

Opportunistic Relaying in Wireless Networks

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A world of connections

- *“Today's wireless device is the sleek mobile phone nestling in your pocket. In coming years wireless will vanish entirely from view, as communications chips are embedded in a host of everyday objects. Such chips, and the networks that link them together, could yet prove to be the most potent wireless of them all.”* **The Economist** April 2007
- New 700 MHz wireless spectrum auctioned in Feb. 2008:
“Licence-holders will have to accommodate any mobile device or type of service, provided it does not harm the network. With these open-access provisions, the FCC wants to create space for more innovation.” **The Economist** Jan. 2008

Peer-to-peer communication among wireless devices will be a dominant mode of communication in the future

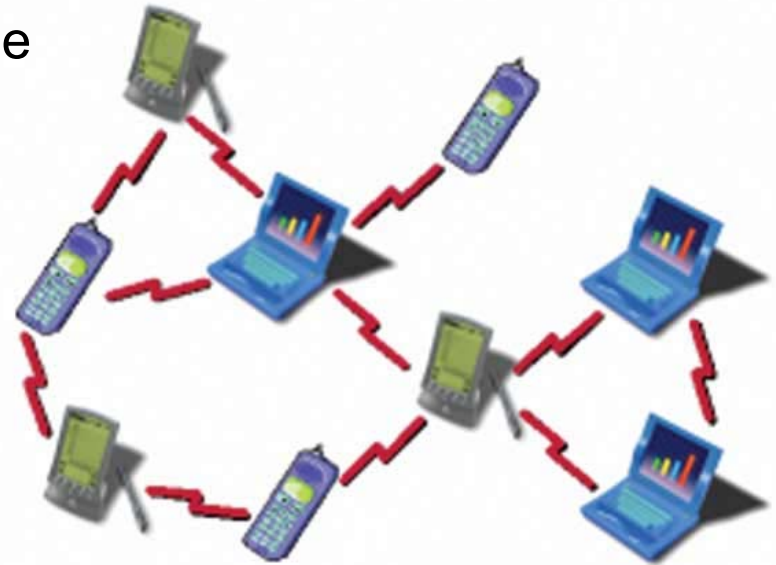
**The
Economist**

Outline

- Interference in ad-hoc wireless networks
- Relaying
- System model
- Opportunistic relaying scheme
- Throughput analysis
- Concluding remarks

Infrastructure and ad-hoc networks

- Historically, early wireless applications were *one-to-many* (e.g., radio, telegraph)
- Modern and emerging applications come in many forms of *one-to-one* communications

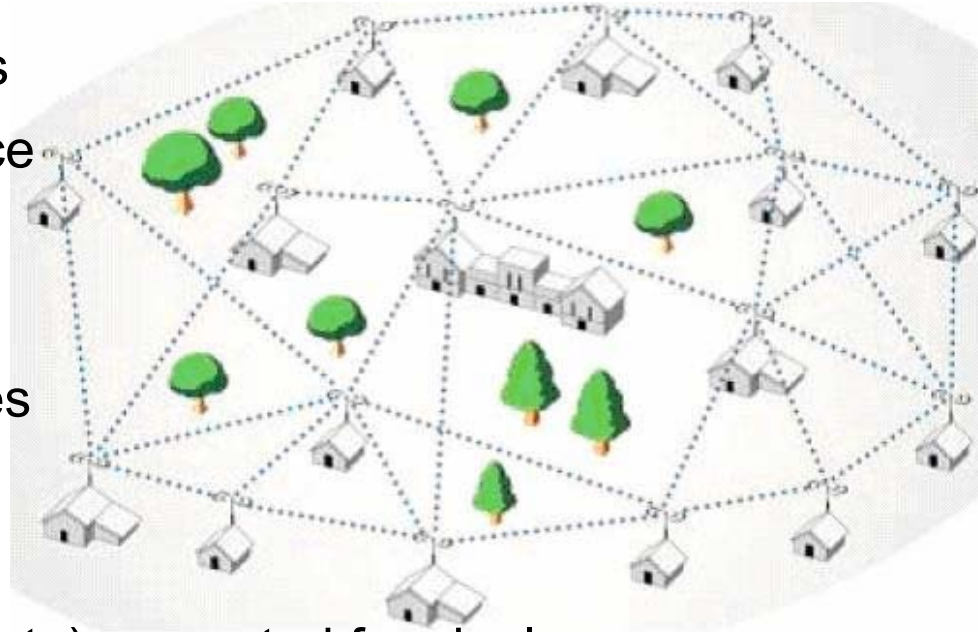


In a cellular network communications take place through an infrastructure node

In an ad-hoc network communications take place between peers.

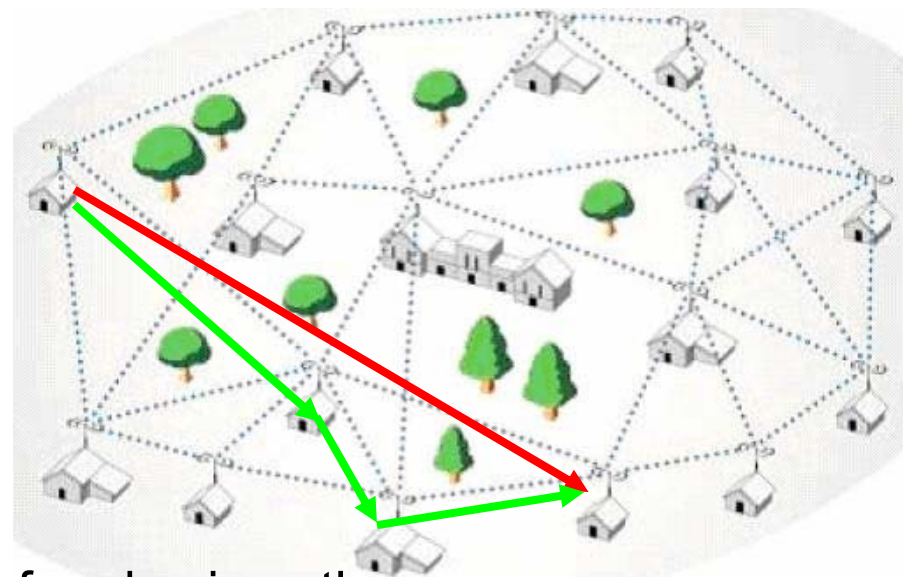
Ad-hoc networks

- Many simultaneous transmissions
- Infrastructure support is a resource
- Assumptions:
 - Pathloss/Rayleigh channel
 - No cooperation between nodes
 - Single user detection
 - Various protocols
- The aggregate throughput (sum-rate) computed for single-user encoding and point-to-point communication: $\Theta(\sqrt{n})$ [Gupta Kumar 2000]
- Throughput scales linearly with the number of users, $\Theta(n)$, if mobility is incorporated [Grossglauser and Tse 2002], with sophisticated cooperation among users [Ozgur, Leveque, Tse 2007] or for certain high pathloss models [Xie and Kumar 2004]



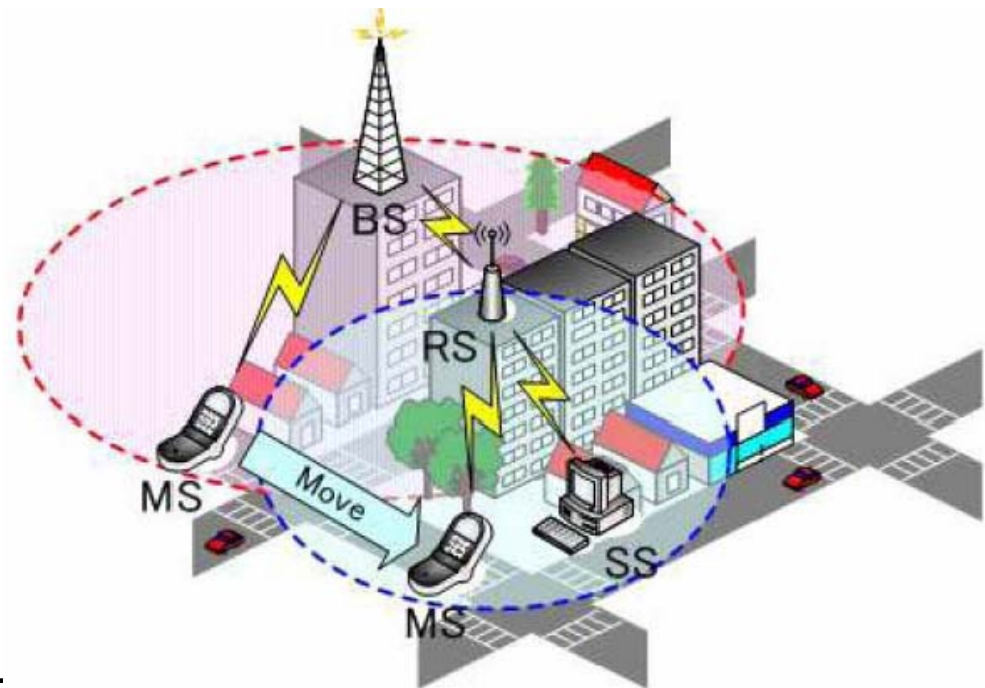
Interference limits scalability

- Communication in ad-hoc networks is interference limited.
- Direct communication is possible with aggregate rate of only $\Theta(1)$
- To avoid interference transmit only to closest neighbor
- If the area = 1 unit and the number of nodes is n , the average distance between nodes is $1/\sqrt{n}$
- Each source needs, on the average, \sqrt{n} retransmissions to reach the destination.
- Throughput heavily depends on channel model; for Rayleigh channel, throughput is $\Theta(\log n)$ [Gowaikar, Hochwald, Hassibi 2006]



Relays in Wireless Networks

- Relays: intermediary, possibly more sophisticated, nodes that help carry the information in a wireless network:
 - No data of their own
 - Ability to schedule resources
 - Channel state information (CSI) global/local
 - May have ability to cooperate
- Relays in infrastructure-based networks: extend coverage to shadowed parts of the cell.
- E.g.: 802.16j Mobile Multihop Relay (MMR)

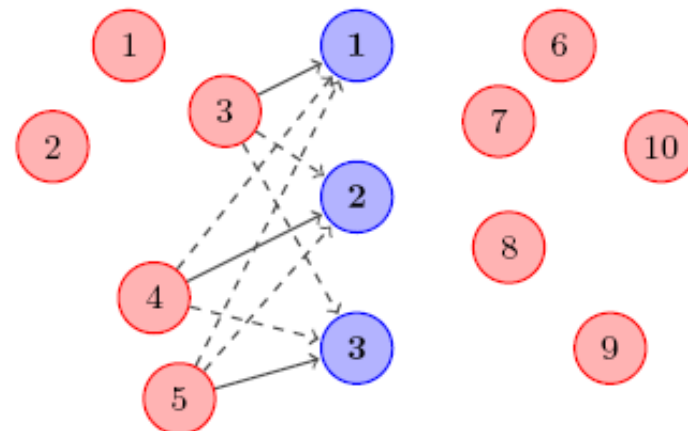


Questions...

- What role can relays play in ad-hoc wireless nets?
- Can relays alleviate the throughput scaling problem?
- What relay capabilities are required?
- What is the effect of cooperation among relays?

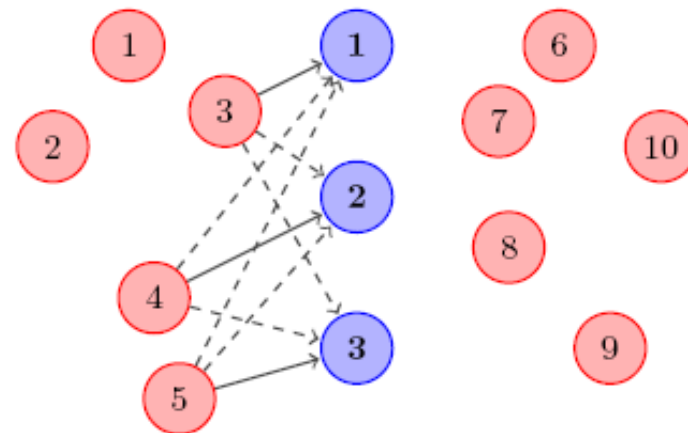
The Set-Up

- Model of interest:
 - n source-destination pairs
 - m relays
 - Rayleigh fading
 - Half duplex, two-hop relaying
 - Source/destination nodes do not cooperate, i.e., are not aware of each other's signals
- Design space:
 - CSI awareness
 - Relay capabilities:
 - Scheduling distributed or centralized
 - Full CSI, global or local
 - Relay cooperation



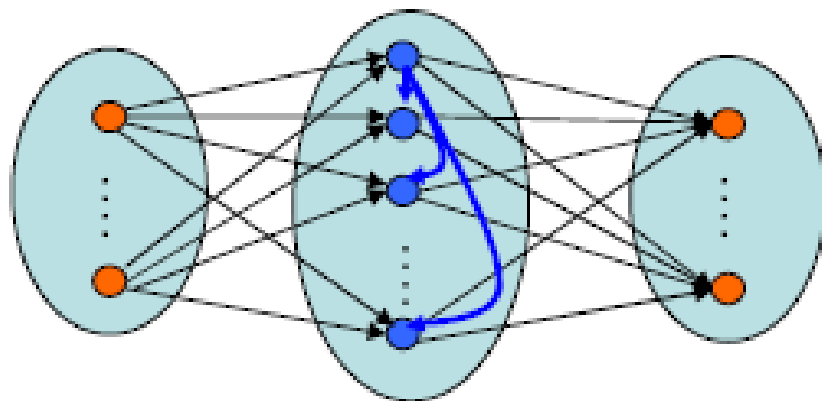
The literature...

- Different assumptions, lead to different roles for the relays and to different throughputs
- Single source-destination pair:
 - Diversity paths – cooperative diversity [Laneman et. al. 2004], [Katz and Shamai 2005 and 2006]
- n source-destination pairs, m relays: What is the effect of relays on the maximum throughput?
 - $\Theta(n)$ with $m > n^3$; relays have only local CSI; distributed beamforming [Morgenshtern and Bölcskei 2007]
 - $\Theta(n)$ with $m > n^2$; relays have global CSI; distributed adaptive beamforming (can place nulls) [Dana and Hassibi 2006]



Relay cooperation

- What is gained if the relays are allowed to cooperate?
 - [Niu, Simeoni, Haimovich, Somekh Allerton 2007] linear throughput scaling can be achieved with relay cooperation and $m > n$.
- Acts as a distributed MIMO system.
- We developed an understanding of what central scheduling and relay cooperation can gain.
- Such a system can be implemented only with relays connected to an infrastructure.

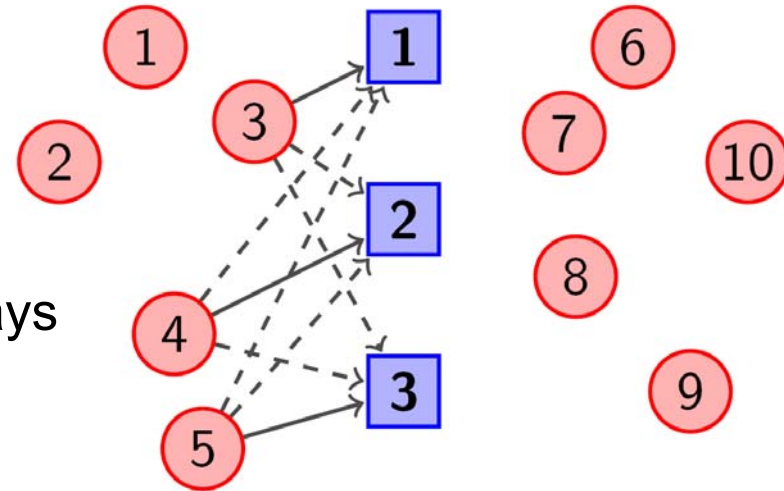


More questions...

1. What if cooperation of relays is not allowed?
2. What is the throughput scaling law if centralized scheduling is not possible, i.e., relays have to provide own scheduling?
3. The requirement of full, global CSI at the relays is onerous. Can the requirement be reduced?
4. What is the impact on throughput of reducing the number of relays?

System model

- n ad-hoc source/destination nodes
- m relay nodes, w/o traffic demands
- Equal power sources and relays
- Two-hop protocol through half-duplex relays
- Sources and relays can buffer data
- All nodes have iid Rayleigh connections
- Block-fading
- No cooperation is allowed
- Single-user encoding
- Distributed scheduling
- Receivers have local CSI and can feedback an integer index number
- What can be achieved with limited number of relays



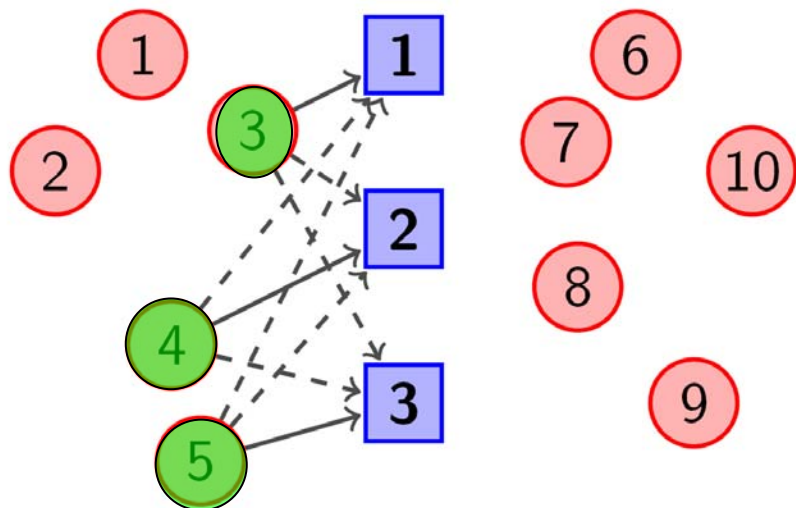
Opportunistic relaying scheme

Opportunistic relaying scheme [Cui, Haimovich, Somekh, Poor 2007]:

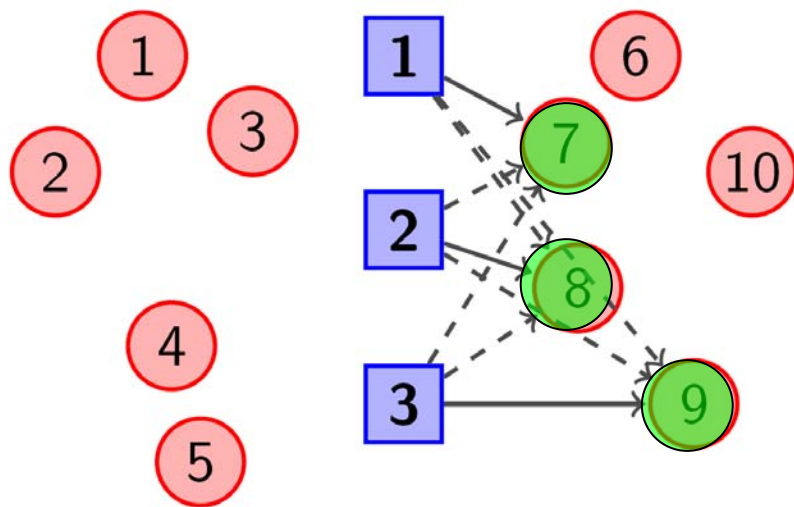
- Communication takes place in 2 phases

Phase 1:

1. CSIR,
2. Each relay computes SNR to all sources and schedules its *best* source by feeding back an index representing the source.
3. The scheduled sources transmit at 1 bit/s/Hz



Scheduling in Phase 2



Phase 2:

1. CSIR,
2. Each destination computes m SINRs, one for each relay
3. If for a relay $\text{SINR} > 1$, the destination feeds back the corresponding relay index
4. The relays transmit to their respective destinations at 1 bit/s/Hz

Key idea: schedule only nodes that enjoy multiuser diversity gain

Throughput analysis

- A transmission at 1 bit/s/Hz is successful if at the destination $\text{SINR} \geq 1$
- Features:
 - Decentralized scheduling – relays schedule themselves
 - Relays do not cooperate
 - Modest CSI assumptions
 - Buffering and latency
- Will these simplifications sacrifice the system throughput scaling in the regime of large n ?
- We are interested in cases where $m < n$
- Throughput analysis
 - Finite n and finite m
 - Large n and finite m
 - How fast can m grow?

Finite n , finite m : Throughput Phase 1

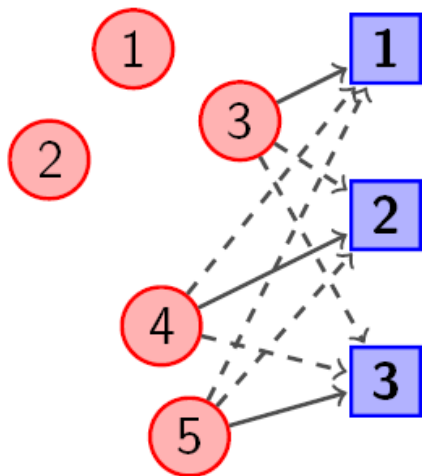
n : # source nodes

m : # relay nodes

ρ : SNR of the S-R link

Lower bound on the throughput

$$R_1 \geq \Pr[N_m] \sum_{i=1}^m \Pr[\text{relay } i \text{ successfully decodes}] \cdot 1 \\ = m \cdot \Pr[N_m] \cdot \Pr[S_m],$$



where N_m denotes the event “ m relays schedule m distinct sources” and S_m is the corresponding probability of successful transmission

$$\Pr[N_m] = n(n-1) \cdots (n-m+1)/n^m$$

$$\Pr[S_m] = \Pr[\text{SINR} \geq 1] = \Pr\left[\frac{X}{1/\rho + Y} \geq 1\right] \\ \geq (1 - F_X(s)) F_Y(s - 1/\rho).$$

Throughput Phase 2

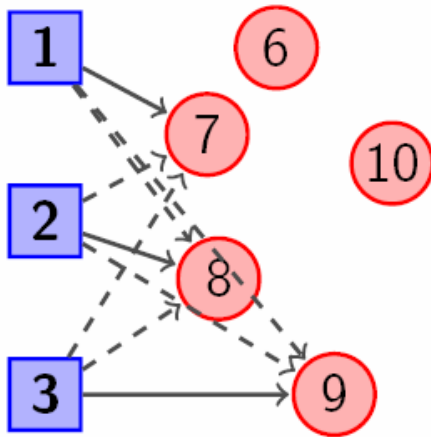
n : # destination nodes

m : # relay nodes

ρ_R : SNR of the R-D link

Average throughput

$$\begin{aligned} R_2 &= \sum_{i=1}^m \Pr[\text{relay } i \text{ is scheduled}] \cdot 1 \\ &= m \Pr[\text{relay } i \text{ is scheduled}] \end{aligned}$$



where

$$\begin{aligned} \Pr[\text{relay } i \text{ is scheduled}] &= 1 - \Pr[\text{relay } i \text{ is NOT scheduled}] \\ &= 1 - \Pr(\text{all SINR}_i < 1) \\ &= 1 - \left(F_{\text{SINR}}(1) \right)^n \end{aligned}$$

Combine the two hops...

Lemma 1: Lower bound on the throughput in Phase 1

For any ρ , $n \gg m$ and $s > 0$, the achievable throughput of the opportunistic relay scheme in Phase 1 is lower-bounded by

$$R_1 \geq m \frac{n(n-1)\cdots(n-m+1)}{n^m} \left(1 - (1 - e^{-s})^n\right) F_Y\left(s - \frac{1}{\rho}\right).$$

Lemma 2: Average throughput in Phase 2

For any ρ_R , m and n , the achievable throughput of the opportunistic relay scheme at Phase 2 satisfies

$$R_2 = m \left(1 - \left(1 - \frac{e^{-1/\rho_R}}{2^{m-1}}\right)^n\right).$$

Throughput scaling: large n , finite m

- The throughput scaling in Phases 1, 2:

Corollaries 1,2: First and second hop

For fixed m , as $n \rightarrow \infty$, $R_1 \rightarrow m$, $R_2 \rightarrow m$.

- Lower bound on the rate in Phase 1:

$$R_1 \geq m \frac{n(n-1)\cdots(n-m)}{n^m} \left(1 - (1 - e^{-s})^n\right) F_Y \left(s - \frac{1}{\rho}\right)$$

Compute the lower bound for $n \rightarrow \infty$:

$$(1) \frac{n(n-1)\cdots(n-m)}{n^m} \rightarrow 1$$

$$(2) \text{ Let } s = \log n - \log \log n, \text{ then } \left(1 - (1 - e^{-s})^n\right) \rightarrow 1$$

$$(3) F_Y(\log n) \rightarrow 1$$

Throughput scaling: large n , finite m

- Summarize results so far

Theorem 1: Two-hop scheme

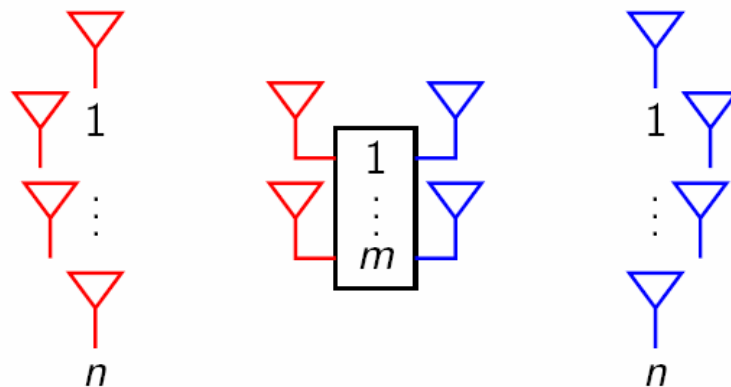
For fixed m , the two-hop opportunistic relaying scheme achieves a system throughput of $\frac{m}{2}$ bits/s/Hz as $n \rightarrow \infty$.

Universal upper bound

For *any* two-hop relaying architecture, with finite m and SNR, the sum rate capacity scales at most like $\frac{m}{2} \log \log n$ as $n \rightarrow \infty$.

Universal upper bound

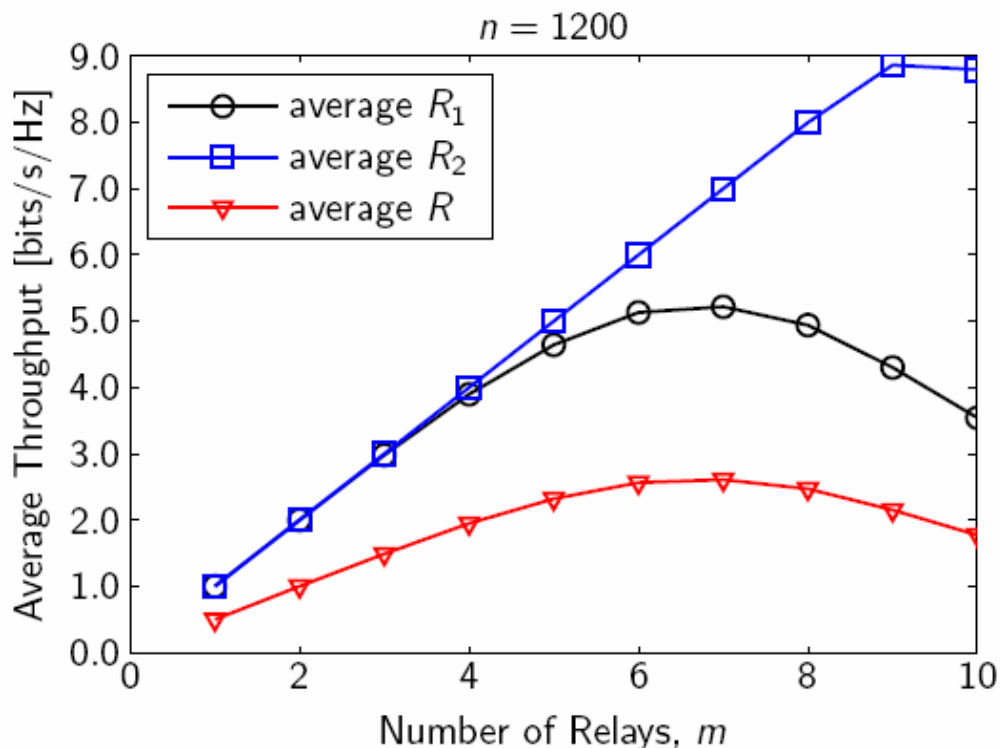
- The universal upper bound is the MIMO bound $\frac{m}{2} \log \log n$
 - With **full cooperation and full CSI at the relays**, the two-hop scheme is equivalent to a **(n, m) uplink MIMO** followed by a **(m, n) downlink MIMO**.



- MIMO-BC capacity region [Weingarten, Steinberg, Shamai 2006]
- For $n \rightarrow \infty$, the sum-rate capacity of the MIMO downlink is $m \log \log n$ [Sharif and Hassibi 2005]
- By uplink–downlink duality, the uplink also has a sum-rate of $m \log \log n$ [Jindal et al. 2004]

How fast can m grow?

- We already have shown that for increasing number of source-destination pairs n and for finite number of relays m , $R = m/2$.
- What happens if m also increases?



- What is the optimal m that maximizes the system throughput?

Increasing $m...$

What is the effect of increasing m ?

- Phase 1:

$$R_1 \geq m \frac{n(n-1)\cdots(n-m)}{n^m} \left(1 - (1 - e^{-s})^n\right) F_Y \left(s - \frac{1}{\rho}\right)$$

(1) $m \uparrow$

(2) $\frac{n(n-1)\cdots(n-m)}{n^m} < 1 \downarrow$

(3) Let $s = \log n - \log \log n$, then $\left(1 - (1 - e^{-s})^n\right) \rightarrow 1$

(4) $F_Y(\log n) < 1 \downarrow$

- Phase 2:

$$R_2 = m \left(1 - \left(1 - \frac{e^{-1/\rho_R}}{2^{m-1}}\right)^n\right)$$

Phase 1, increasing n and m

- We find lower and upper bounds and show that they are equal within a constant independent of n or m
- For a threshold $s = \log n - \log \log n$ and number of relays $m = \log n$, the lower bound on the rate in phase 1 is given by

$$R_1 \geq 0.5 \log n$$

- Genie scheme: relax assumptions of decentralized scheduling and only local CSI.

Theorem 2: Genie bound

With probability approaching 1,

- there is no set of $\frac{\log n}{\log 2} + 2$ nodes whose simultaneous transmissions to relays are all successful
- there is a set of $(1-\epsilon) \frac{\log n}{2 \log 2} + 2$ nodes whose simultaneous transmissions are all successful

Phase 1, lower bound, $m = \log n$

- Lower bound on the rate in Phase 1:

$$R_1 \geq m \frac{n(n-1)\cdots(n-m)}{n^m} \left(1 - (1 - e^{-s})^n\right) F_Y \left(s - \frac{1}{\rho}\right)$$

For $n \rightarrow \infty$, $m = \log n$:

Interference term Y is asymptotically chi-square with

$$2(\log n - 1) \text{ DOF} \xrightarrow{\text{Central Limit Theorem}} N(\log n, \log n)$$

$$\text{It follows that } F_Y \left(\log n - \log \log n - \frac{1}{\rho} \right) \approx F_Y(\log n) = \frac{1}{2}$$

- Put it all together, $R_1 \geq \frac{1}{2} \log n$
- It is possible to schedule $m = \log n$ nodes; 1/2 of them will fail.
But that means that throughput of $\Theta(\log n)$ is achieved.

Phase 2, increasing n and m

Theorem 3:

With probability approaching 1,

- if the number of relays $m = \frac{\log n - \log \log n - 1/\rho_R}{\log 2} + 1$,

then $R_2 = \Theta(m) = \Theta(\log n)$

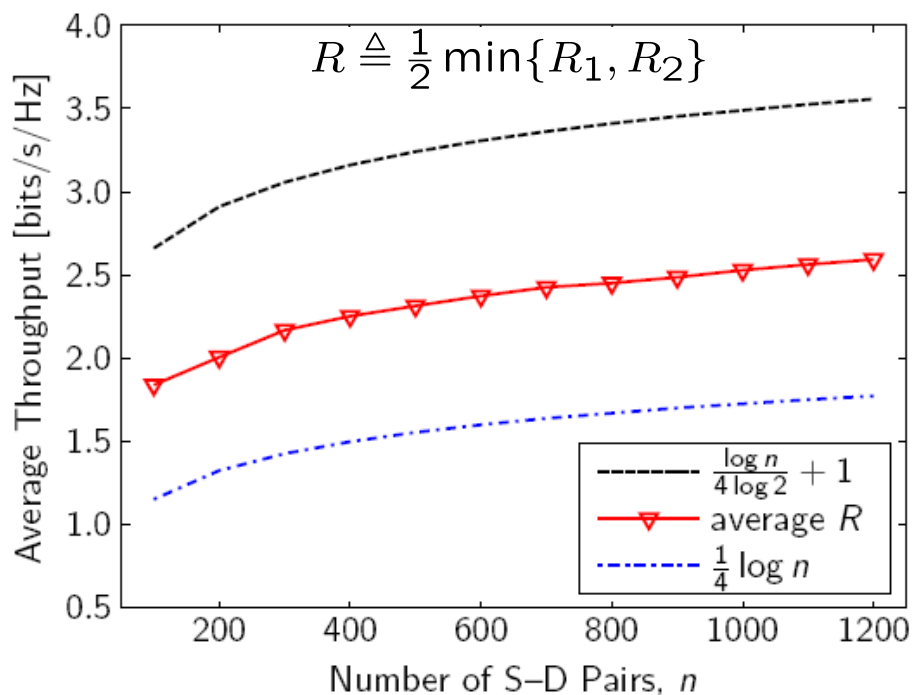
- conversely, if $m = \frac{\log n + \log \log n - 1/\rho_R}{\log 2} + 1$,

then $R_2 = o(m)$

- Optimal value of the number of relays m exhibits sharp phase transition
- With a number of relays $m > \log n$, higher than the optimal value, the throughput R_2 does not retain the linearity in the number of relays.
- In such case, with probability 1, the SINR = 1 cannot be supported.

Throughput scaling: summary

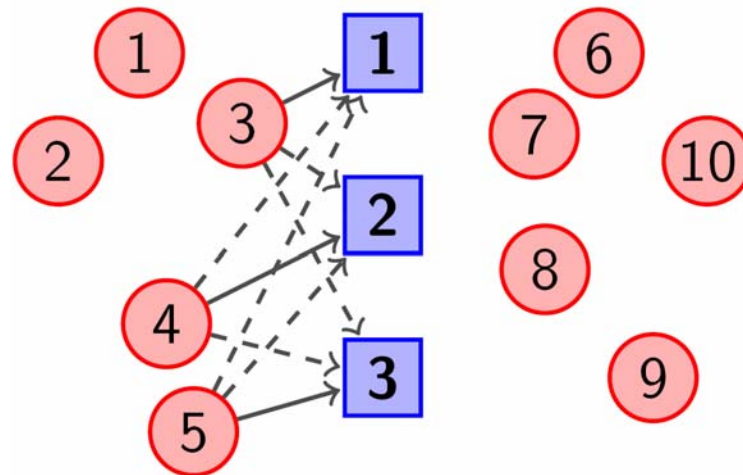
Regime	R_1	R_2	R	Upper Bound
large n , finite m	m	m	$\frac{m}{2}$	$\frac{m}{2} \log \log n$
large n , large m	$\Theta(\log n)$	$\Theta(\log n)$	$\Theta(\log n)$	$\frac{m}{2}$



Multiuser diversity interpretation

- Recall: multiuser diversity gain in cellular system

- Single base-station with n i.i.d. Rayleigh fading users
- the best user has effective channel gain $\log n$
- power gain translates to throughput of $\log \log n$



- In wireless network, we have multiple concurrent transmissions
- Multiuser diversity is used to make these transmissions reliable
- E.g., look at the first hop, the throughput is in the form of $m \Pr[\text{SINR} \geq 1]$

$$\begin{aligned} \text{SINR} &= \frac{\text{signal power}}{\text{noise power} + \text{interference power}} \\ &= \frac{\log n}{1/\rho + (m - 1)} \end{aligned}$$

Beyond Rayleigh fading model

- So far, we focused on the Rayleigh fading model
 - Well-accepted model in wireless communication
 - Mathematically tractable
- For other fading models, closed-form expressions are hard to compute, but the interpretation of multiuser diversity sheds light on the throughput scaling
 - Multiuser diversity depends only on the upper tail of the channel PDF and has been well studied
- The genie scheme can be used to develop an upper bound on the throughput scaling
 - For a class of fading channel models with finite mean and variance, the throughput scaling for *any* two-hop scheme cannot be greater than $\Theta(\sqrt{n})$

Concluding remarks

- Proposed an opportunistic two-hop relaying protocol for delay-tolerant wireless networks over Rayleigh channels
 - Does not require cooperation between users or relays
 - Decentralized scheduling
 - Assumes CSIR and only limited CSIT
 - Exploits multiuser diversity
- Developed expressions for the throughput for various cases
- Characterized the system throughput to be $\Theta(\log n)$, which is proven to be the optimal scaling in the Rayleigh fading model.
- Proposed scheme extends the philosophy of multiuser diversity from cellular systems to wireless ad-hoc networks.

Furture work

- Throughput analysis for other (that Rayleigh) fading
 - Generalize the results to general fading model with finite mean and variance
 - Applicable for most of channel models in wireless communication
 - It can be shown that the throughput cannot be better than the order of \sqrt{n}
 - It is interesting to investigate
 - Is the bound tight? Achievable?
 - How the performance of specific scheme?
 - Beyond \sqrt{n}
 - [Grossglauser-Tse'02] mobility model achieves $O(n)$
 - Equivalent to Pareto distribution (infinite variance and sometimes infinite mean)
 - Can we reproduce $O(n)$ within random connection model?
- Throughput-Delay tradeoff
- In sum, this research helps understand the fundamental limits of wireless network under fading channel; in addition, simplified schemes are proposed to approach throughput limit

For More Information

S. Cui, A. M. Haimovich, O. Somekh, and H. V. Poor, "Opportunistic relaying in wireless networks," IEEE Trans. Inf. Theory, submitted for publication, Dec. 2007. [Online].

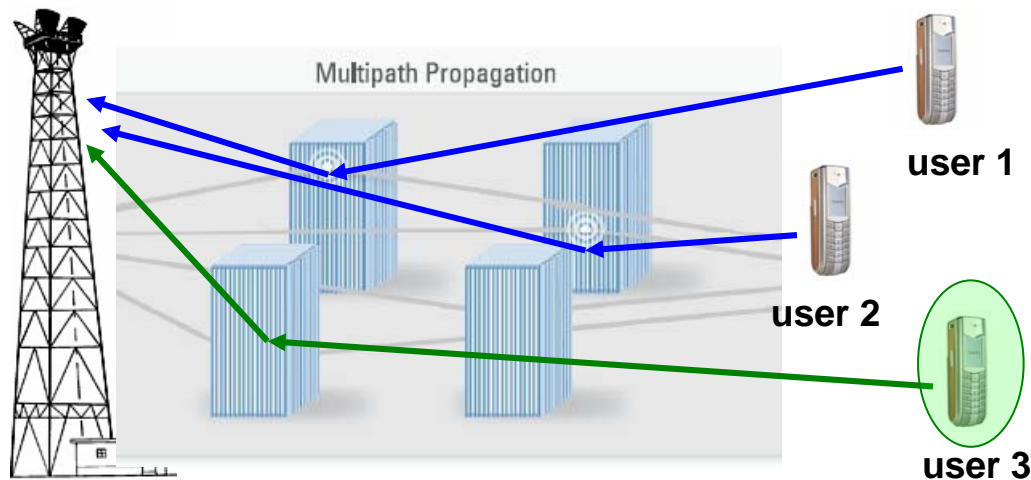
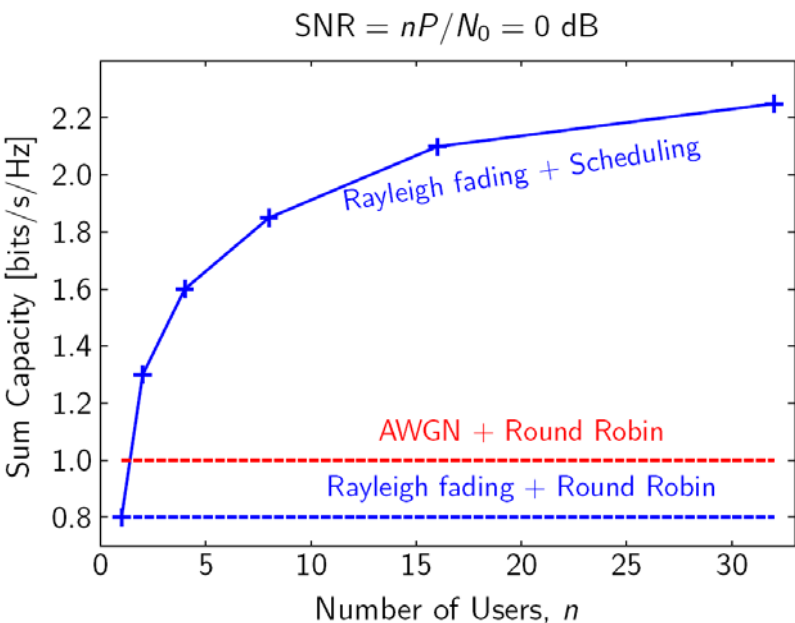
Available: <http://arxiv.org/pdf/0712.1169>

Shengshan Cui, Alexander M. Haimovich, Oren Somekh and H. Vincent Poor, "Decentralized Two-Hop Opportunistic Relaying With Limited Channel State Information," submitted to IEEE International Symposium on Information Theory (ISIT), Toronto, Canada, 2008.

Shengshan Cui and Alexander M. Haimovich, "Opportunistic Relaying in Wireless Networks," in Proceedings of Allerton Conference on Communications, Control, and Computing, Monticello, IL, September, 2007.

B. Niu, O. Simeone, O. Somekh and A. M. Haimovich, "Throughput of Two-Hop Wireless Networks with Relay Cooperation," 45th Annual Allerton Conference on Communication, Control, and Computing, Monticello, IL, September, 2007.

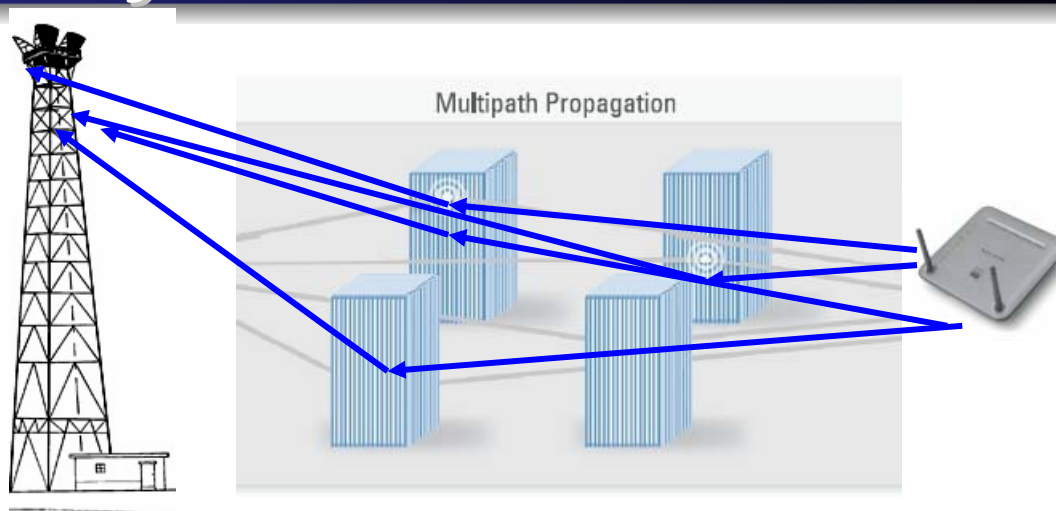
Multiuser Diversity



1. Base station sends pilot
2. Users measure CSI
3. User feedback CSI
4. Base station selects user

- In a large system with users fading independently, at any given time, there is likely to be a user with a very good channel.
- Long term total throughput can be maximized by always serving the user with the strongest channel [Knopp and Humblet 1995]
- Choosing the strongest channel provides a power gain of $\log n$
- Notions of multiuser diversity have been applied in IEEE 802.16e, LTE

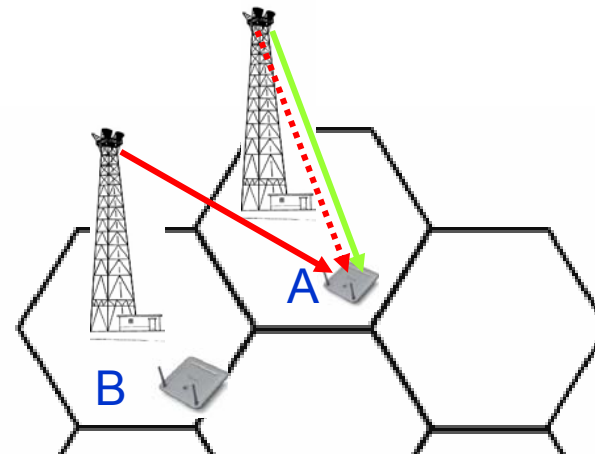
Increase Capacity with MIMO



- Scattering in the channel supports distinct, parallel channels between user and base station – multipath is an advantage
- Requires multiple transmit and receive antennas
- For a system with M transmit antennas and N receive antennas, the sum rate scales as $\Theta(\min(M,N) \log n)$
- MIMO is being incorporated in 3G cellular standards, WiFi, WiMax and other technologies.

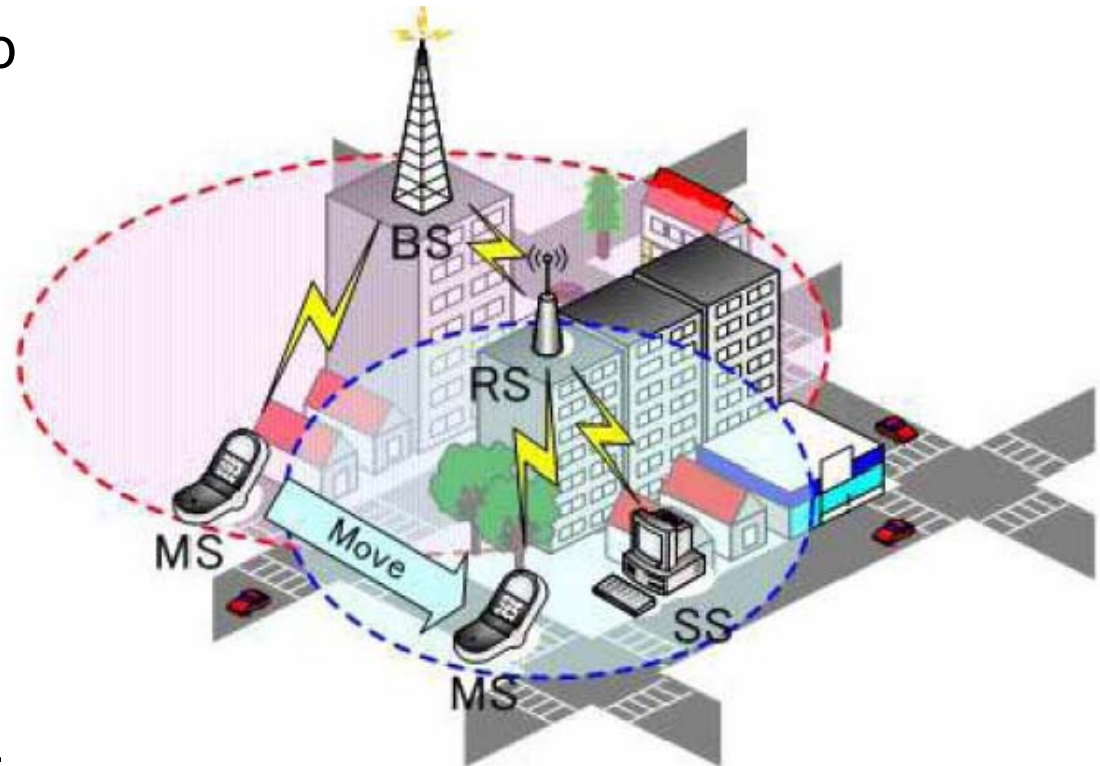
Cooperation

- Signal received at user A is subject to interference from cell B.
- Cooperation between the base stations in A and B enables base station A to transmit a signal that subtracts out the interference from B.
- Requires time synchronization, global CSI



Relaying

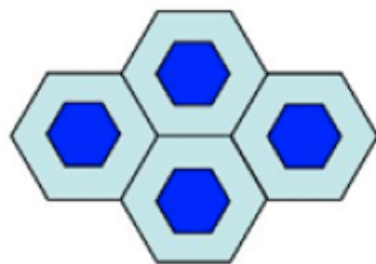
- Relay: a node without traffic of its own
- Industry view of the role of relays in wireless networks: a carrier-owned infrastructure that links between basestations and mobile stations.
- 802.16j Mobile Multihop Relay (MMR) network elements:
 - Base station
 - Relay station
 - Mobile stations



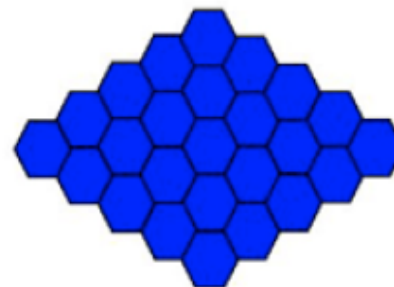
Relays: Current Industry Vision

- Industry has competing visions on the application of MMR networks
- Some see RSs being used mainly at cell edge to extend coverage.
- Capabilities of RS being debated: schedule resources?
- A different application being proposed is of low-cost, meshed picocells that offer uniform coverage over a macrocell including “shadowed” areas, indoor, and cell-edge.
 - Large number of RSs per square mile
 - Mesh architecture since infeasible to run backhaul to a large number of cells

Macro-Cellular Coverage



Pico-Cellular Coverage



CHARIoT

- (CHARIoT: Cooperative, Hybrid wireless ARchitecture for the next generation Internet): study the capability of relays to increase capacity of wireless networks.
- We ask ourselves:
 - Can “relays” alleviate the throughput scaling problem?
 - What relay capabilities are required?
 - What is the effect of cooperation among relays?