

Impact of Interference on Multi-hop Wireless Network Performance

Venkat Padmanabhan
Microsoft Research

February 2004

Collaborators

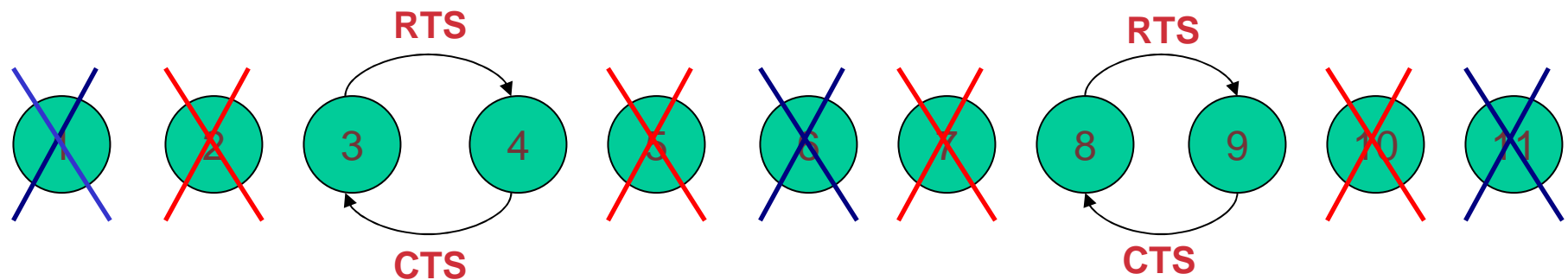
- Kamal Jain
- Jitu Padhye
- Lili Qiu

Motivation

- Multi-hop wireless networks are becoming increasingly common:
 - community "mesh" networks
 - sensor networks
 - in-home entertainment networks
- Hard to engineer or analyze such networks
 - I am not talking of the RF engineering challenge
- Q: given network topology and identities of the communicating pairs, what is the maximum throughput that the network can support?
 - easy to answer for a wired network (MAXFLOW)
 - but much harder for a wireless network due to wireless **interference**

Interference is the Key Challenge

Interference \Rightarrow links are not independent



4 nodes active, 2 packets in flight

Previous Work

- Focus on asymptotic bounds on wireless network capacity
- Homogeneous network and random communication pattern
- Network capacity:
 - Gupta and Kumar (2000)
 - Asymptotic bound of $1/\sqrt{N}$
 - Li *et al.* (2001)
 - Impact of other traffic patterns, esp. power-law patterns
 - Grossglauser and Tse (2001)
 - Impact of mobility
- Information-theoretic capacity:
 - Shepard (1996)
 - assumed spread-spectrum communication, power control
 - Gastpar and Vetterli (2002)
 - impact of network coding and arbitrary node cooperation

Network Capacity

- Gupta & Kumar (2000)
 - all-or-nothing interference model
 - per-node throughput capacity is:
 - $\Theta(1/\sqrt{n \log n})$ with random node placement and random communication pattern
 - $\Theta(1/\sqrt{n})$ with optimal node placement and communication pattern
 - intuition (Li *et al.* (2001)):
 - assuming uniform node density, one-hop capacity is $O(n)$
 - path length is $O(\sqrt{n})$
 - \Rightarrow total throughput capacity is $O(n/\sqrt{n}) = O(\sqrt{n})$
 - \Rightarrow per-node throughput capacity is $O(1/\sqrt{n})$
 - quite pessimistic

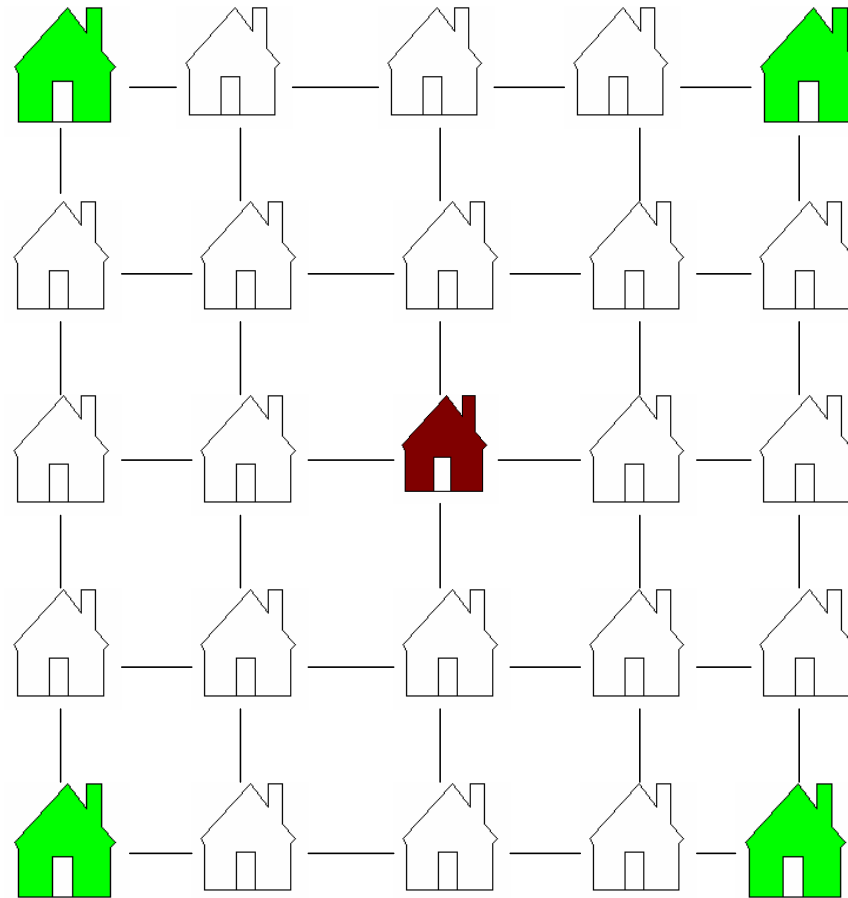
Doing Better

- Locality (Li *et al.* (2001))
 - considered power-law traffic pattern (d^α)
 - $\alpha < -1 \Rightarrow$ constant per-node capacity
 - $\alpha \geq -1 \Rightarrow$ as bad as random traffic pattern
- Mobility (Grossglauser and Tse (2001))
 - carry packet to within $O(1)$ distance of destination
 - constant path length \Rightarrow constant per-node capacity
 - large latency (mobility timescale)
 - multiple copies of each packet to decrease latency

Community Networking Scenario

Four nodes talk to a central ITAP.

Q: What is the maximum possible throughput?



Asymptotic analysis is not directly useful

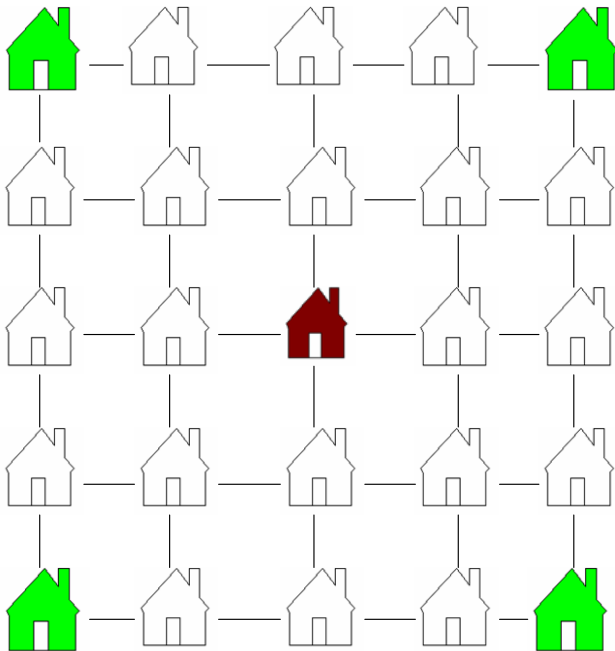
"What-if" Analysis

- We'd like to be able to answer questions about the impact of various factors:
 - radio power/range
 - number of orthogonal channels
 - number of radios at each node
 - directional antennae
 - number of ITAPs

Our Work

- Framework to answer questions about capacity of **specific topologies with specific traffic patterns**
- Assumptions
 - No mobility
 - Fluid model of data transmission
 - Data transmissions can be finely scheduled by an omniscient central entity
- Appeared in *ACM Mobicom 2003*

Sample Results Using Our Framework



Scenario	Aggregate Throughput
Baseline	0.5
Double range	0.5
Two ITAPs	1
Two Radios	1

Nodes talk to immediate neighbors, all links are capacity 1, 802.11-like MAC, multipath routing

Overview of Our Framework

1. Model as a standard network flow problem
 - Described as a linear program
2. Represent interference among wireless links using a **conflict graph**
3. Derive constraints on utilization of wireless links using **cliques** in the conflict graph
 - Augment the linear program to obtain upper bound on optimal throughput
4. Derive constraints on utilization of wireless links using **independent sets** in the conflict graph
 - Augment the linear program to obtain lower bound on optimal throughput

Iterate over steps 3 and 4 to find progressively tighter bounds on optimal throughput

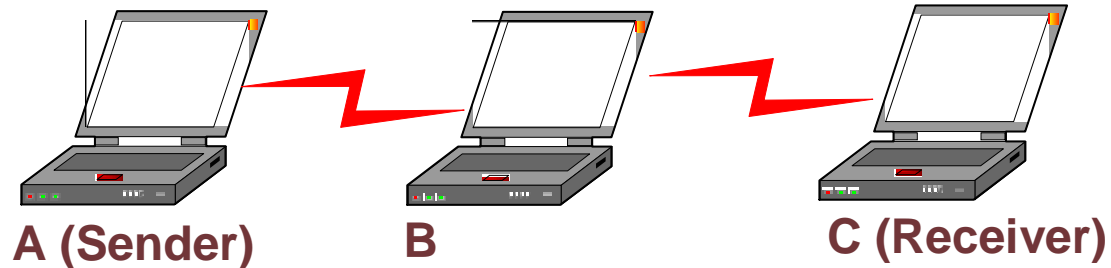
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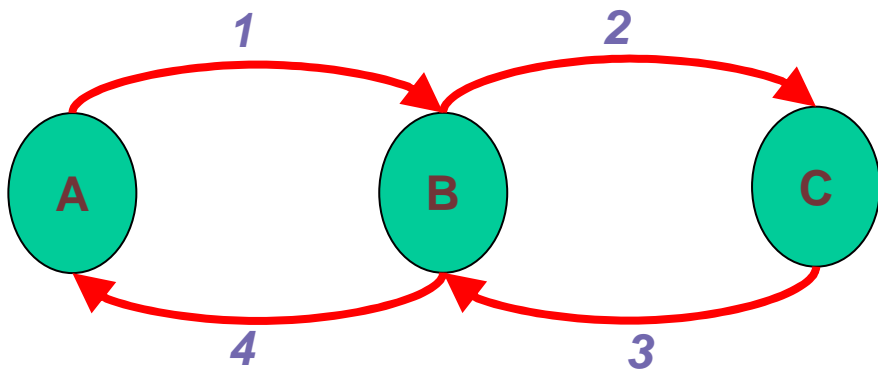
Step 1: Network Flow Model

- Create a connectivity graph
 - Each vertex represents a wireless node
 - Draw a directed edge from vertex A to vertex B if B is within range of A
- Write a linear program that solves the basic **MAXFLOW** problem on this connectivity graph
- Several generalizations possible
 - Discussed later in the talk.

Example: Network Flow Model



Connectivity Graph



Link capacity = 1

Linear Program:

Maximize Flow out of A

Subject to:

1. Flow on any link can not exceed 1
2. At node B, Flow in == Flow out.

Answer: 1 (Link 1, Link 2)

Overview of Our Framework

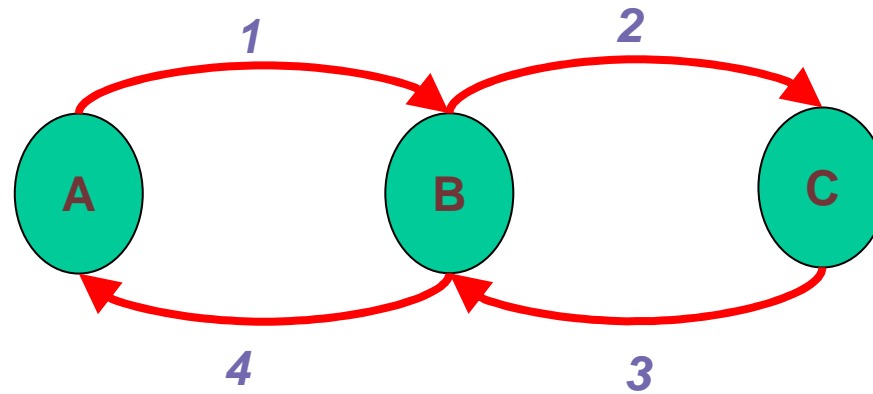
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Step 2: Model Interference using Conflict Graph

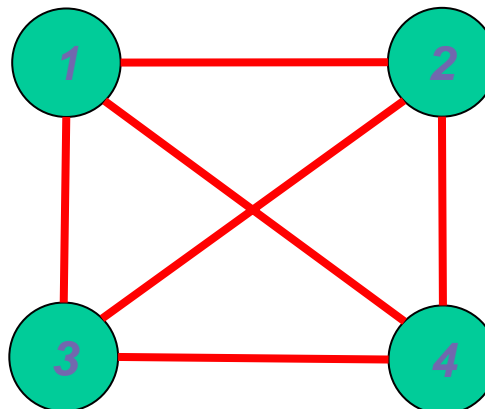
- A conflict graph shows which wireless links interfere with each other
- Each edge in the connectivity graph represented by a vertex
- Draw an edge between two vertices if the links interfere with each other
- Several generalizations possible
 - Discussed later in the talk.

Example: Conflict Graph

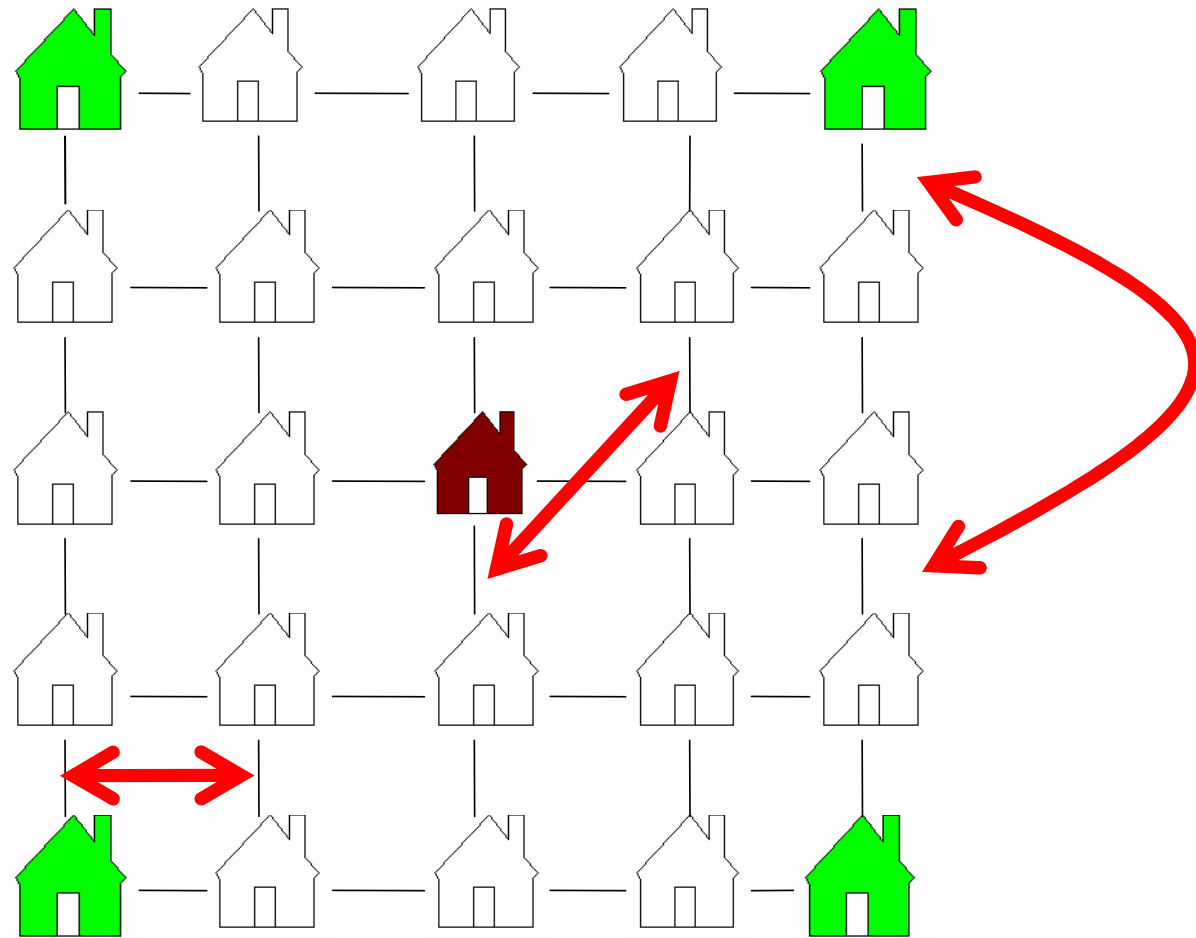
Connectivity Graph



Conflict Graph



Versatility of Conflict Graphs



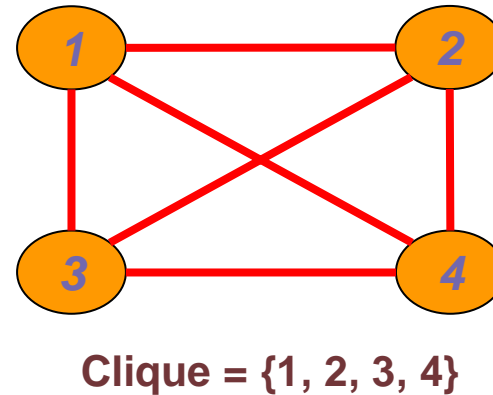
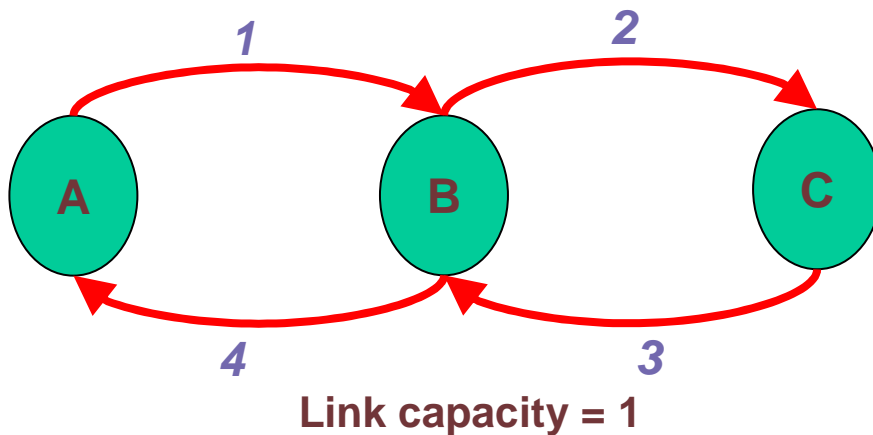
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Step 3: Clique Constraints

- Consider Maximal Cliques in the conflict graph
 - A maximal clique is a clique to which we can not add any more vertices
- At most one of the links in a clique can be active at any given instant
 - Sum of utilization of links belonging to a clique is ≤ 1
- MAXFLOW LP can be augmented with these clique constraints to get a tighter upper bound

Example: Clique Constraints



Linear Program:

Maximize Flow out of A

Subject to:

1. Flow on any link can not exceed link utilization
2. Link utilization can not exceed 100%
3. Sum of utilizations of links 1, 2, 3 and 4 can not exceed 100%
4. At node B, Flow in == Flow out.

Answer = 0.5 (Link1, Link 2)

Properties of Clique Constraints

- Finding all cliques can take exponential time
 - Moreover, finding all cliques does not guarantee optimal solution (will discuss later in talk)
- The upper bound is monotonically non-increasing as we find and add new cliques
 - As we add each clique, the link utilizations are constrained further
- More computing time can provide better solution

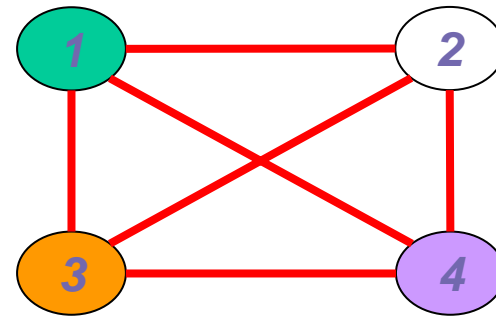
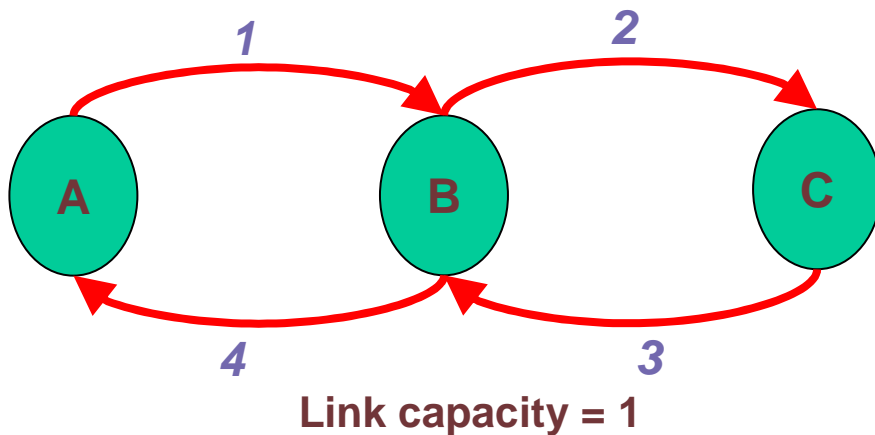
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Step 4: Independent Set Constraints

- Consider Maximal Independent sets in the conflict graph
- All links belonging to an independent set can be active at the same time.
- No two independent sets are active at the same time.
- MAXFLOW LP can be augmented with constraints derived from independent sets to get a lower bound

Example: Independent Set Constraints



Independent sets: {1}, {2}, {3}, {4}

Linear Program:

Maximize Flow out of A

Subject to:

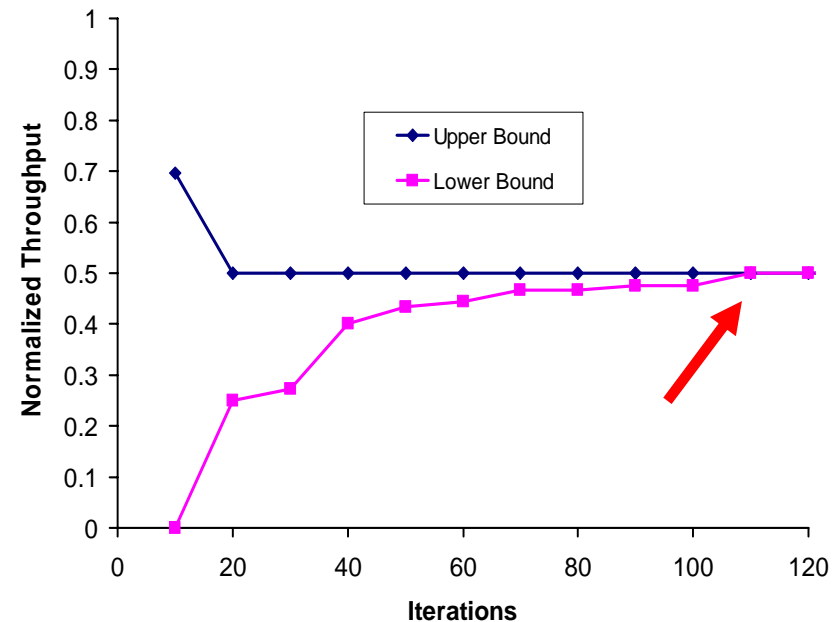
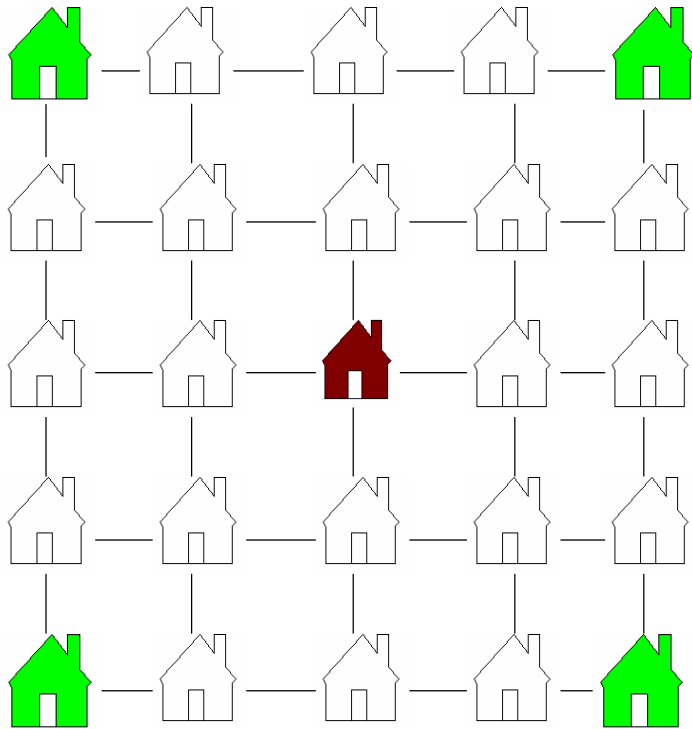
1. Flow on any link can not exceed link utilization
2. Sum of utilizations of independent sets can not exceed 100%
3. Utilization of a link can not exceed the sum of utilization of independent sets it belongs to.
4. At node B, Flow in == Flow out.

Answer = 0.5 (Link1, Link 2)

Properties of Independent Set Constraints

- Lower bound is always feasible
 - LP also outputs a transmission schedule
- Finding all independent sets can take exponential time
 - If we do find all independent sets, the resulting lower bound is guaranteed to be optimal
- Lower bound is monotonically non-decreasing as we find and add more independent sets
 - More computing time provides better answers
- If upper and lower bounds converge, optimality is guaranteed

Putting It All Together



Houses talk to immediate neighbors, all links are capacity 1, 802.11-like MAC, Multipath routing

Advantages of Our Approach

- “Real” numbers instead of asymptotic bounds
 - This is the optimal bound, unlikely to be achieved in practice for a variety of reasons
- The model permits several generalizations:
 - Multiple radios/channels
 - Directional antennas
 - Single path or Multi-path routing
 - Different ranges, data rates
 - Different wireless interference models
 - Different topologies
 - Senders with limited (but constant) demand
 - Optimize for fairness or revenue instead of throughput
- Useful for “what if” analysis

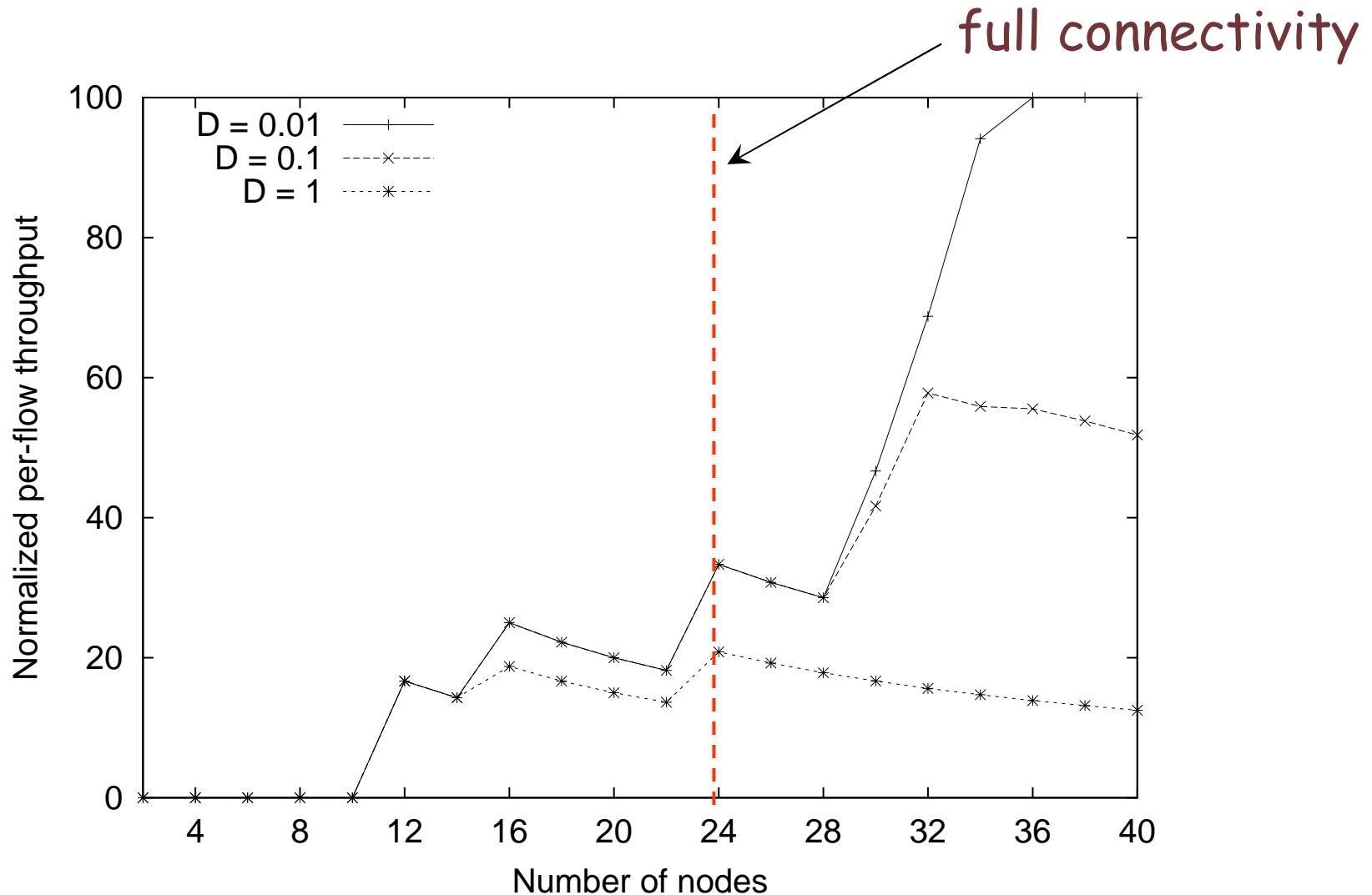
Some Generalizations

- Multiple radios on orthogonal channels
 - Represent with multiple, non-interfering links between nodes
- Directional antennas
 - Include appropriate edges in the connectivity graph
 - Conflict graph can accommodate any interference pattern
- Multiple senders and/or receivers
 - Write LP to solve Multi-commodity flow problem
- Non-greedy sender
 - Create a virtual sender
 - Include a "virtual link" of limited capacity from the virtual sender to the real sender in the connectivity graph
 - This link does not conflict with any other links
 - LP maximizes flow out of virtual sender

Some Generalizations: Physical model of interference

- Directed conflict graph
- Edge between every pair of vertices
 - Vertices in conflict graphs are wireless links.
- Weight on edge $X \rightarrow Y$ represents noise generated at the source of Y when X is active
- Non-schedulable sets instead of cliques
- Schedulable sets instead of independent sets

Counterintuitive Result

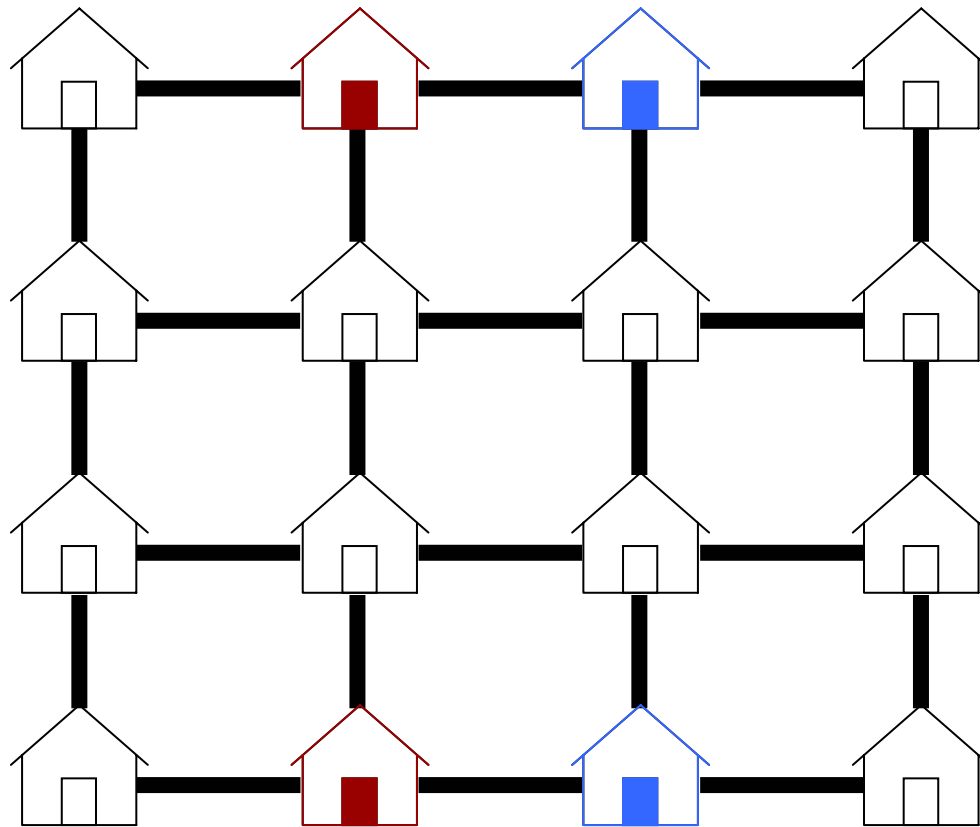


With low duty cycle, per-node throughput improves because richer connectivity offsets increase in offered load

Routing

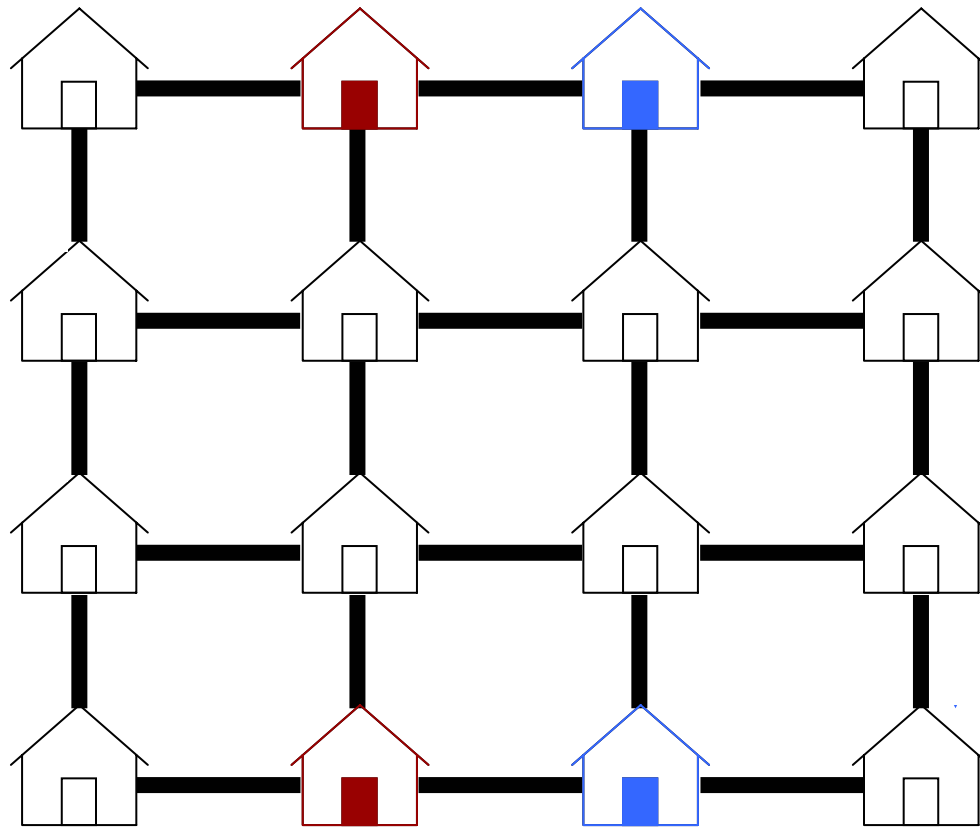
- Shortest-path routing is known to be suboptimal
 - encourages long hops of marginal quality (De Couto *et al.* 2002)
- Another reason: interference
 - encourages routes through the congested "core"
- Interference-aware routing
 - prefer routes that use up minimum amount of spectrum resource
 - advantageous even with contention-based MAC

Shortest Path Routing



Total throughput = 0.33

Interference-aware Routing



Total throughput = 0.67

Limitations

- Linear programs can take a long time to solve
 - Especially when single path routing is used
 - 2-5 minutes for ~100 nodes
- There is no guarantee that optimal solution will be found in less than exponential time
- Upper bound might not converge to optimal even if we find all cliques
 - Graphs with odd-holes and anti-holes

Summary

- Interference is key determinant of performance in multi-hop wireless networks
- Asymptotic analysis assuming random communication yields pessimistic results
- We have presented a flexible framework to answer questions about capacity of specific topologies with specific traffic patterns

Future Work

- Better convergence of upper and lower bounds
- Interference-aware routing
 - Can we generate/maintain the conflict graph, or its approximation in a distributed manner?
 - If yes, can we design a routing algorithm that attempts to minimize interference?
 - Initial idea: minimize number of links interfered with