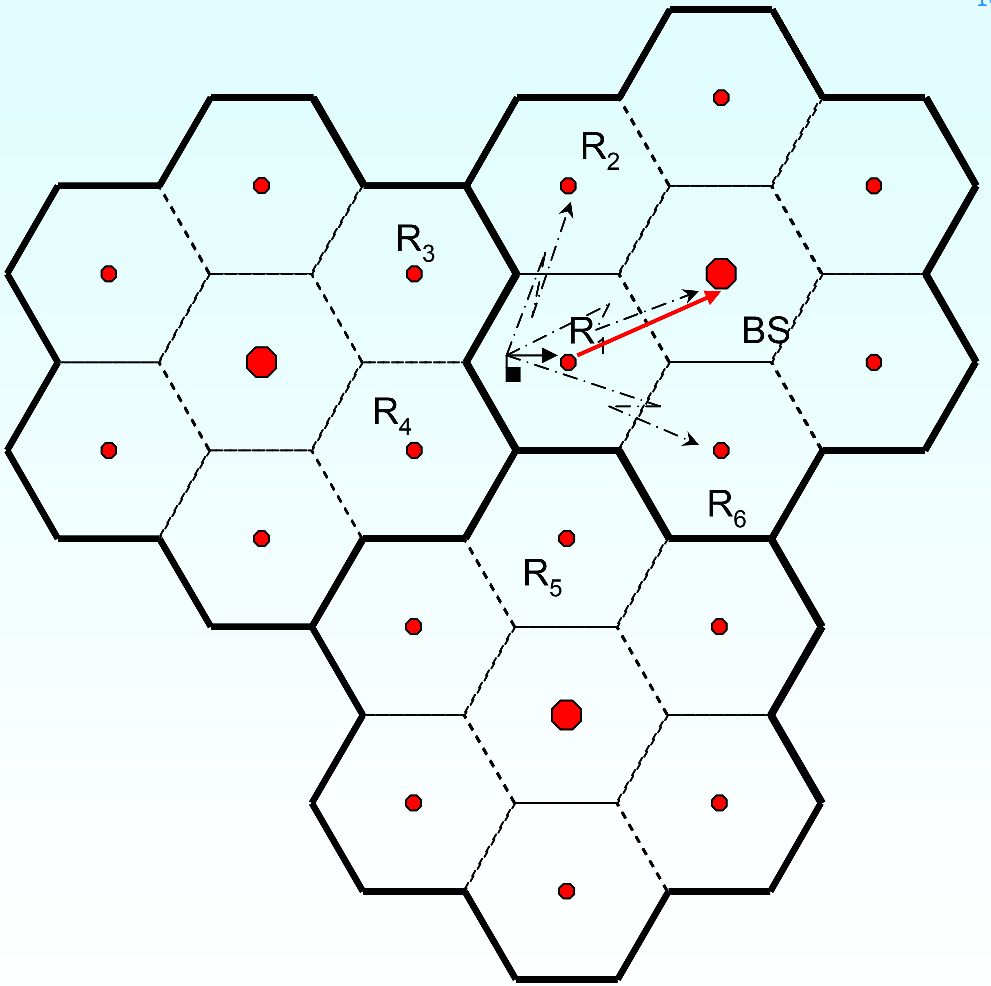
Mobile terminal

SYSTEM ARCHITECTURE FOR TWO-HOP COMMUNICATIONS



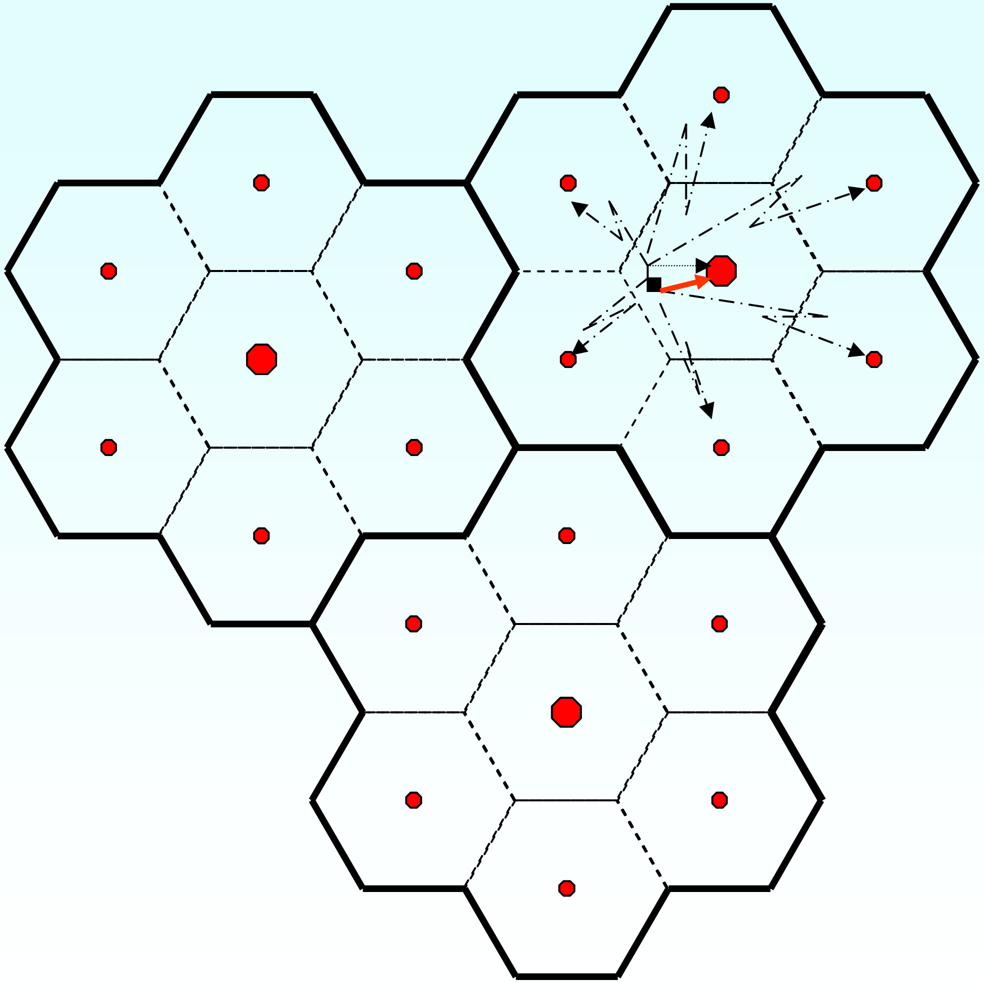
DFH with LIMITED INFORMATION (Time Slot 2)

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

DFH with LIMITED INFORMATION (Time Slot 2)

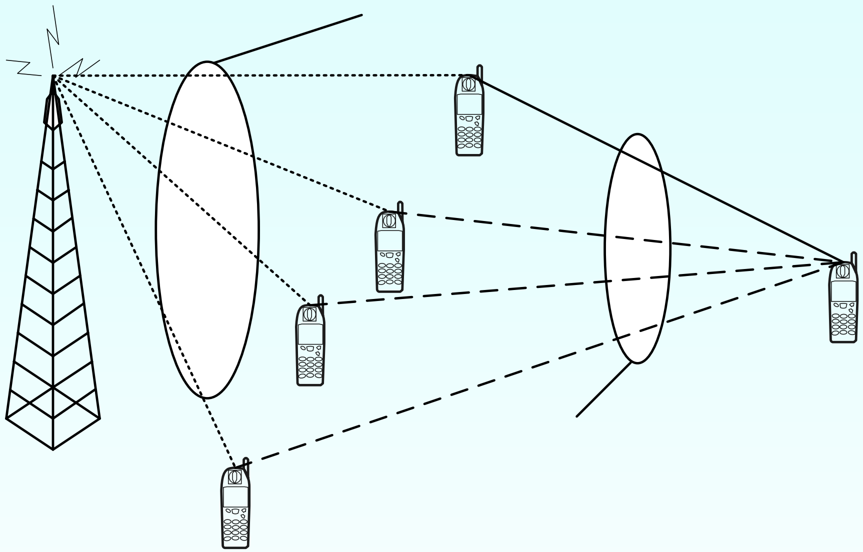


UE in BS service region:
DFH with full information

Cooperative Induced Multi-user Diversity Relaying (CIMDR)

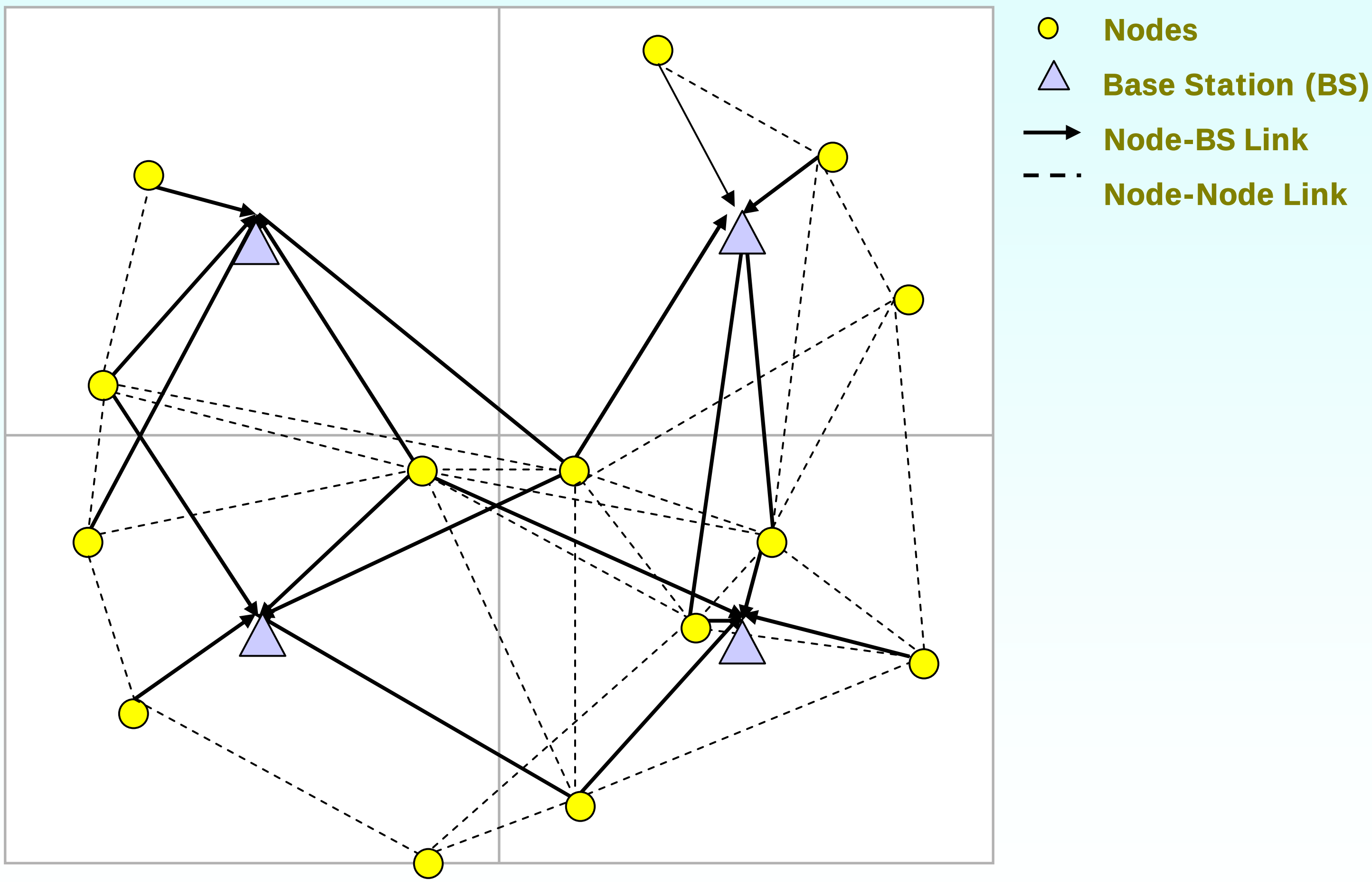
Navaie, Yanikomeroglu

VTC'S06



- First hop
  - Multi-user diversity exploits through transmission with maximum bit-rate
- Second-hop
  - Multi-user diversity exploits through transmission on a "good channel"
- Two phase protocol: Feeding and delivery phase

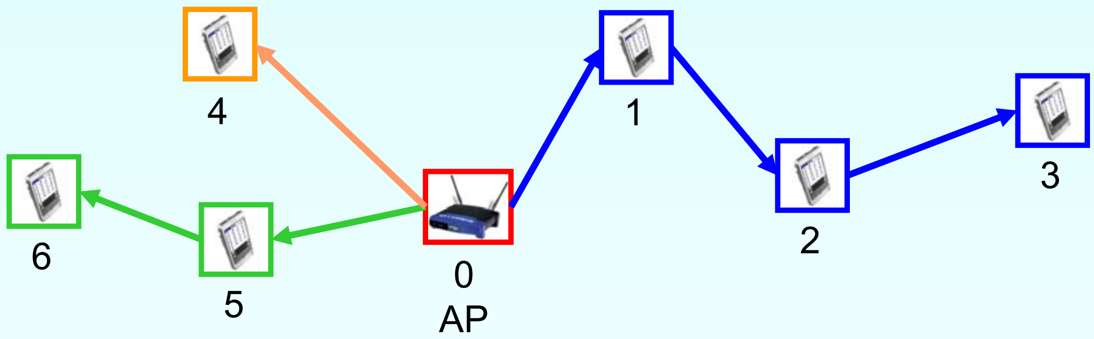
Cellular Mesh Network with Global Resource Allocation



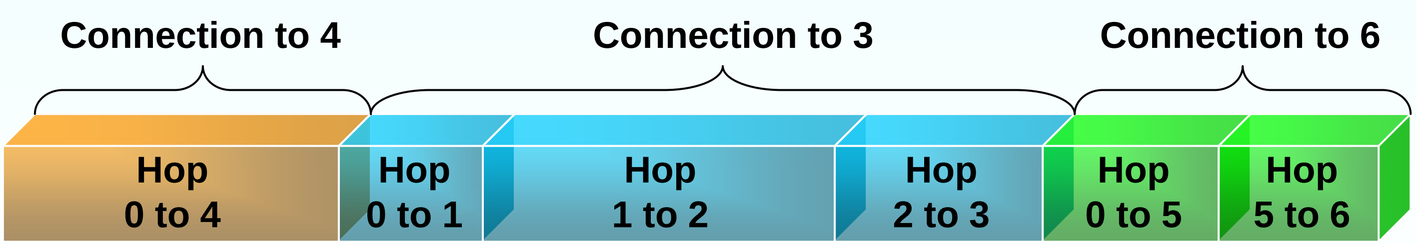
Diversity- and AMC (Adaptive Modulation and Coding)-Aware Routing in Infrastructure-based TDMA Multihop Networks

Hares, Yanikomeroglu, Hashem

VTC'F03 & Globecom'03



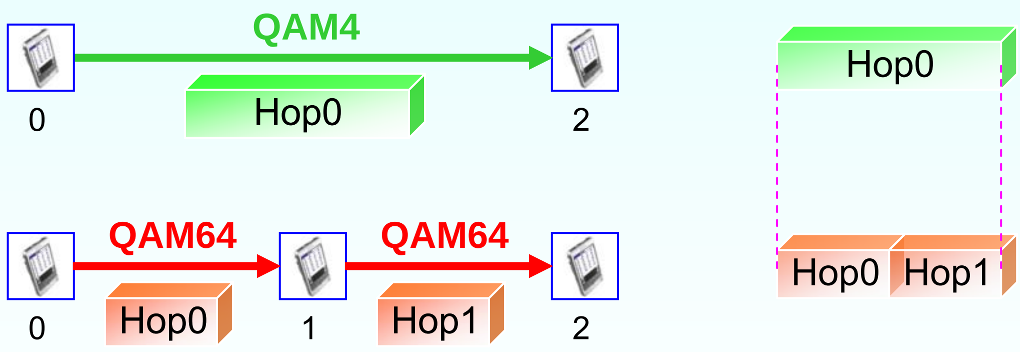
Time Domain – MAC Frame



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

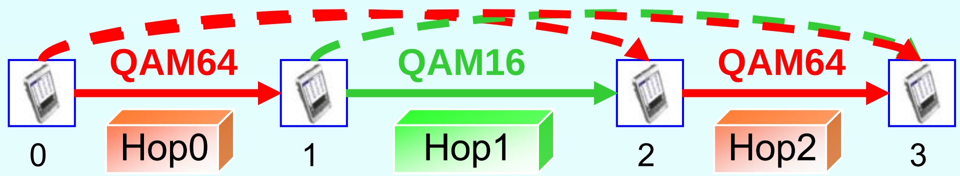
Frame Allocation for Relaying

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

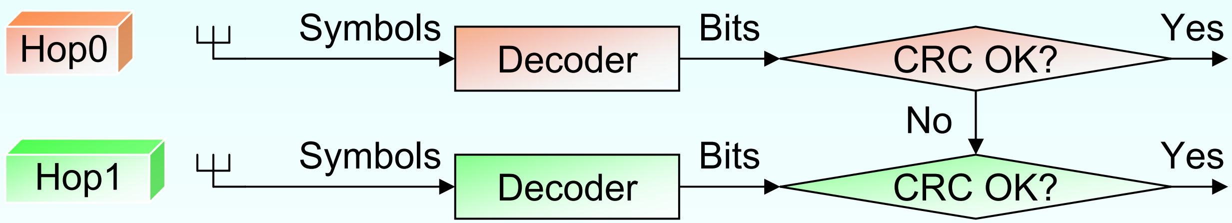


Multihop Diversity

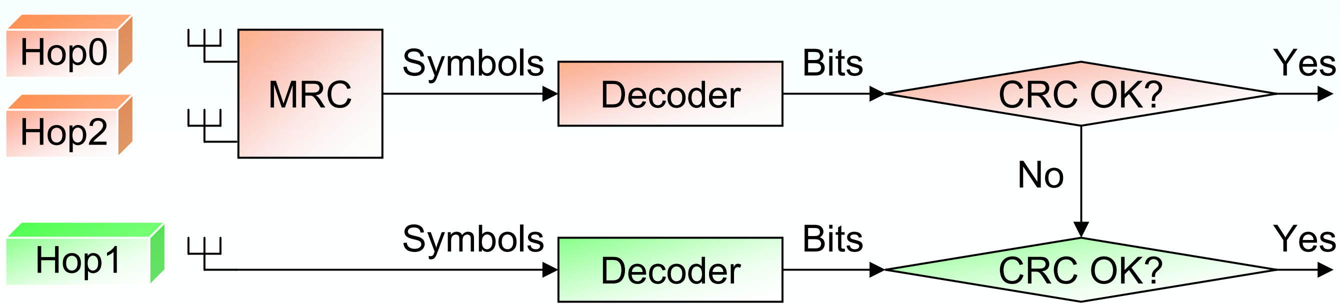
Time Domain



Node 2 Receiver Operation Equivalent

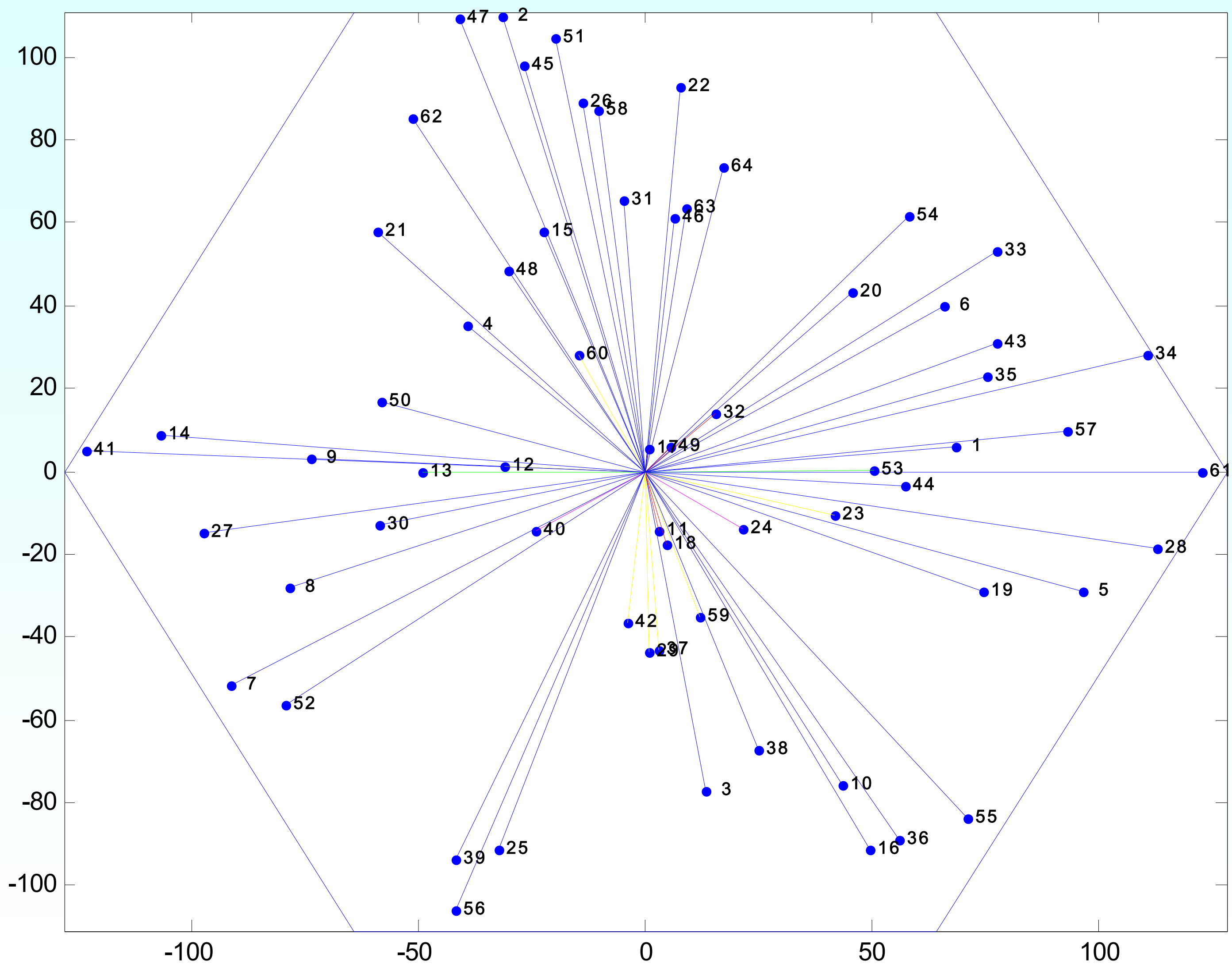


Node 3 Receiver Operation Equivalent

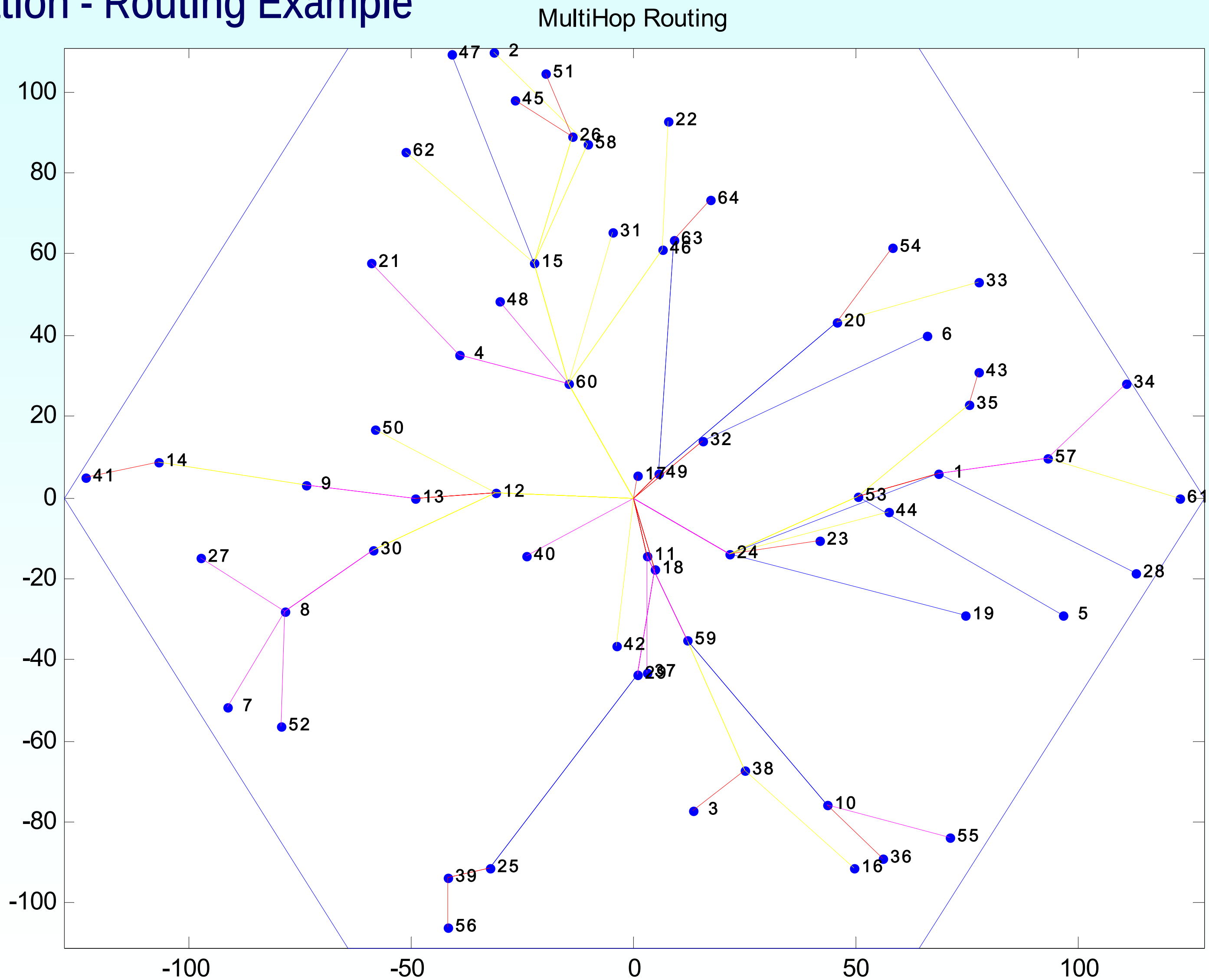


Simulation - Routing Example

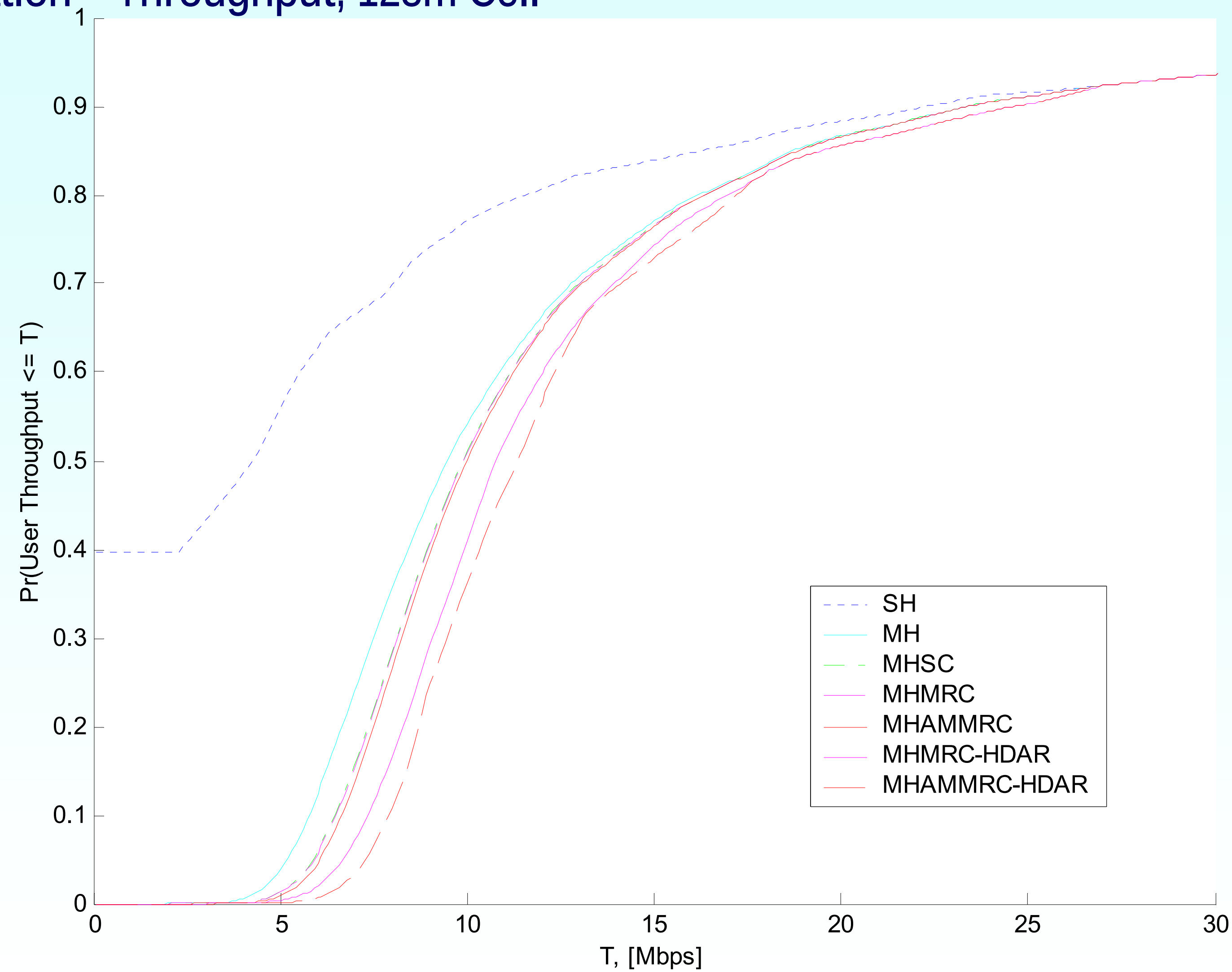
SingleHop Routing



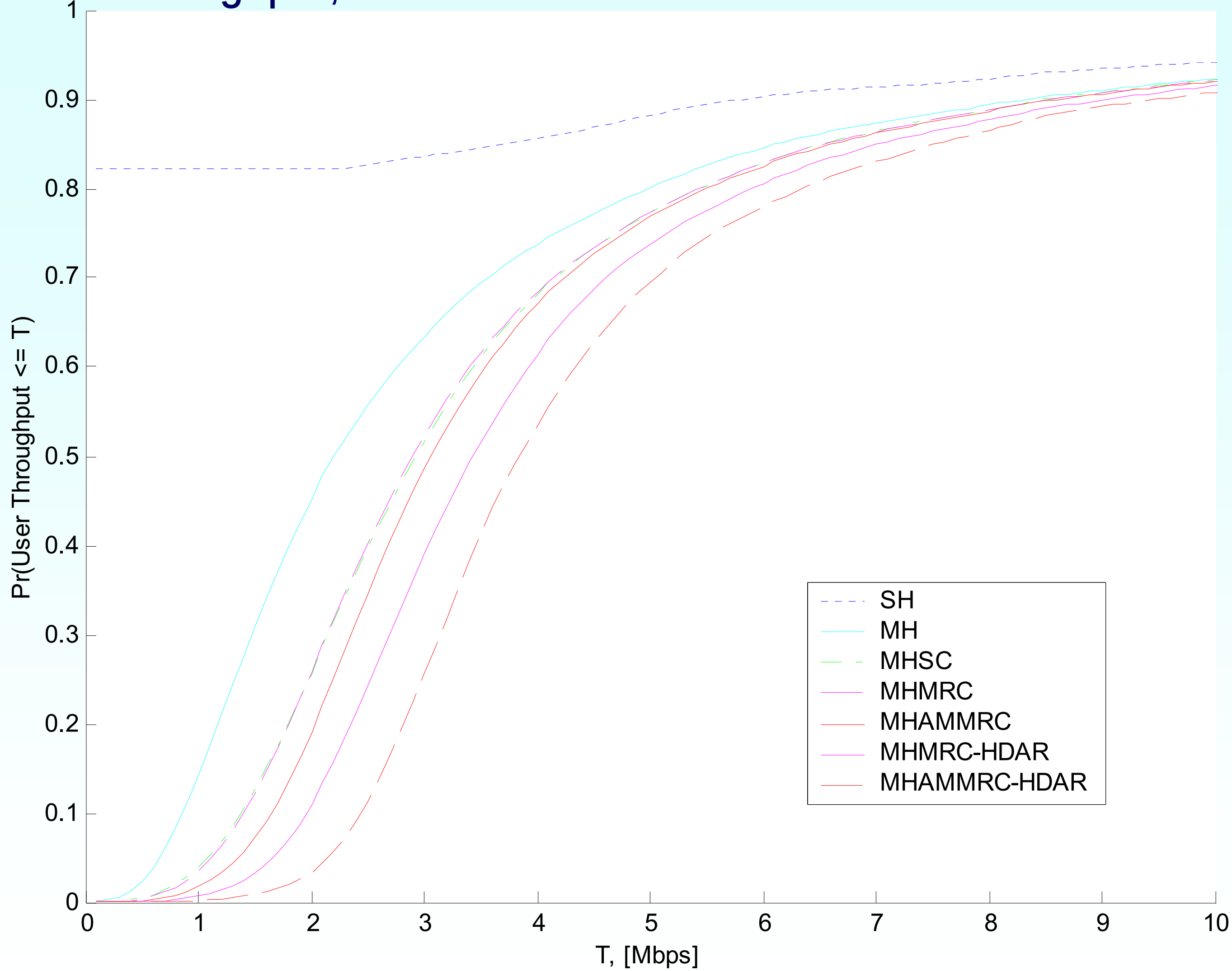
Simulation - Routing Example



Simulation – Throughput, 128m Cell



Simulation – Throughput, 256m Cell



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

- IEEE 802.11s – WLAN (Wireless Local Area Network) ESS Mesh Networking
  - Auto-configuring multihop paths between APs in a wireless distribution system.
  - Targeted to be approved by 2008.

- 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.
  - Targeted to be approved by 2007.

- IEEE 802.16 – WMAN (Wireless Metropolitan Area Network)
  - 802.16-2004 standard "Air Interface for Fixed Broadband Wireless Access Systems": approved in July 2004. MAC layer supports an optional mesh topology.
  - 802.16e amends 802.16 to support mobility for the devices operating in the 2-6 GHz licensed bands.
  - An optional mesh mode is being considered based on 802.16e-2005 OFDMA
    MMR-SG: Mobile Multihop Relay Study Group → 802.16j
    (Taipei, Sep'05; Vancouver, Nov'05; New Delhi, Jan'06; Denver, Mar'06)
    http://grouper.ieee.org/groups/802/16/sg/mmr/
    http://ieee802.org/16/sg/mmr/

- 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

Concluding Remarks

- Infrastructure-based multihop networks: cost-effective ubiquitous high data rate coverage in future wireless networks
- Fixed relay stations with add-on terminal relays
- Impact in all layers of wireless communications
  - Propagation, PHY, MAC, networking, higher layers and protocols
- Relay networks will soon become a reality

  Goal: to develop advanced cooperation protocols and algorithms among relays and APs to obtain further performance gains at
  - physical layer (cooperative diversity, virtual antenna arrays, …)
  - systems layer (interference avoidance and management)
  - networking layer (smart scheduling and routing, load balancing, …)

  by relying on other advanced technologies, such as OFDM(A) and MIMO, as much as possible.

Evolution of Wireless Communications

→ 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: paradigm shift in systems level

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, RRM, 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