ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

ICWS
Illinois Center for Wireless Systems

Multi-Channel Wireless Networks: Capacity, Protocols, and Experimentation

Nitin Vaidya
University of Illinois at Urbana-Champaign

In collaboration with
Pradeep Kyasanur
Chandrakanth Chereddi
Vartika Bhandari

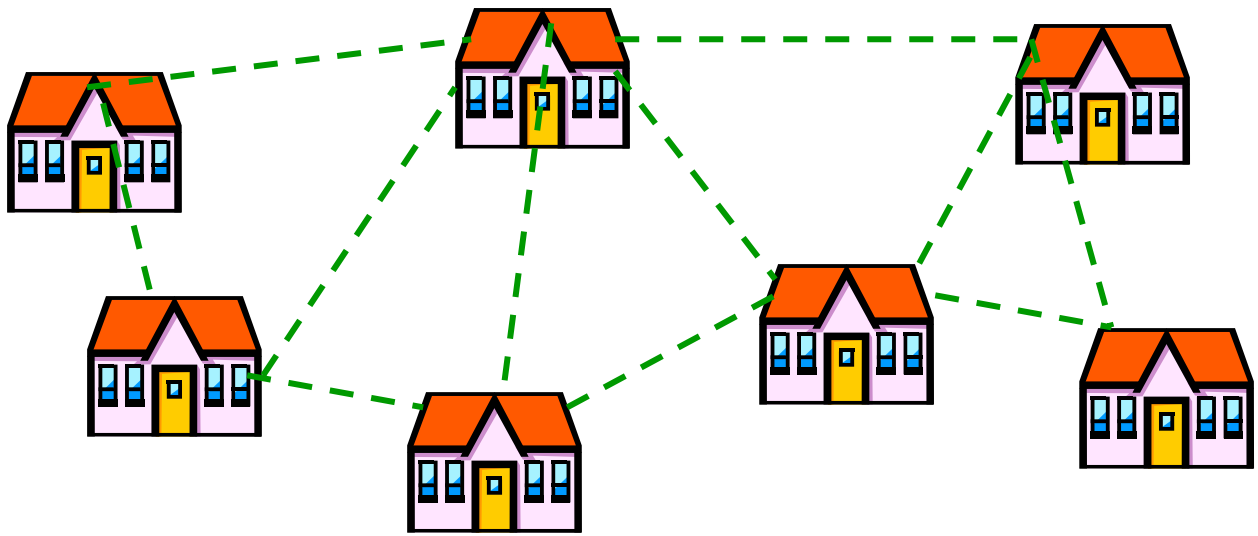
Multi-hop Wireless Networks

- Wireless paradigms:

  Single hop versus Multi-hop

- Multi-hop networks:

  Mesh networks, ad hoc networks, sensor networks



Wireless Capacity

- Wireless capacity limited
- In dense environments, performance suffers
- How to improve performance ?

Improving Wireless Capacity

- Exploit physical resources,
  and resource diversity/multiplicity
- Exploiting diversity requires appropriate protocols
- Examples …
  - Beamforming antennas
  - Exploiting infrastructure (hybrid networks)
  - Better spatial reuse via rate/power/carrier sense adaptation
  - Multi-channel

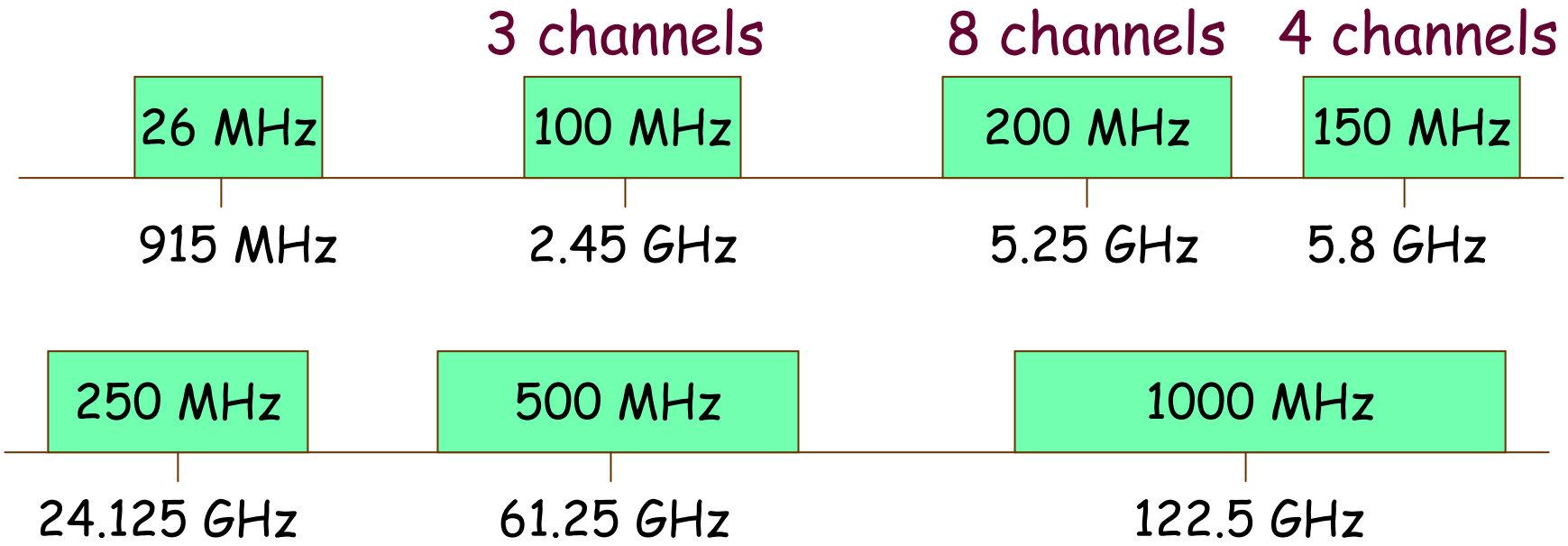
This Talk

Utilizing multiple channels in wireless networks

- Capacity bounds
- Protocol design
- Experimentation (Net-X testbed)

Multiple Channels

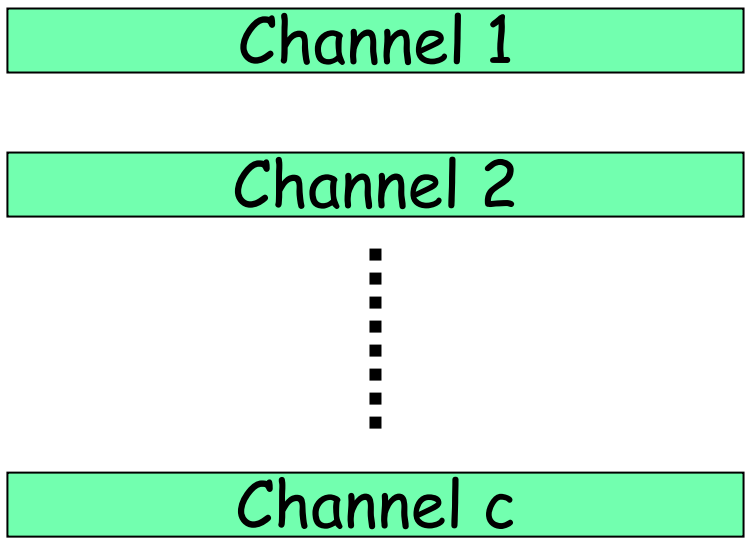
- Typically, available frequency spectrum is split into multiple channels



Large number of channels available

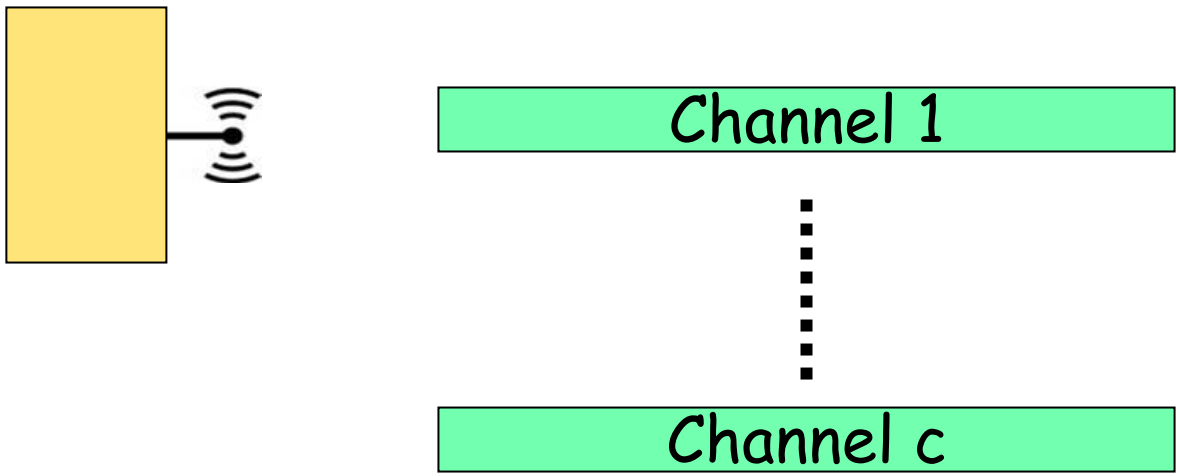
Channel Model

- c channels available
- Bandwidth per channel W



Radio Interfaces

- An interface can only use one channel at a time

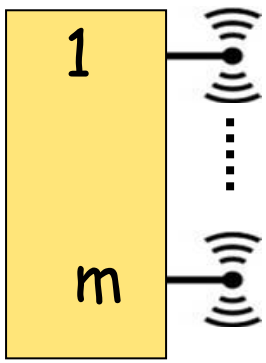


- Switching between channels may incur delay

Interface Model

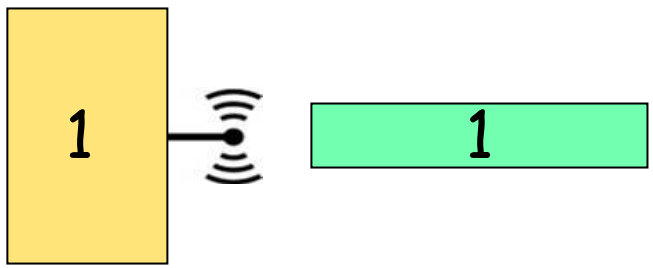
- Reducing hardware cost allows for multiple interfaces

- m interfaces per node: Typical values of m small

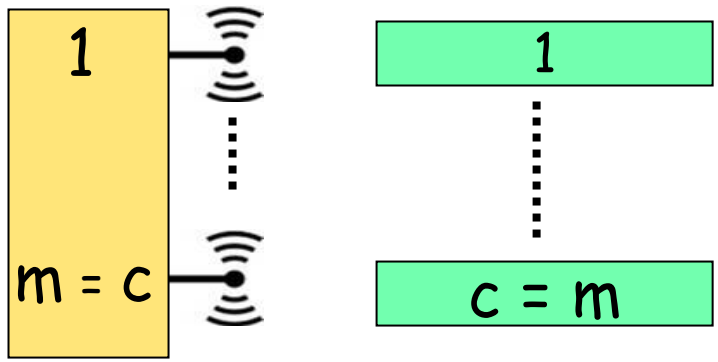


Channel-Interface Scenarios

- Scenario 1: m = c One interface per channel



Common case

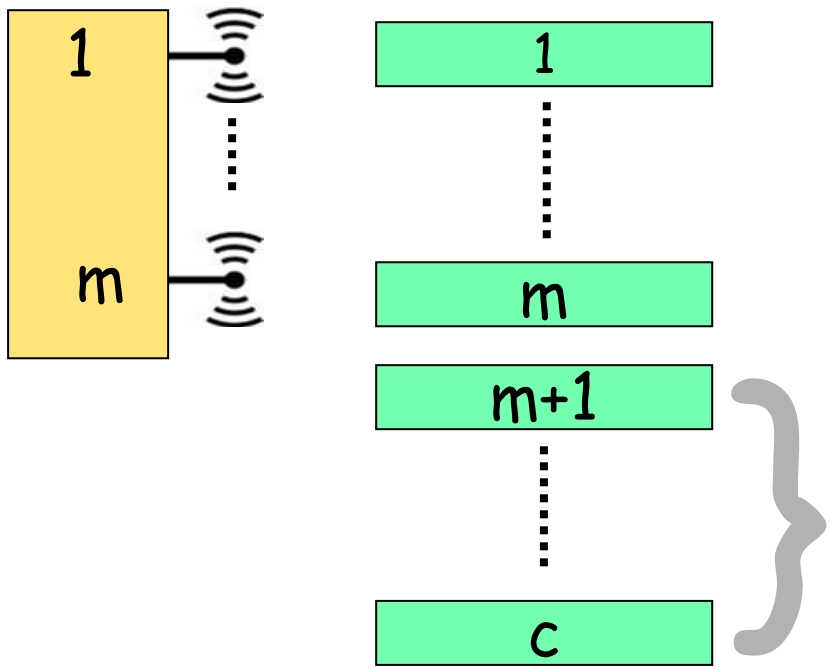


With sufficient hardware

Channel-Interface Scenarios

- Scenario 2: $m < c$ A host can only be on subset of channels

Likely scenario

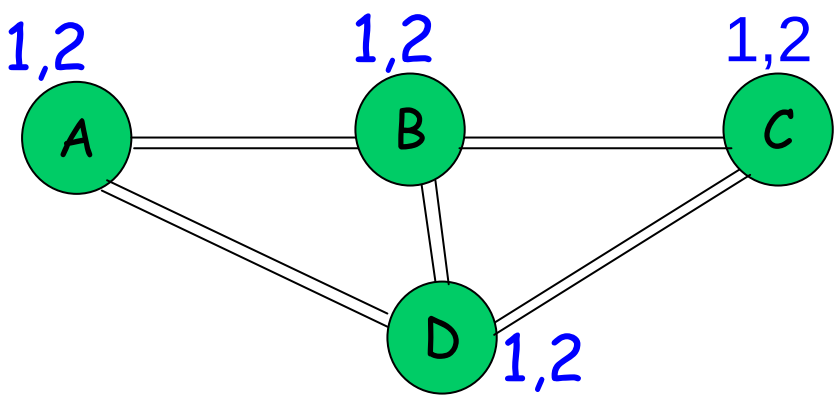


Multi-Channel Mesh

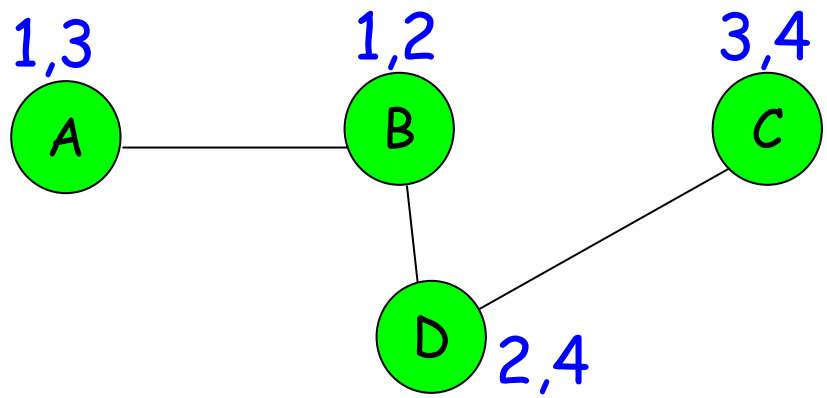
- How to best utilize multiple channels
  in a mesh network
  with limited hardware ?

Need for New Protocols

- When m < c
  - How to assign channels to interfaces at each host?
  - When to switch an interface among channels?
  - How to select good routes?



Some channels not used



Network poorly connected

c = 4, m = 2

Outline

Utilizing multiple channels in wireless networks

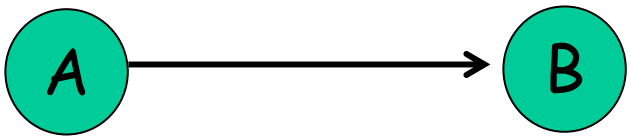
- Capacity bounds
- Protocol design
- Experimentation (Net-X testbed)

Capacity Analysis

- How does capacity improve with more channels ?
- How many interfaces needed to best use c channels ?
  - Clearly, m = c suffices for maximum performance
  - Not always possible to have c interfaces

Worst Case

- Worst case capacity is m/c fraction of the best-case



Channel data rate = W

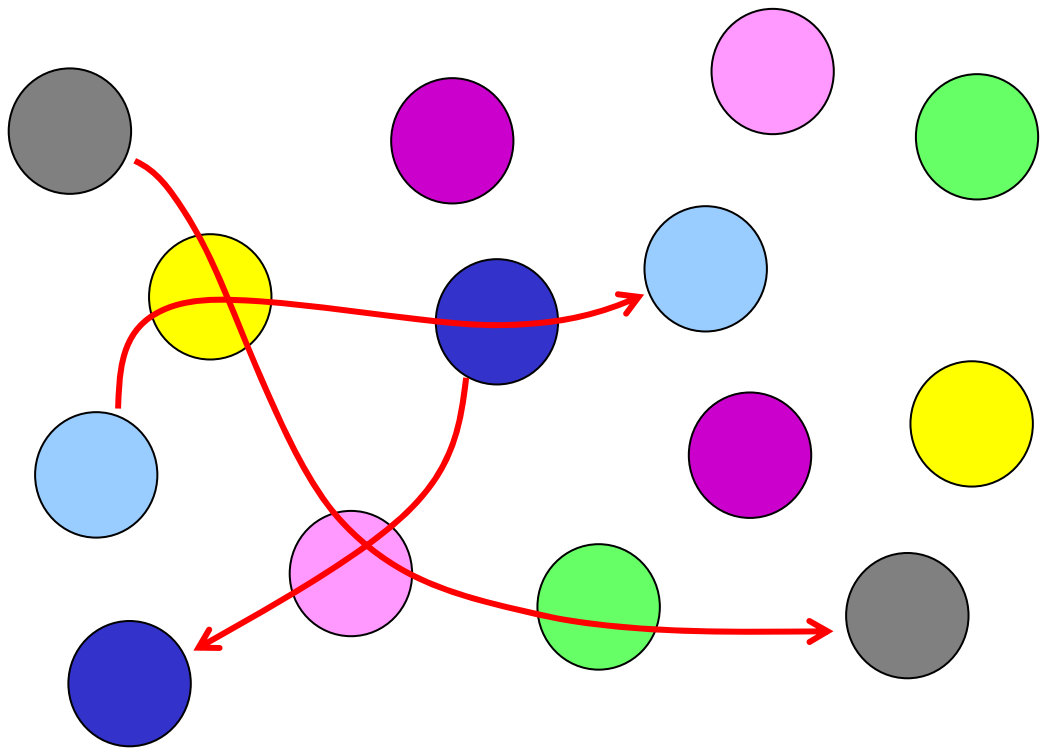
c interfaces: cW throughput

m interfaces: mW throughput

- What about other scenarios ?

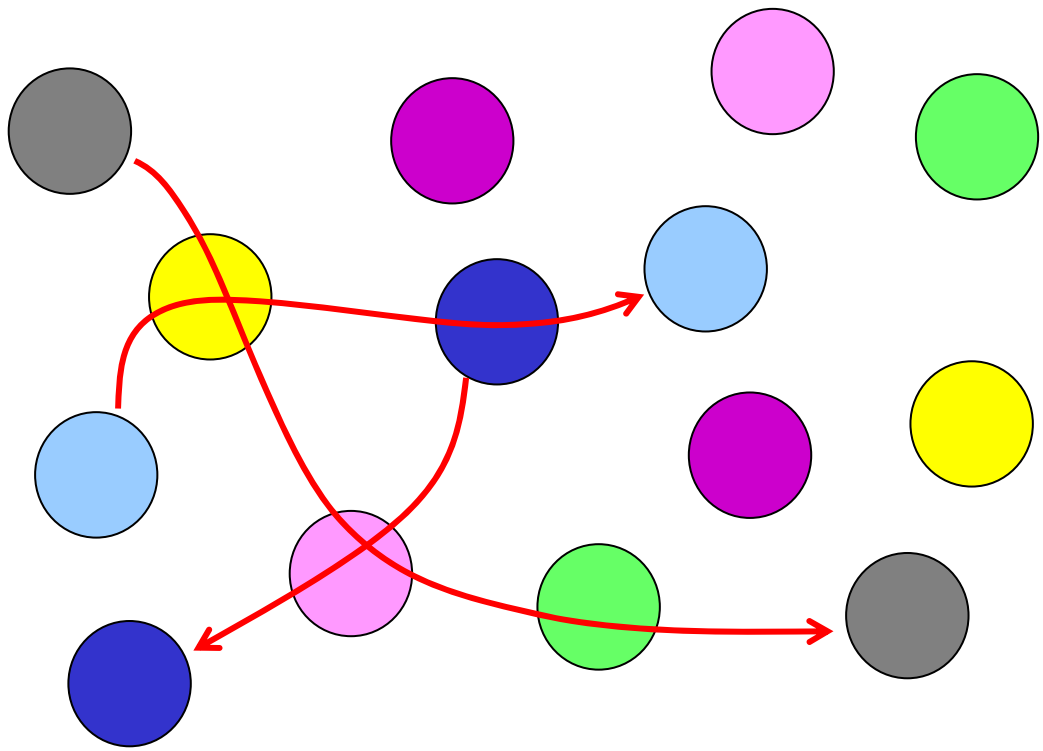
Capacity = ?
[Gupta-Kumar]

- Random source-destination pairs among randomly positioned n hosts in unit area, with $n \to \infty$



Capacity = ?

- λ = minimum flow throughput
- Capacity = n λ



Capacity Constraints

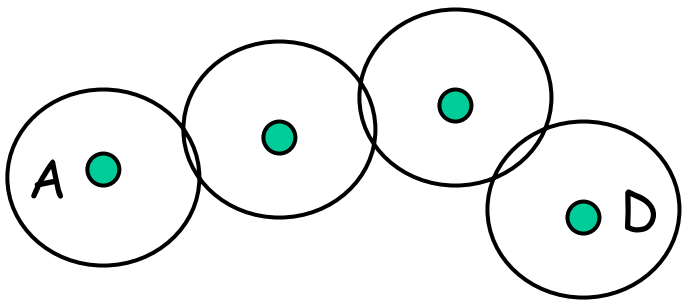
- Capacity constrained by available spectrum bandwidth

- Other factors further constrain wireless network capacity …

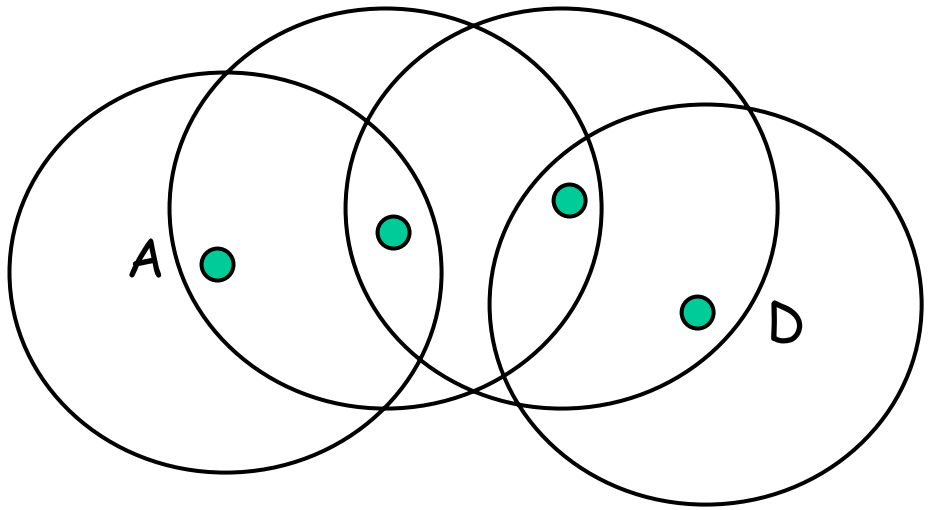
Connectivity Constraint
[Gupta-Kumar]

- Need routes between source-destination pairs

  Places a lower bound on transmit power



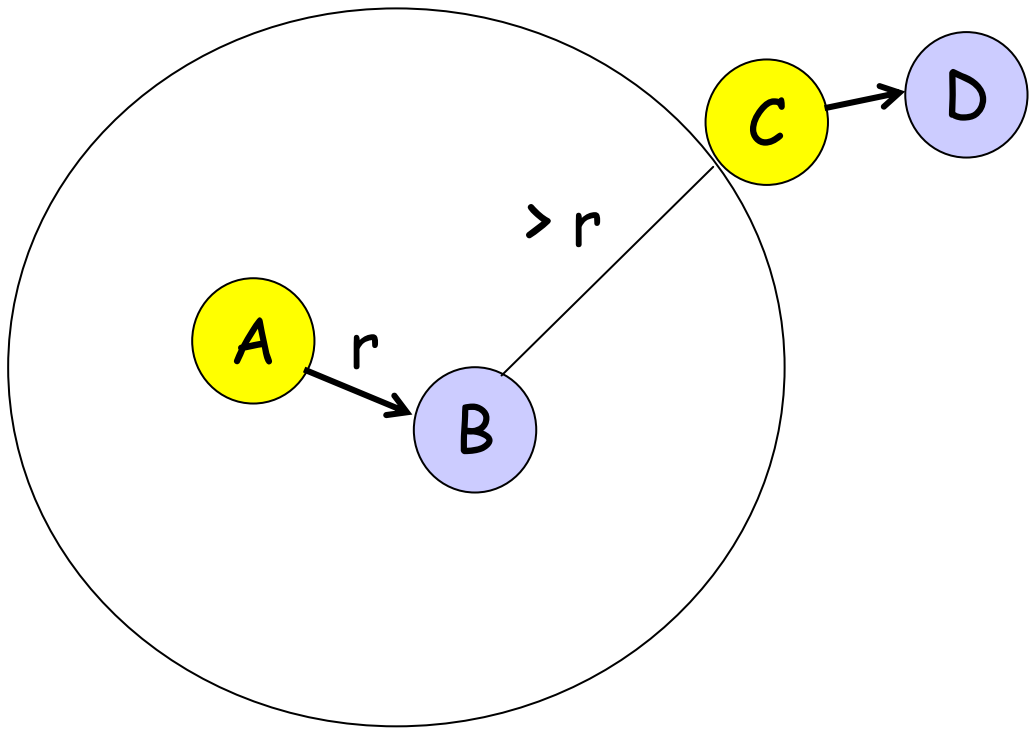
Not connected



Connected

Interference Constraint
[Gupta-Kumar]

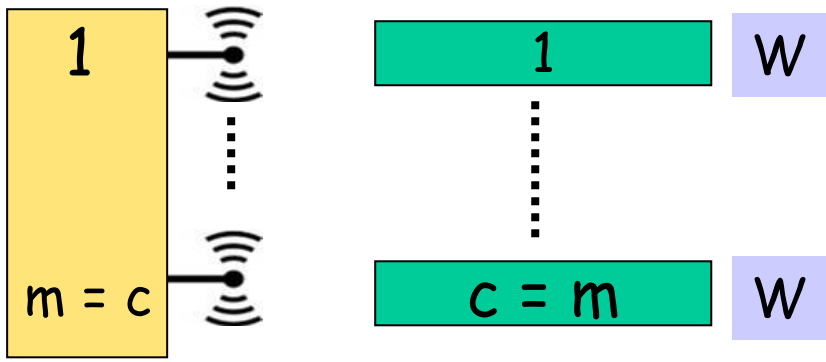
- Interference among simultaneous transmissions
- Limits spatial reuse $O\left(\frac{1}{r^2}\right)$



Capacity of Wireless Networks
[Gupta-Kumar]

- When c = m,

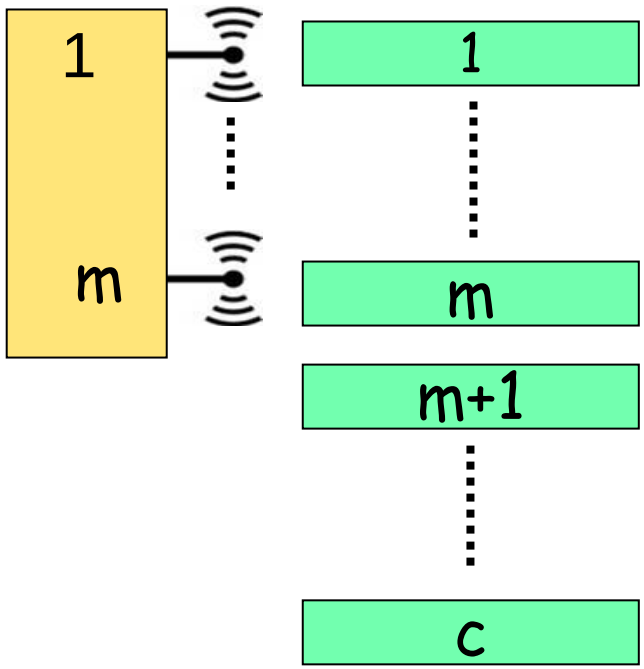
network capacity α $c\,W\sqrt{\frac{n}{\log n}}$



Capacity increases linearly with channels

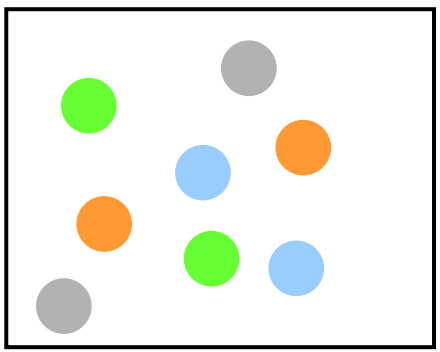
Capacity

- What if fewer interfaces ?



Interface Constraint

- Throughput is limited by number of interfaces in a neighborhood



N nodes in the "neighborhood"

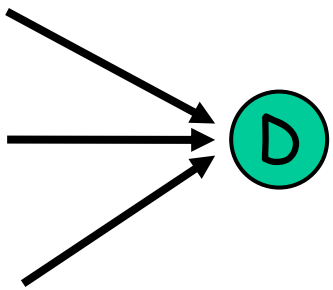
➔ total throughput ≤ N * m * W

Interface, a constrained resource

in addition to spectrum, time and space

Destination Bottleneck Constraint

- A node may be destination of multiple flows
- Node throughput shared by all the incident flows

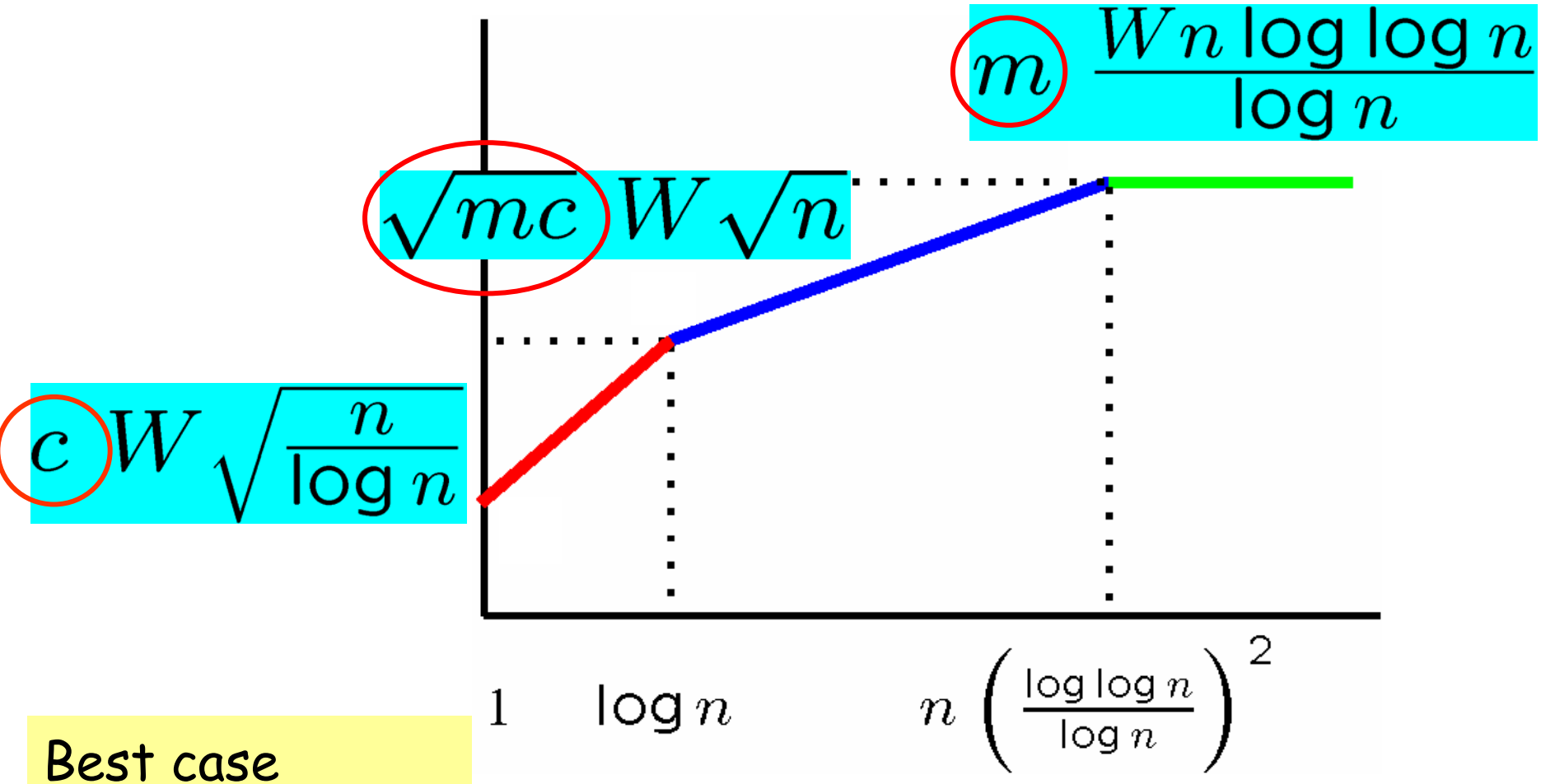


Node throughput $T \leq m*W$

Per-flow throughput = T / f

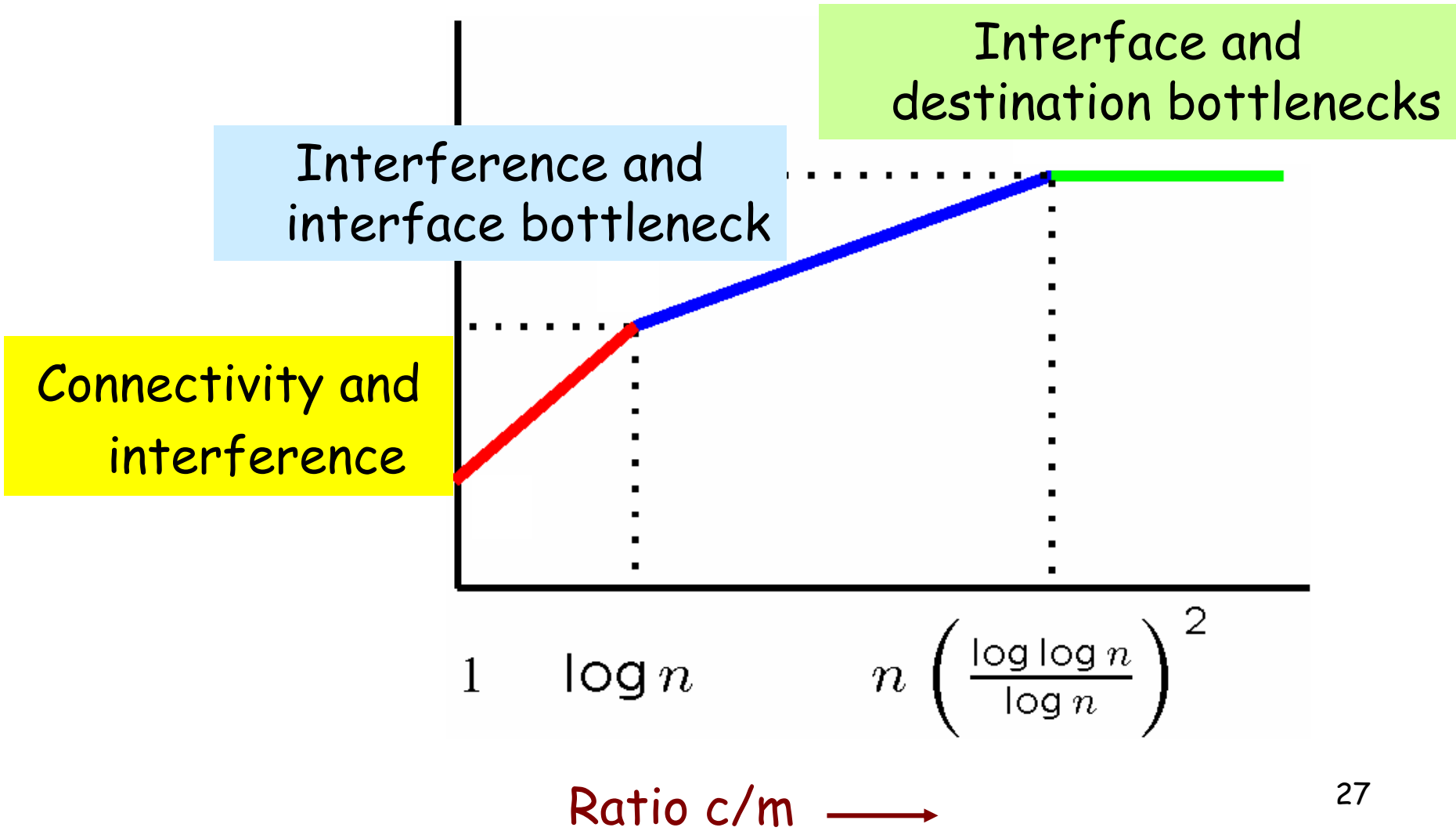
Mutlti-Channel Network Capacity

[Kyasanur-Vaidya]



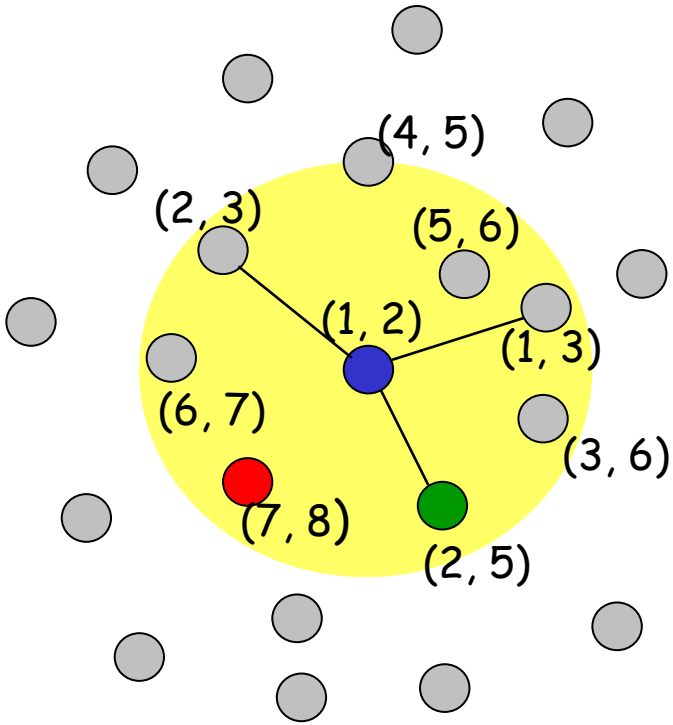
Best case Capacity α c W

Mutlti-Channel Network Capacity



Constrained Channel Switching

[Bhandari-Vaidya]



- "Untunable radios" [Petrovic05] restricted to use a subset of channels (vary across devices)

  or, spatially correlated channel assignments

- A device can communicate directly with only a subset of in-range nodes that share usable channel

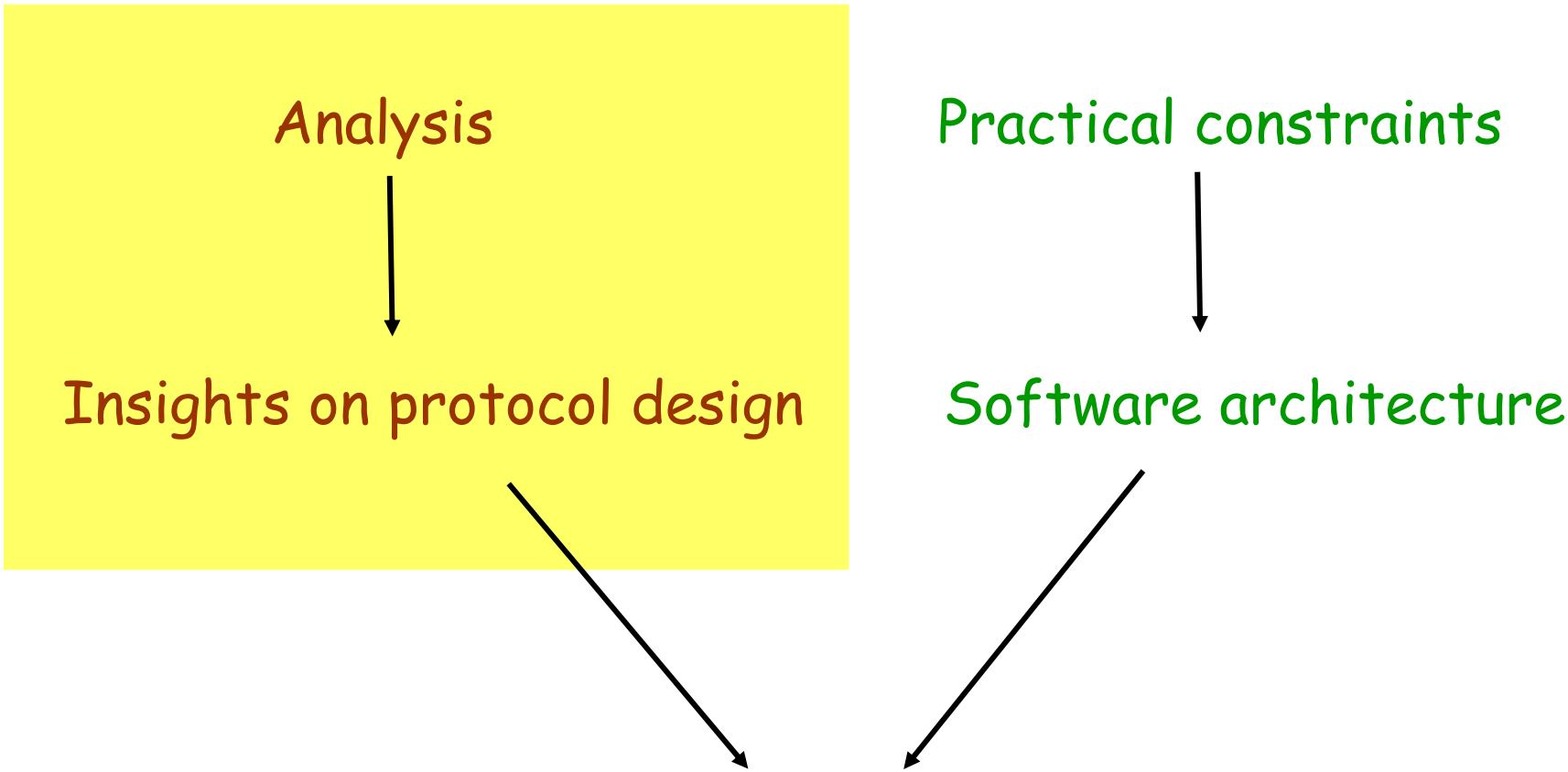
Possible to benefit from larger spectrum despite channel switching constraints

Outline

Utilizing multiple channels in wireless networks

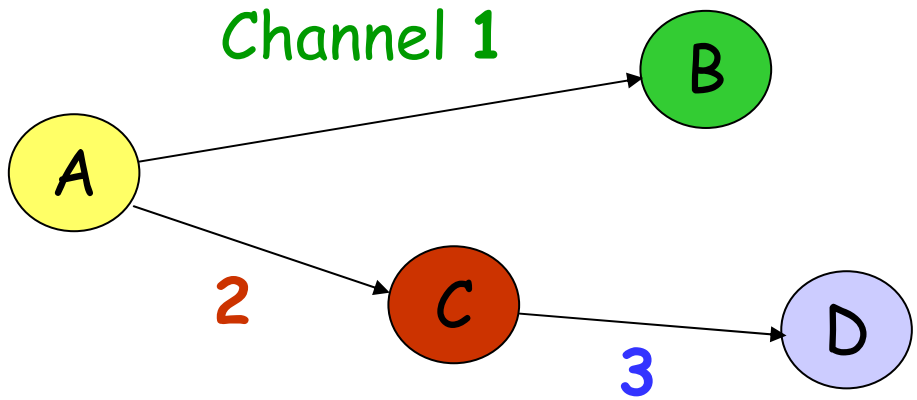
- Capacity bounds
- Protocol design
- Experimentation (Net-X testbed)

Towards Protocols



Insights from Analysis (1)

- Static channel allocation does not yield optimal performance in general
- Must dynamically switch channels
- Need protocol mechanisms for channel switching



Insights from Analysis (2)

- Optimal transmission range function of

  density of nodes and

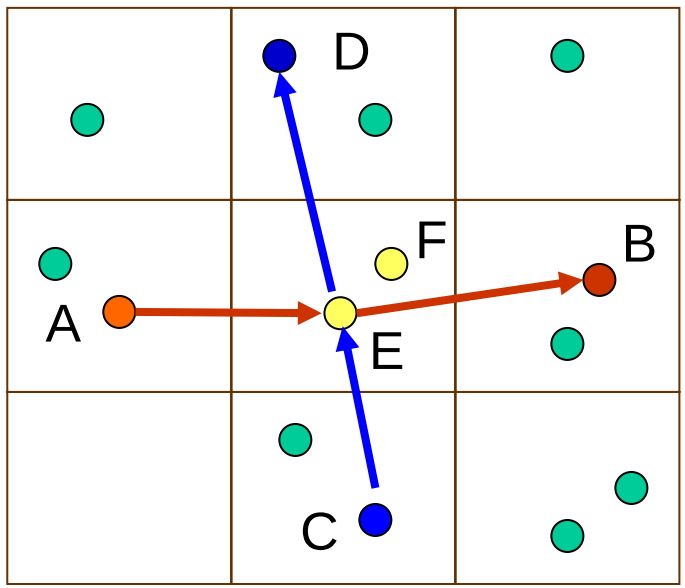
  number of channels

  Intuition:

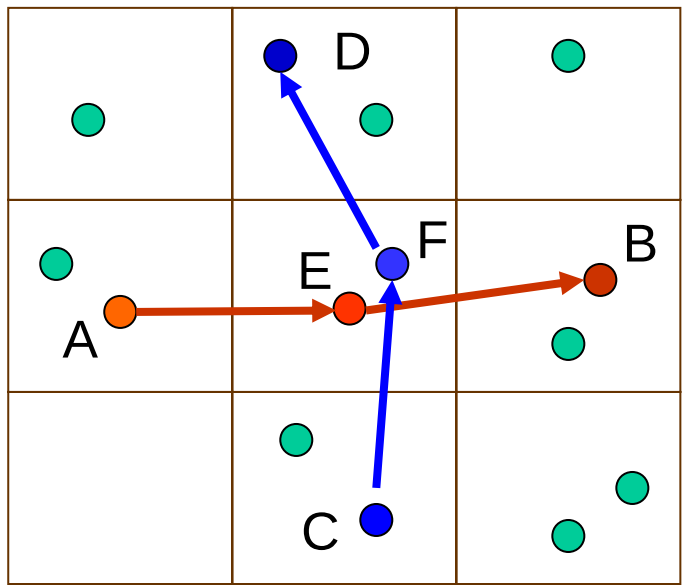
  # of interfering nodes ≈ # of channels

Insights from Analysis (3)

- Routes must be distributed within a neighborhood
- This is not necessary in single channel networks



Single Channel (m=c=1)
Optimal strategy



Multi-Channel (m<c)
Optimal strategy

Insights from Analysis (4)

- Channel switching delay potentially detrimental, but may be hidden with
  - careful scheduling – create idle time on interfaces between channel switches
  - additional interfaces
- Idle interfaces can switch channels without penalizing performance

Insights from Analysis (5)

Channel Assignment

- Need to balance load on channels
- Local coordination in channel assignment helpful

Practical Constraints

- Legacy MAC : 802.11
- Non-trivial topology discovery costs
- Non-trivial channel switching cost

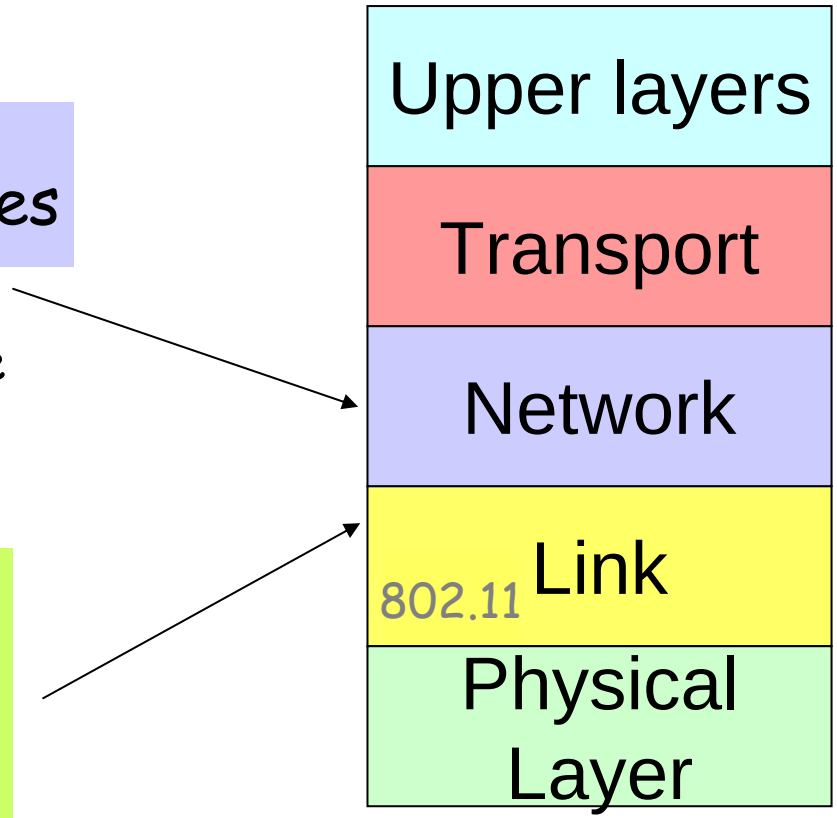
Design decisions:

- Multi-channel awareness above MAC layer
- Channel management on two timescales

Channel Management: Timescale Separation

[Kyasanur-Vaidya]

- Routing: Longer timescales
  - Multi-channel aware route selection metrics
- Interface management: Shorter timescales
  - Dynamic channel assignment
  - Interface switching

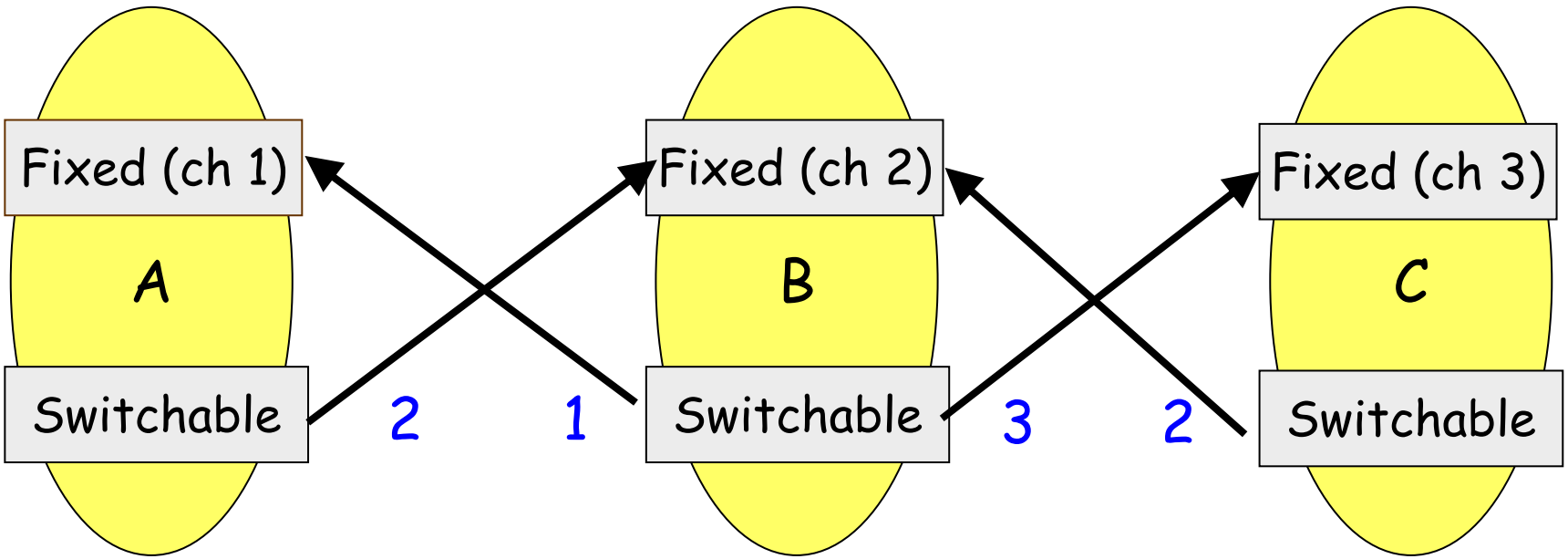


Channel Assignment

- Interfaces may be switched or kept fixed
- Classification:
  - Static strategy: All interfaces of a node fixed
  - Dynamic strategy: All interfaces of a node can switch
  - Hybrid strategy: Some interfaces fixed, others switch
- We use a hybrid strategy requiring at least two interfaces per node

Channel Assignment

- Two interfaces much better than one
- Hybrid channel assignment: Static + Dynamic



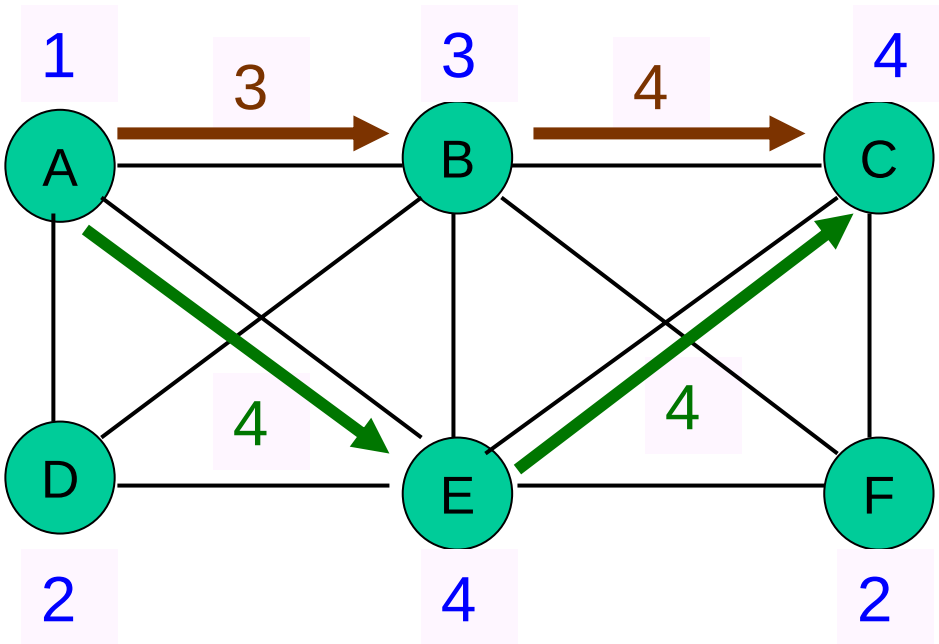
Channel assignment locally balanced

Routing Approach

- Legacy routing protocols can be operated over our interface management layer
  - Does yield significant benefits from multiple channel
  - Does not consider cost of channel switching
- An alternative
  - Develop a channel-aware metric
    (aware of channel diversity and switching costs)

Selecting Channel Diverse Routes

- Most routing protocols use shortest-hop metric
  - Not sufficient in most multi-channel networks



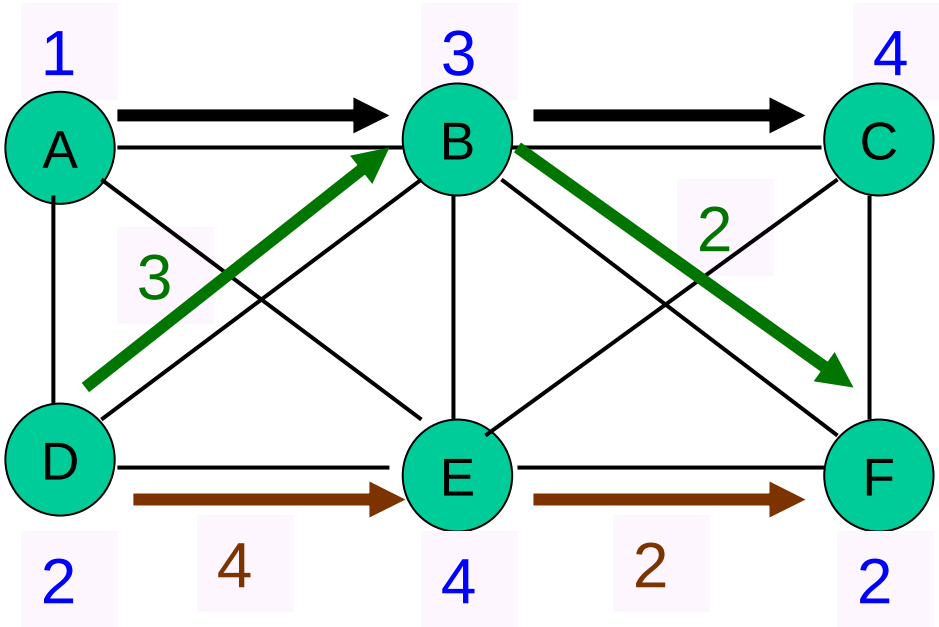
A needs route to C

Route A-B-C better

Prefer channel diverse routes

Impact of Switching Cost

- Interface switching cost has to be considered
  - A node may be on multiple routes, requiring switching



Route A-B-C in use

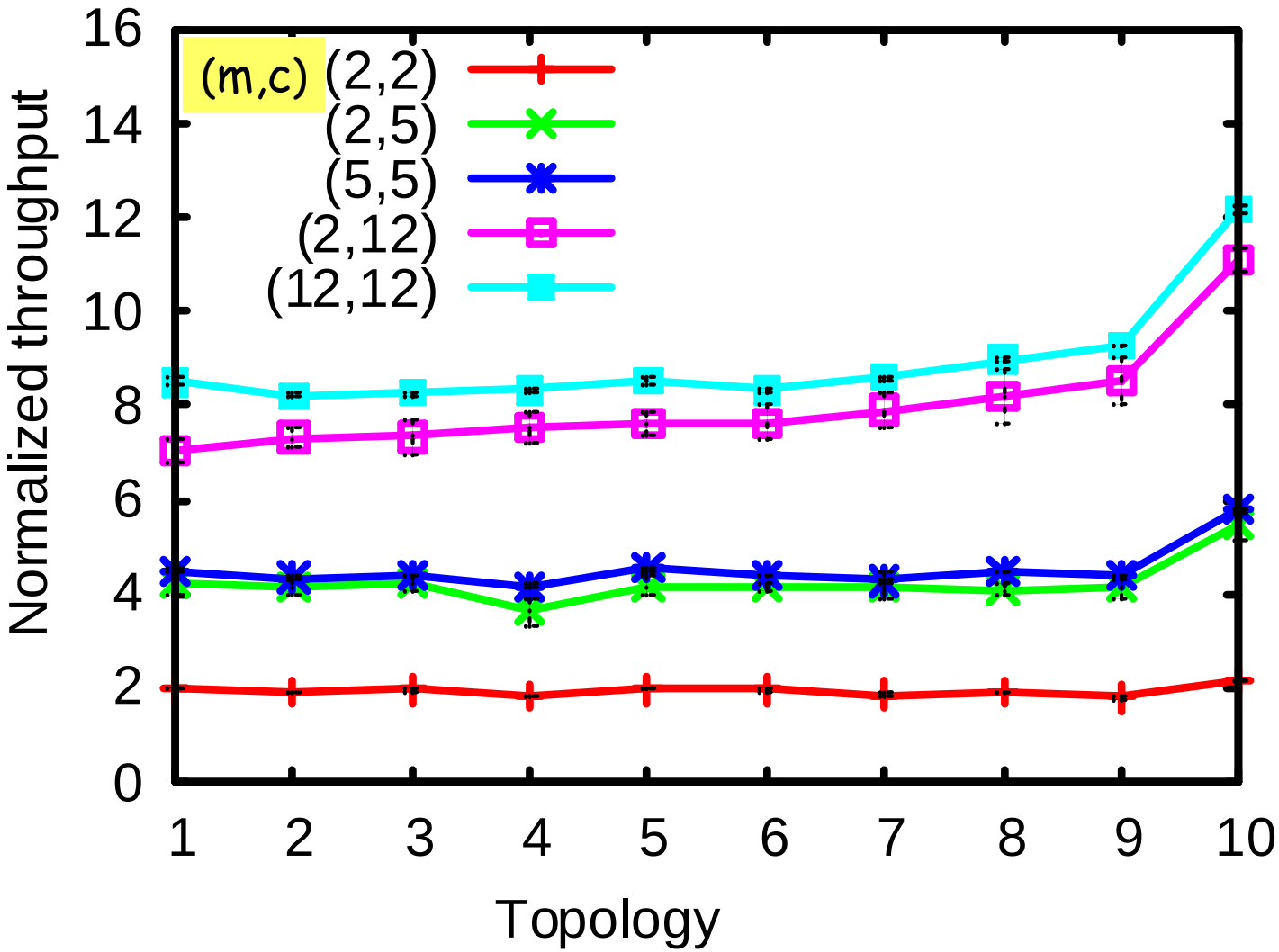
D needs route to F

Route D-E-F better

Select routes that do not require frequent switching

CBR - Random topology

(50 nodes, 50 flows, 500m x 500m area)



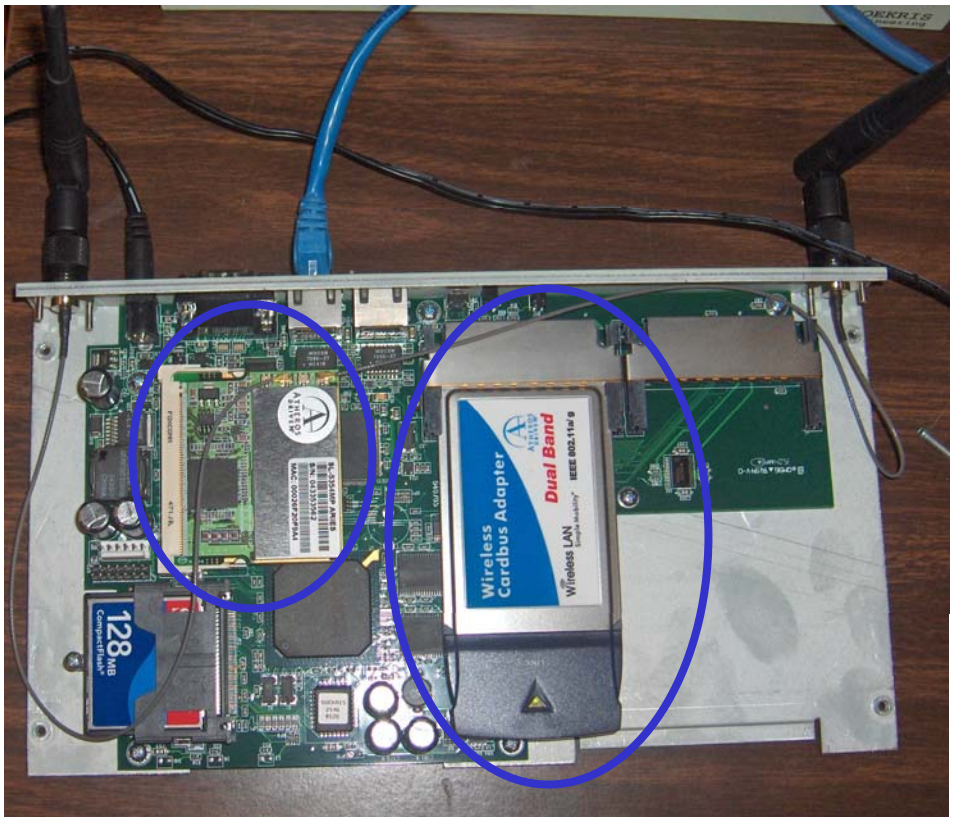
Outline

Utilizing multiple channels in wireless networks

- Capacity bounds
- Protocol design
- Experimentation (Net-X testbed)

Net-X Testbed

[Kyasanur-Chereddi-Vaidya]

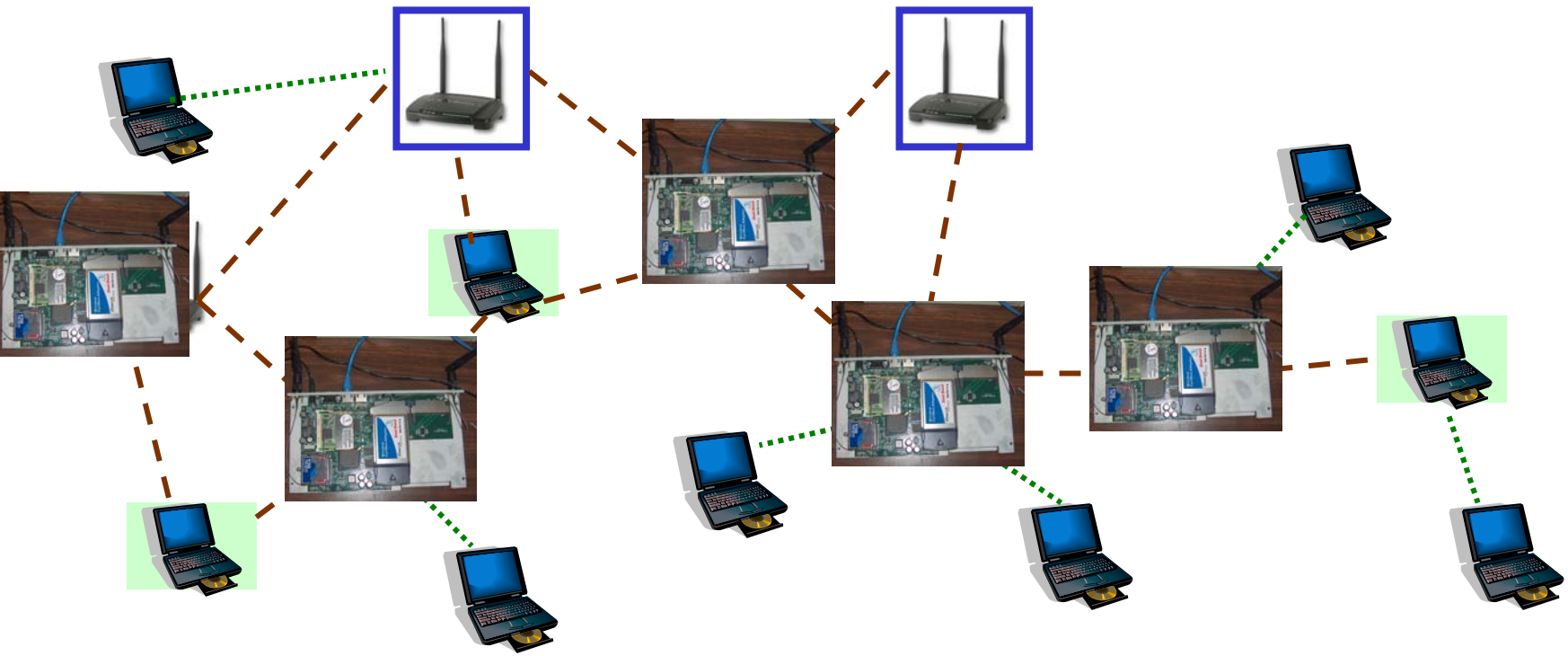


- Linux 2.4
- Two 802.11a radios per mesh node (m = 2)
- Legacy clients with 1 radio
- c = 5 channels

Soekris 4521

Net-X source code to be released soon

Net-X Testbed



Two radio mesh node

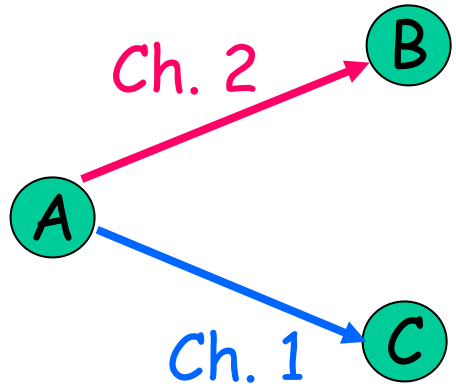
Internet gateway node

Single radio mesh node

Single radio unmodifed client

New Kernel Support

- O.S. support needed to choose channels based on destination

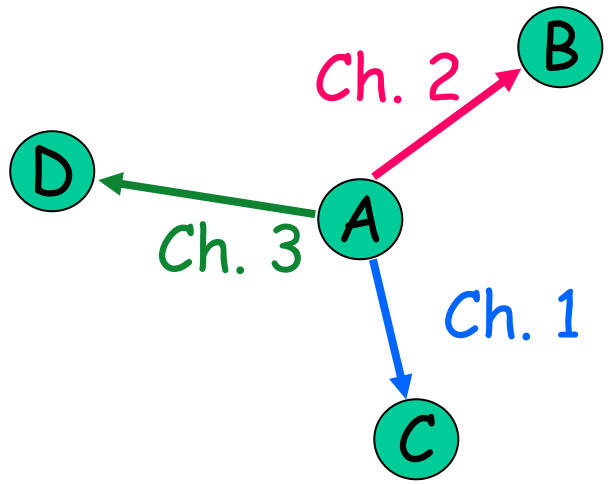


Next hop **not** equivalent to a wireless interface id

- Phy-aware routing not supported traditionally
- In general, need a "constraint" specification for desired channel(s), antenna beamform, power/rate, … to be used for the next hop

New Kernel Support

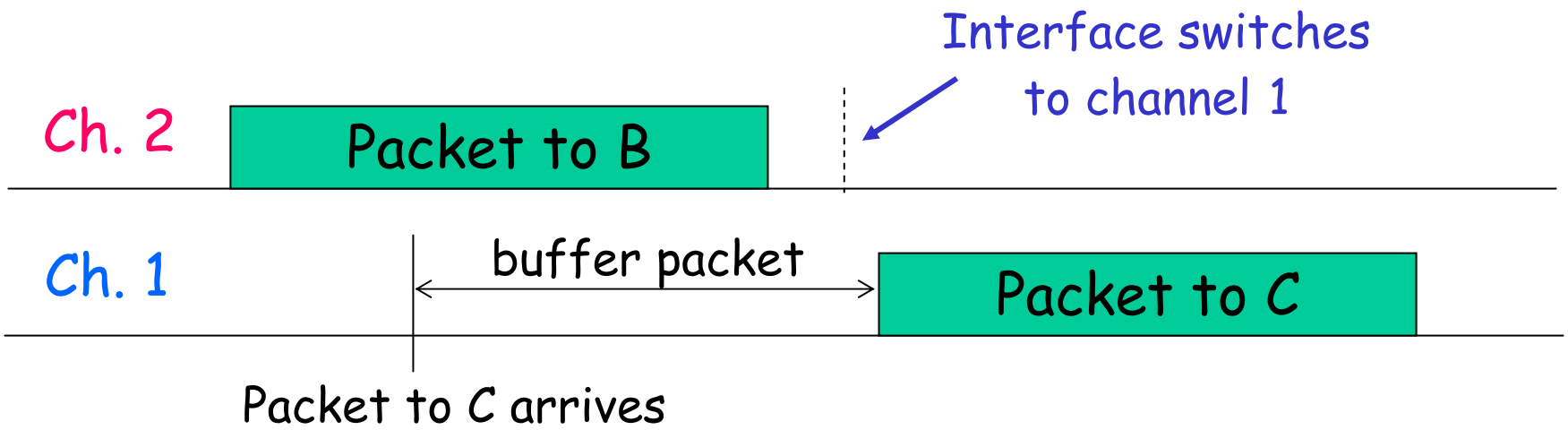
- Multi-channel (phy-aware) broadcast support needed



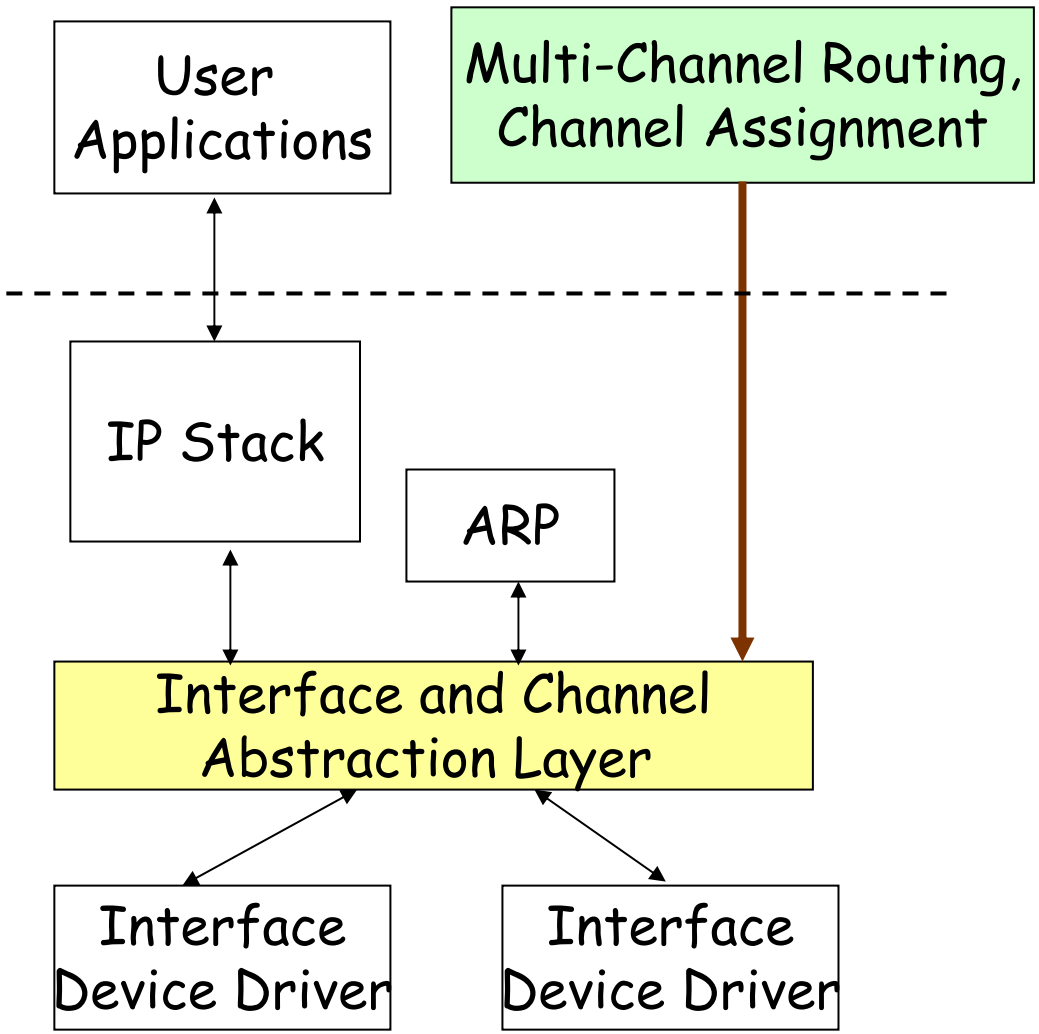
- Channel switching from user space has high latency: frequent switching from user space undesirable

New Kernel Support

- Interface management needs to be hidden from "data path"
  - Buffering packets for different channels
  - Scheduling interface switching



Net-X Architecture



- Abstraction layer simplifies use of multiple interfaces

  Implemented by extending Linux "bonding driver"

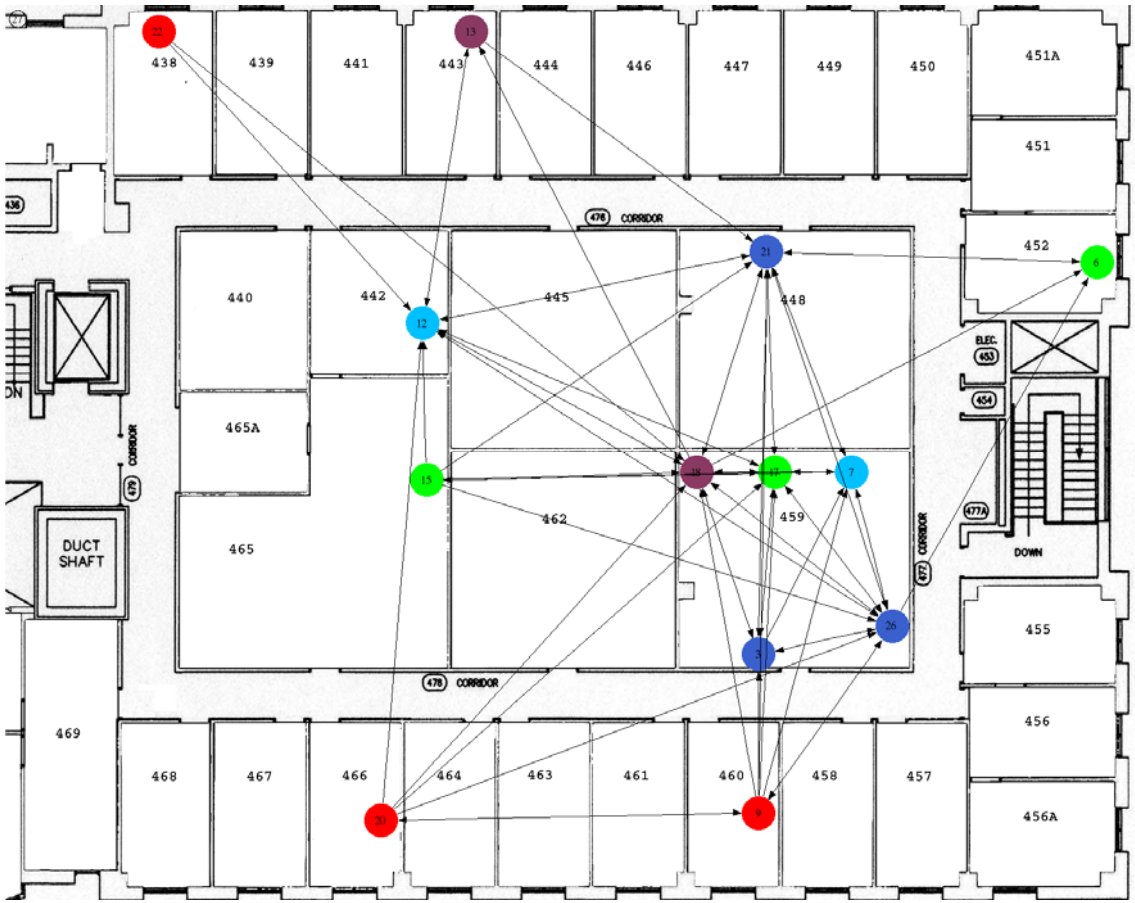
Channel Abstraction Module

- Unicast Component:
  - Allows choosing channels based on destination
- Broadcast Component:
  - Multi-channel broadcast support
- Queueing and Scheduling Component:
  - Queue packets if interface is not immediately available
  - Schedule interface switching

Ongoing Work

- Testbed deployment ongoing (approximately 30 nodes when fully deployed)
- Extensive measurements planned

Partial testbed view



CSL South wing

Research Opportunities

- > 2 interfaces
  - Channel assignment issues
  - Multi-path routing
  - Protocol simplification
- QoS differentiation
- Interpreting results in time-domain:
  Channel = power-save duty cycle
- Cognitive radios: Dynamically determine channel availability
- Constrained channel switching

Conclusions

- Insights from the analysis useful in protocol design
- Significant performance benefits using many channels despite limited hardware
- Implementation requires new O.S. support
  - Net-X source to be made public soon
- Significant research opportunities remain

Thanks!

www.crhc.uiuc.edu/wireless