Hybrid Networks: Cellular-Relay Architecture

Harish Viswanathan, Sayandev Mukherjee and Ram Ramjee

Bell Labs, Lucent Technologies

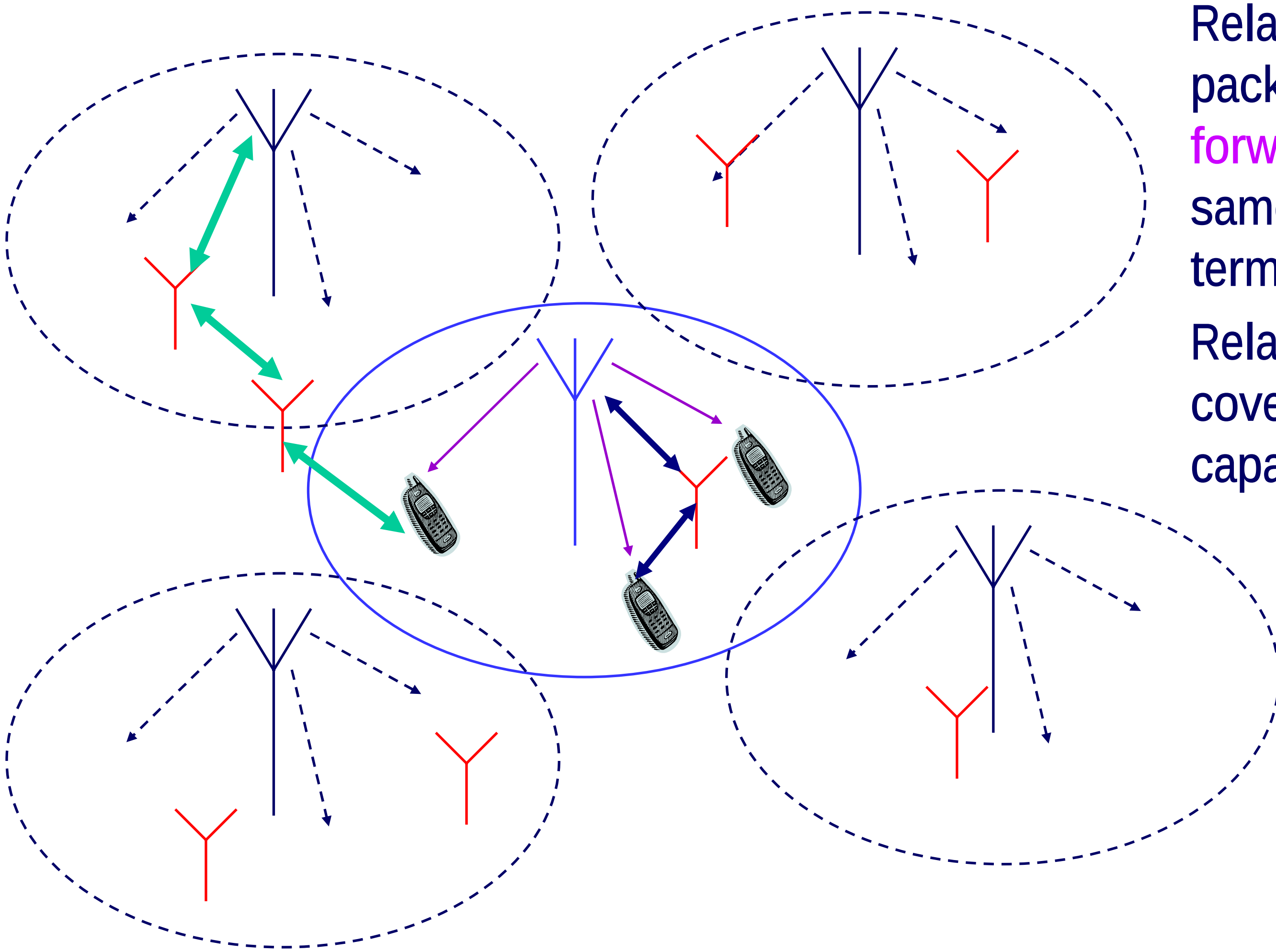
Murray Hill, NJ

Network Architecture for 4G

- **Macro-cell architecture may not have enough capacity and coverage for ubiquitous high data rates**
- **Alternatives**
  - **Pico-cellular, Hierarchical, Ad Hoc, etc.**
  - **Integrated cellular and WLAN**
- **Focus: Can macro-cellular capacity be significantly enhanced through deployment of cheap "pseudo base stations" or *relays*?**
  - **Multiple hops to and from base station through the relays**
  - **Intermediate step towards multihop through terminals**

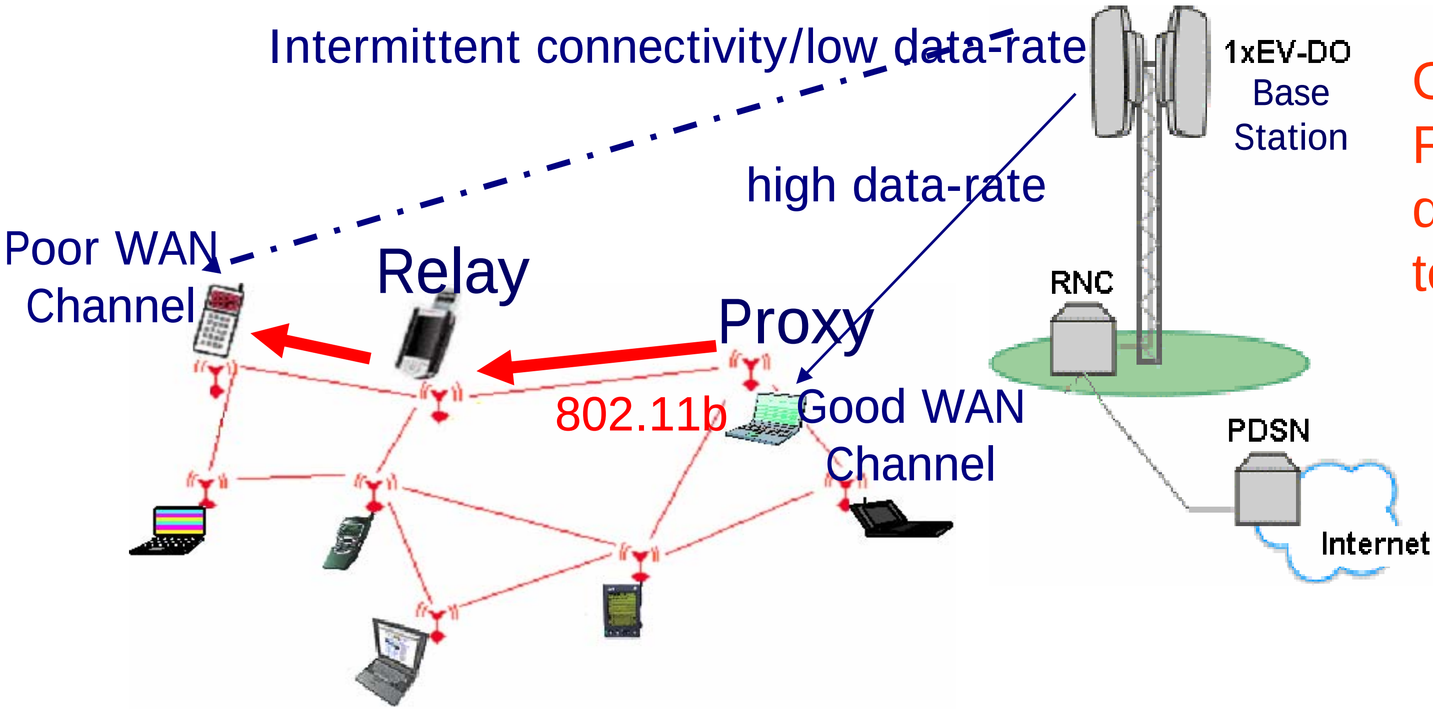
Cellular Networks with Relays

Lucent Technologies
Bell Labs Innovations



- Relays decode received packets, then store and forward them on the same/different frequency to terminals
- Relays can improve coverage and capacity
  - Mobile relays to cover hot spots
  - Adaptation to traffic imbalance
  - Additional delay due to multihop

Cellular-WLAN Architecture



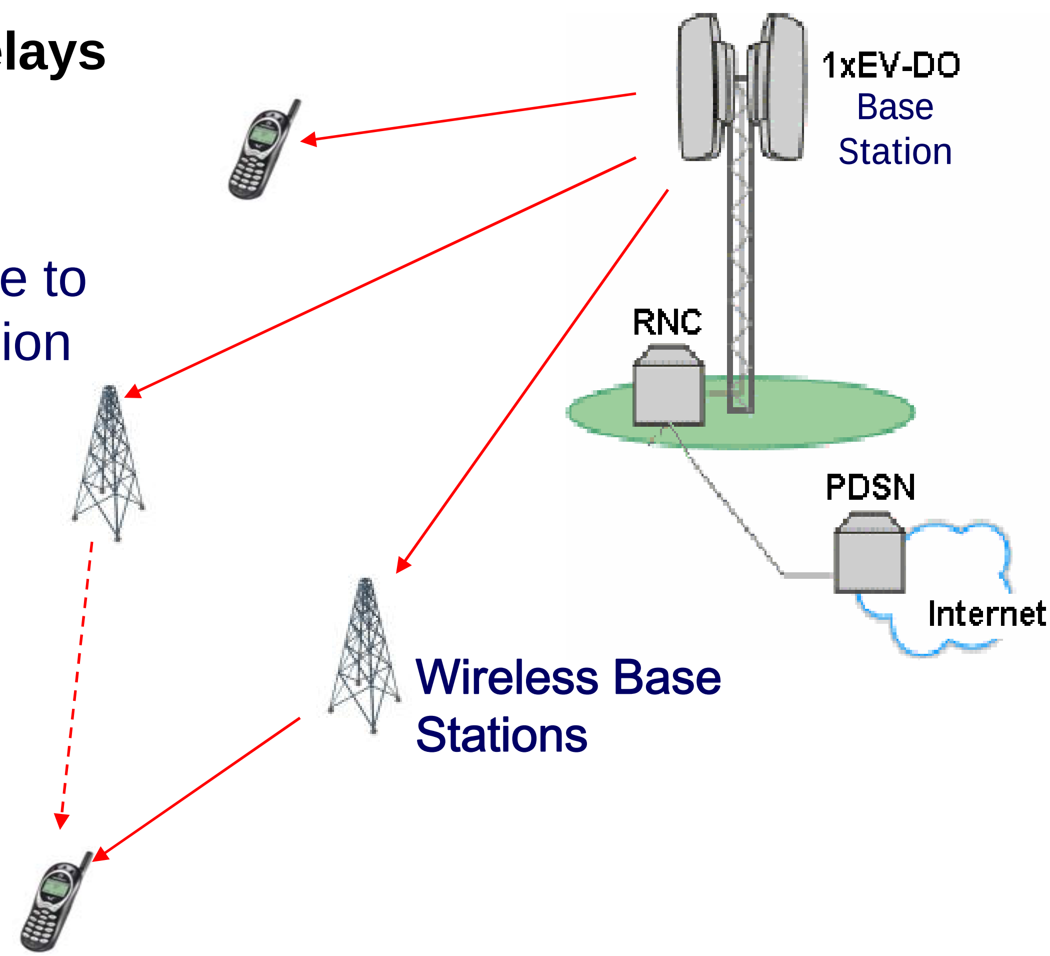
Opportunistic Relaying using dual-mode terminals

- **Proxy discovery and maintenance**
- **Routing**
  - **Node mobility**
  - **3G channel dynamics**
- **Incentives**
  - **WAN operator**
  - **Proxy & relay**

Cellular-Relay Architecture

- **Service provider deployed relays to cover hot spots or enhance coverage (eg. in-building)**
- Same spectrum is used for base to relay and relay to user transmission
- Low cost base stations with no backhaul

- **Routing and Scheduling**
- **Signaling**
- **Location of Relays**

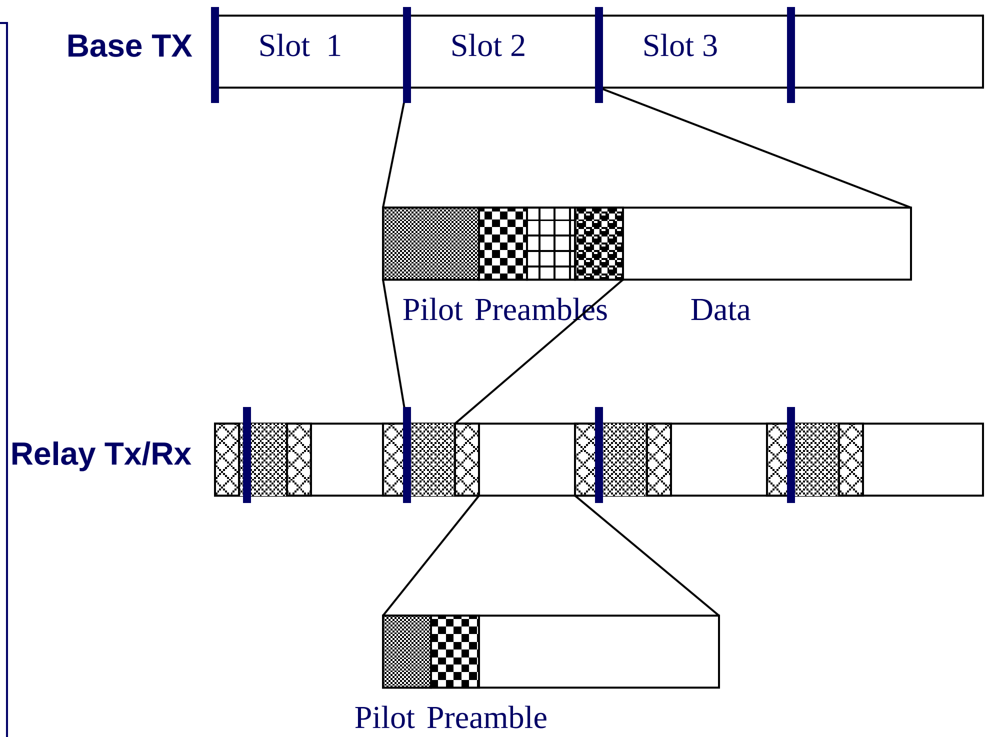


Ev-DO Based System

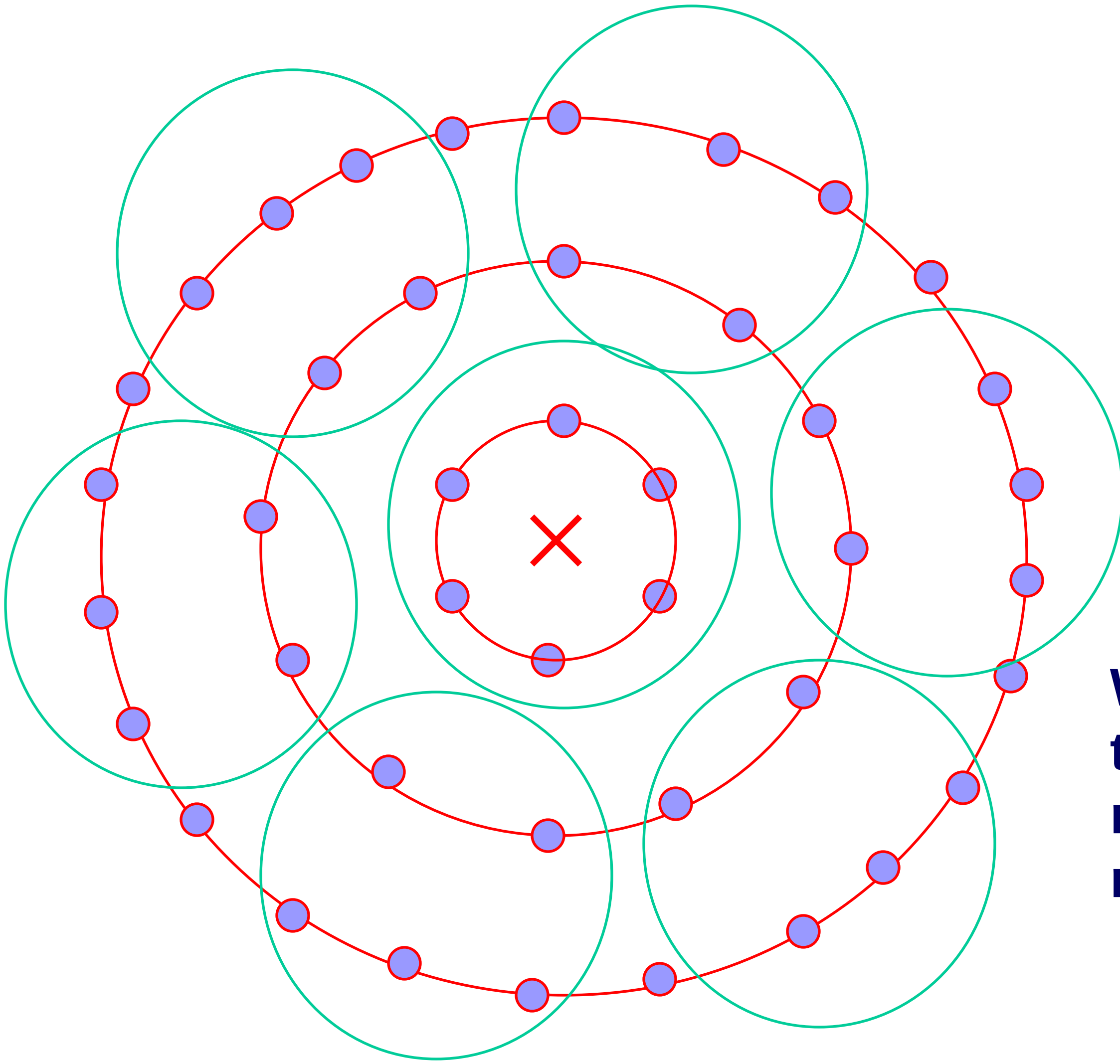
Medium Access Features

- Time division multiplex transmission with spreading
- Base and relay transmissions identified by unique PN scrambling (allows simultaneous transmission)
- Rate adaptation based on link quality
- CDMA reverse link
- Link quality feedback on the uplink (as in 1X EV-DO) – helps deal with mobility across relays

Downlink Frame Structure



Why do relays provide a gain?



Multiple simultaneous transmissions possible

With increasing number of relays the size of each relay region decreases - transmit power can be reduced

With power control, one transmission for every k relays even for a large number of relays

Large System Performance Gain

Number of simultaneous transmissions ~ $\frac{N}{k}$

Number of Hops ~ $\sqrt{N}$

Throughput Gain ~ $\sqrt{N}$

Assumes no peak rate limit from base station

First Ring Bottleneck

In the multihop system, data has to be first transmitted to the first ring of relays before the reuse efficiency kicks in

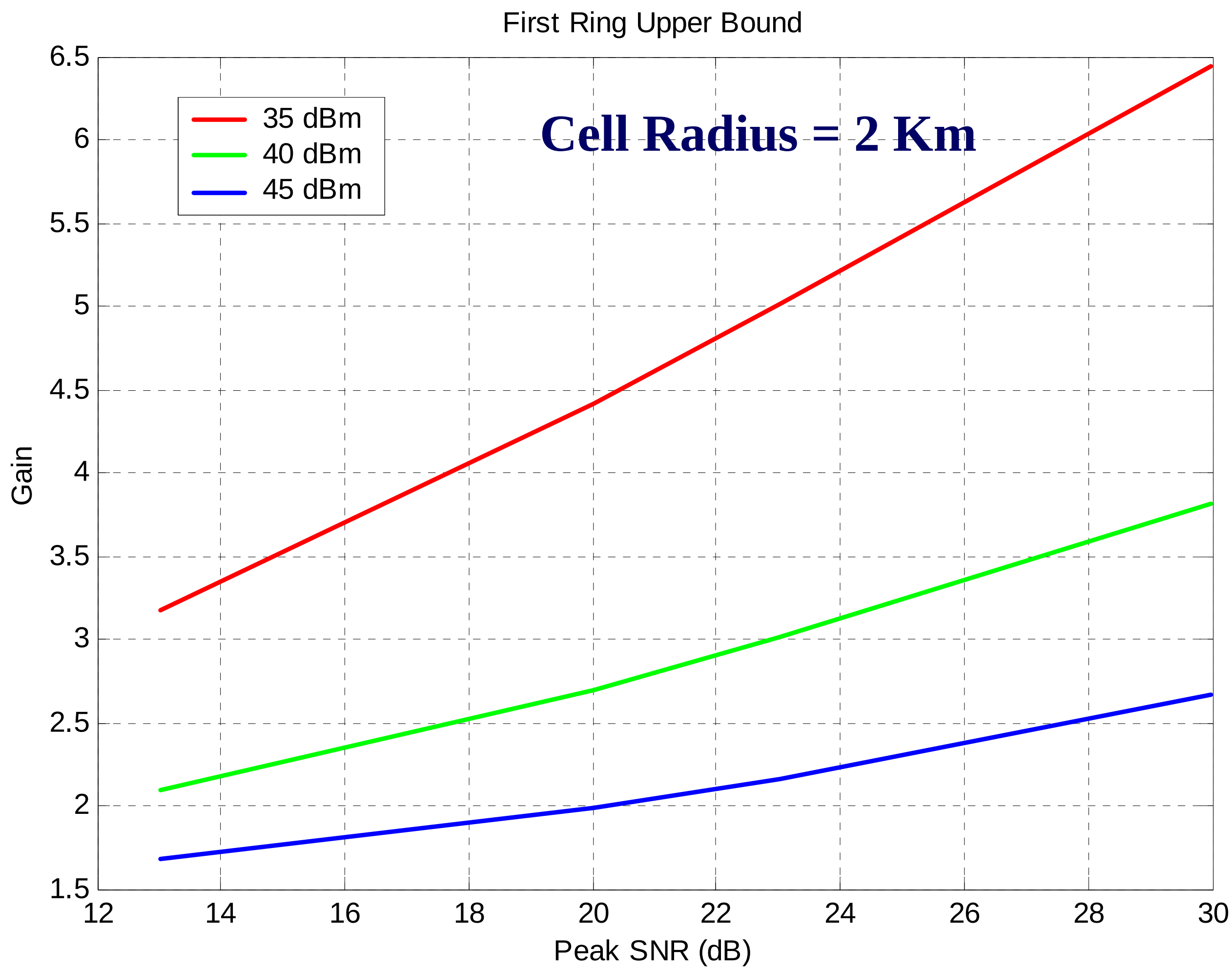
In the limit of large number of hops transmission from the base to the first ring can be the bottleneck since base has to transmit one at a time to each of the receivers in the first ring

- peak rate limit

Multiple antennas at the base station can alleviate the problem

$$\text{Gain} \leq \frac{R_{peak}}{R_{avg}}$$

First ring upper bound with peak rate limit



Rate from base to first ring of relays is limited by peak SNR achievable

One hop performance is sensitive to the base transmit power while p-hop performance bound is not

Higher gains can be achieved with multiple antenna transmission in the first hop

Routing and Scheduling with relays

- **Which terminals to schedule at each time step?**
- **Constraints:**
  - **Relays cannot transmit and receive in same frame**
  - **Queues at base and each relay for every user; packets transmitted by relay must have been queued from base to relay first**
  - **Transmission rates dictated by interference power**
- **Optimization: given instantaneous feedback about transmission rates on all links, determine the optimal set of active links on the next frame so as to achieve *throughput-optimality*: stable queues for each user for largest possible set of arrival rates**

Throughput-Optimal Scheduling

(Derived from Tassiulas & Ephremides 1992)

$$\max_{\underline{r} \in \mathbf{R}(t)} \sum_{i,j} D_{ij} \underline{r}_j$$

$i -$ index of user

$j -$ index of the link

$$D_{ij} = Q_{iq(j)}(t) - Q_{ih(j)}(t)$$

$q(j) -$ source node of link

$h(j) -$ destination node of link

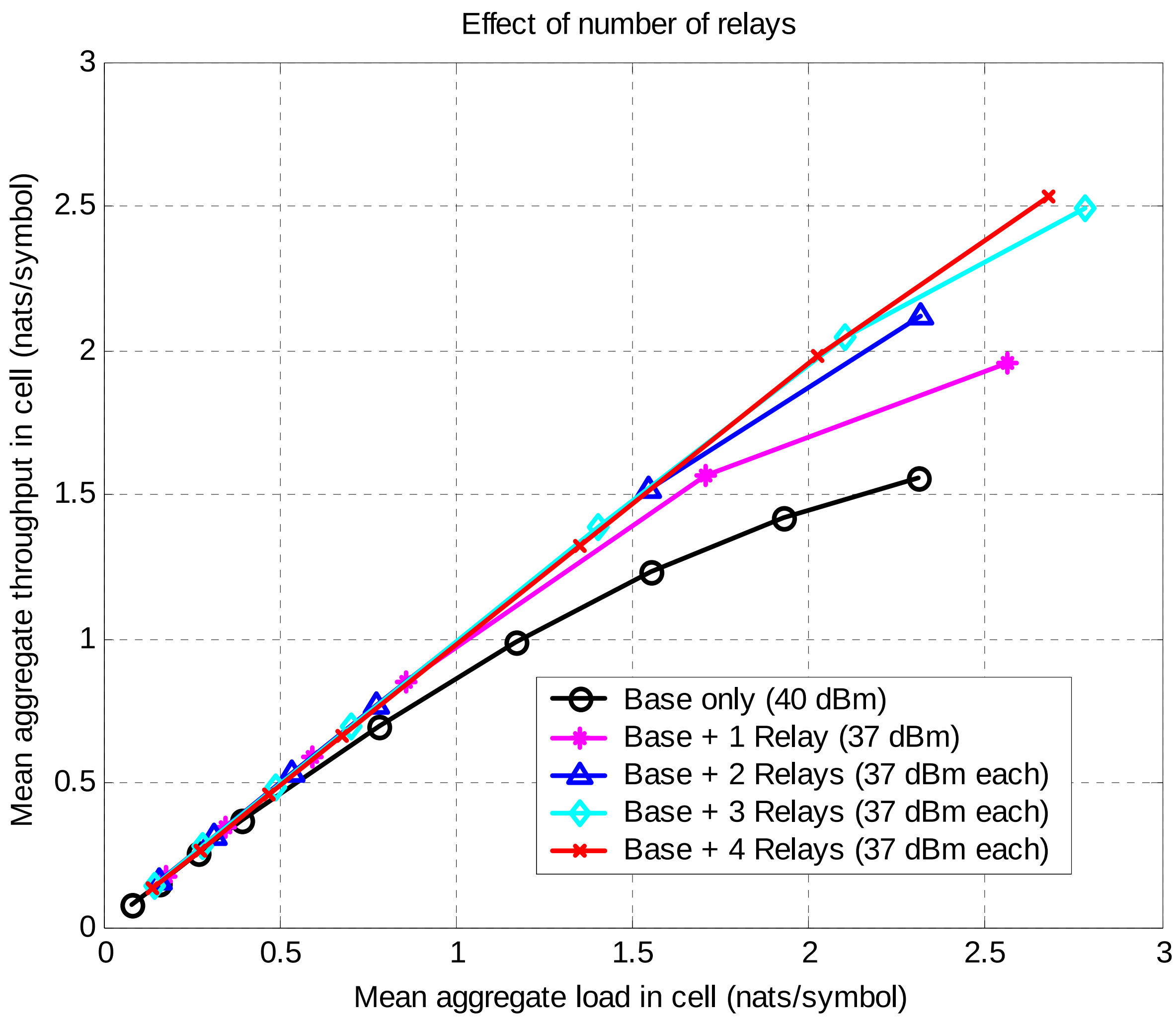
R(t) is the feasible set of link rates that depends on power allocation and interference

Algorithm determines optimal reuse based on fading conditions

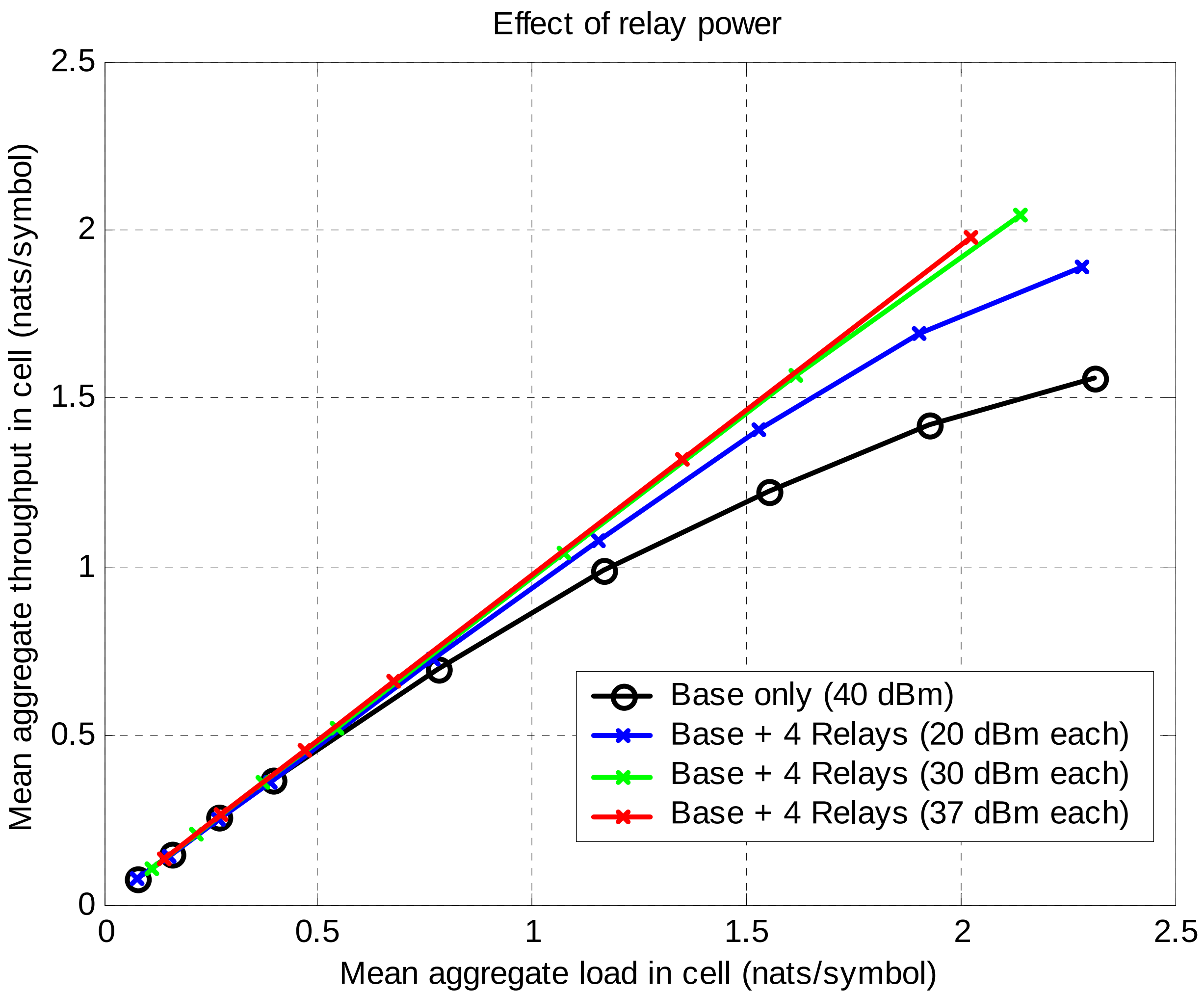
Simulation Setup

- Cell has three 120º sectors; 20 users/sector and 0, 1, 2, 3 or 4 relays/sector
- Relays are at a distance of half the cell radius from the center, on lines that divide the central angle of the sector equally
- In each slot, packets arrive independently for each user with equal probability. The size of the packets is exponential with a chosen mean
- Cell radius is 2 km; we assume full interference from two rings of cells around the cell in question
- Path loss model is COST231-Hata at 1900 MHz, with base height 30m, Relay height 3m, and user terminal height 1.5m

Impact of number of relays

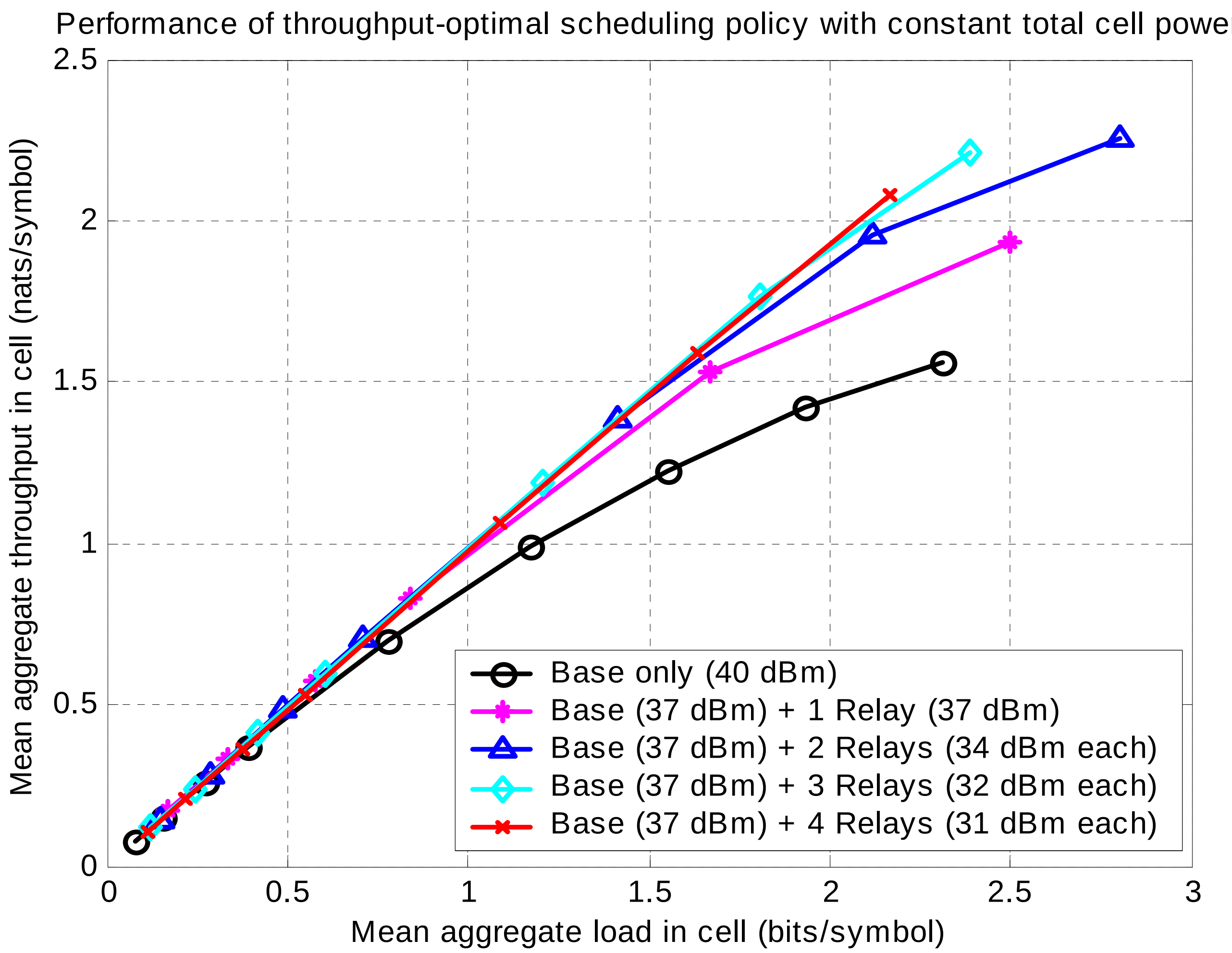


Impact of Relay Transmit Power



Gain saturates with increasing relay power

Results with Constant Total Cell Power



Distributing the power is better

Summary

- Analysis for large number of relays shows gains increasing linearly with number of hops
  - First ring of relays can be a bottleneck
- Simulation results show
  - About 60% gains for 3 relays in uniform traffic distribution
  - Increasing gains with with increasing relays when total cell power is held constant
  - Diversity gains from fading
- Potentially large gains for non-uniform traffic with optimal placement of relays or with multi-hop through WLANs
- Coverage enhancement

Other Results

- Cellular-WLAN Architecture
  - Proxy assignment and Routing protocols
  - ~50% throughput improvement
- Connectivity
  - Significant coverage improvement
  - Energy savings on the reverse link
- Multicasting
  - Significant gains from SINR improvement to cell edge users
  - Use of Network Coding