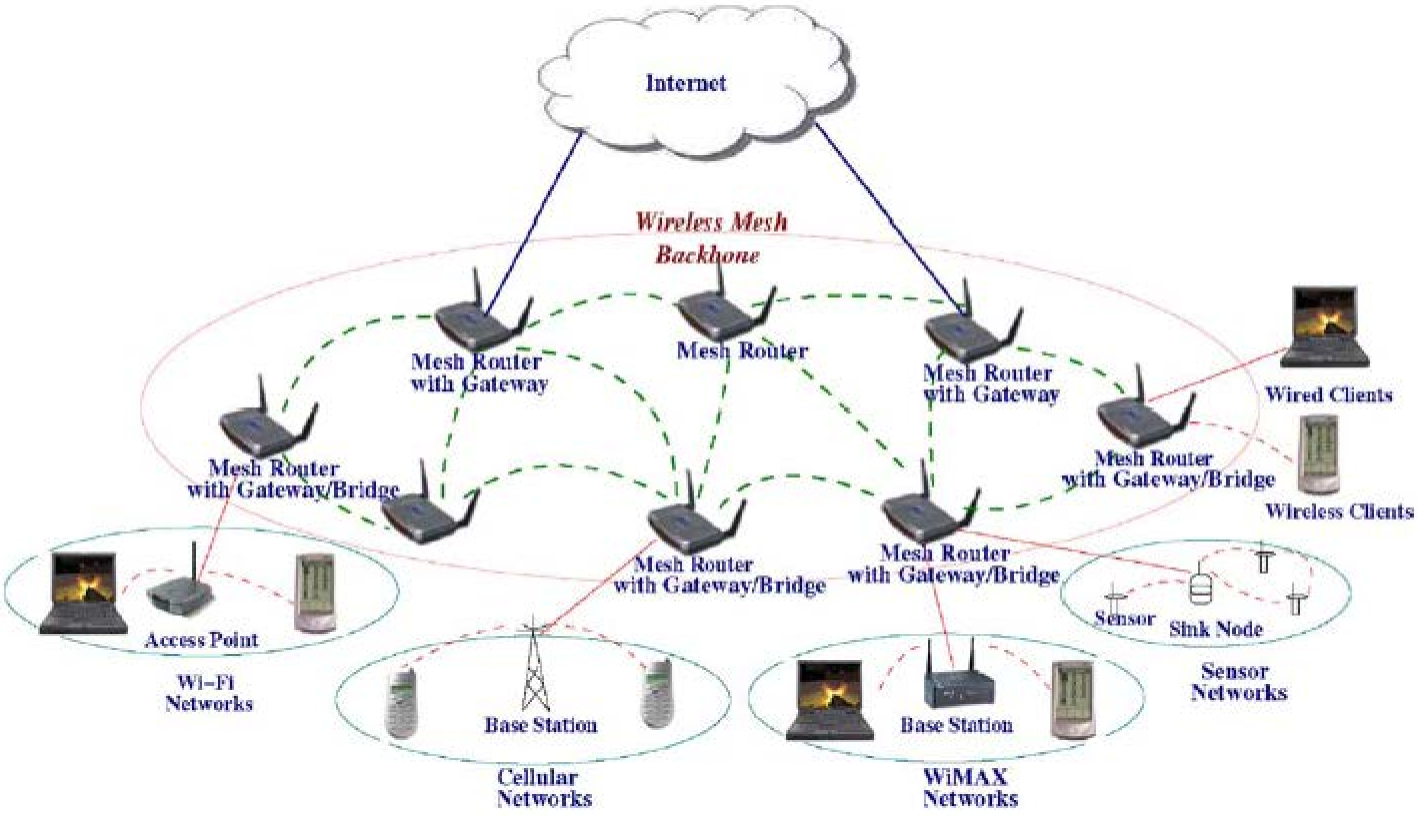
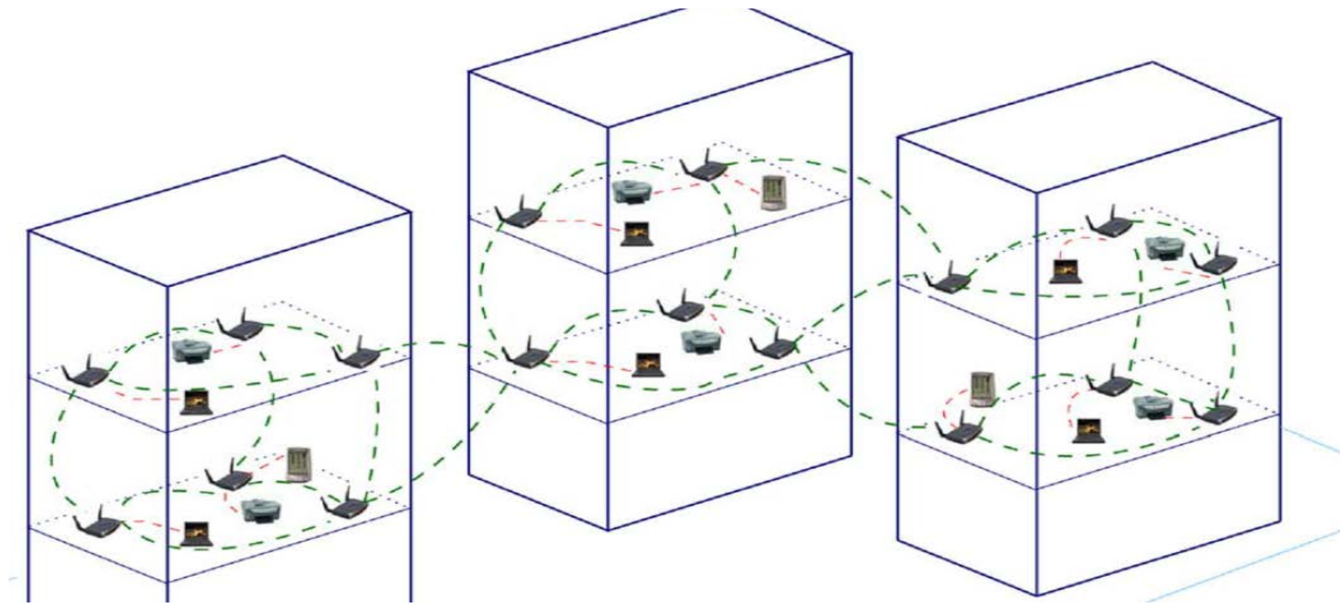
Wireless Mesh Networks

Architecture



Wireless Mesh Networks

- A wireless mesh network (WMN) is a multi-hop wireless network that consists of mesh clients and mesh routers.
- Mesh routers form the backbone of WMNs.
- Some of mesh routers are called gateway nodes that are connected to the wired Internet.
  - provide Internet access



Benefits

- Reduction of installation costs
  - Only a few mesh routers have cabled connections to the wired network
- Large-scale deployment
  - WLAN: One-hop communication has limited coverage
  - WMN: Multi-hop communication offers longer distance communication through intermediate nodes
- Reliability
  - Redundant paths between a pair of nodes in a WMN increases communication reliability (mesh topology)
- Self-Management
  - A WMN is a special ad hoc network

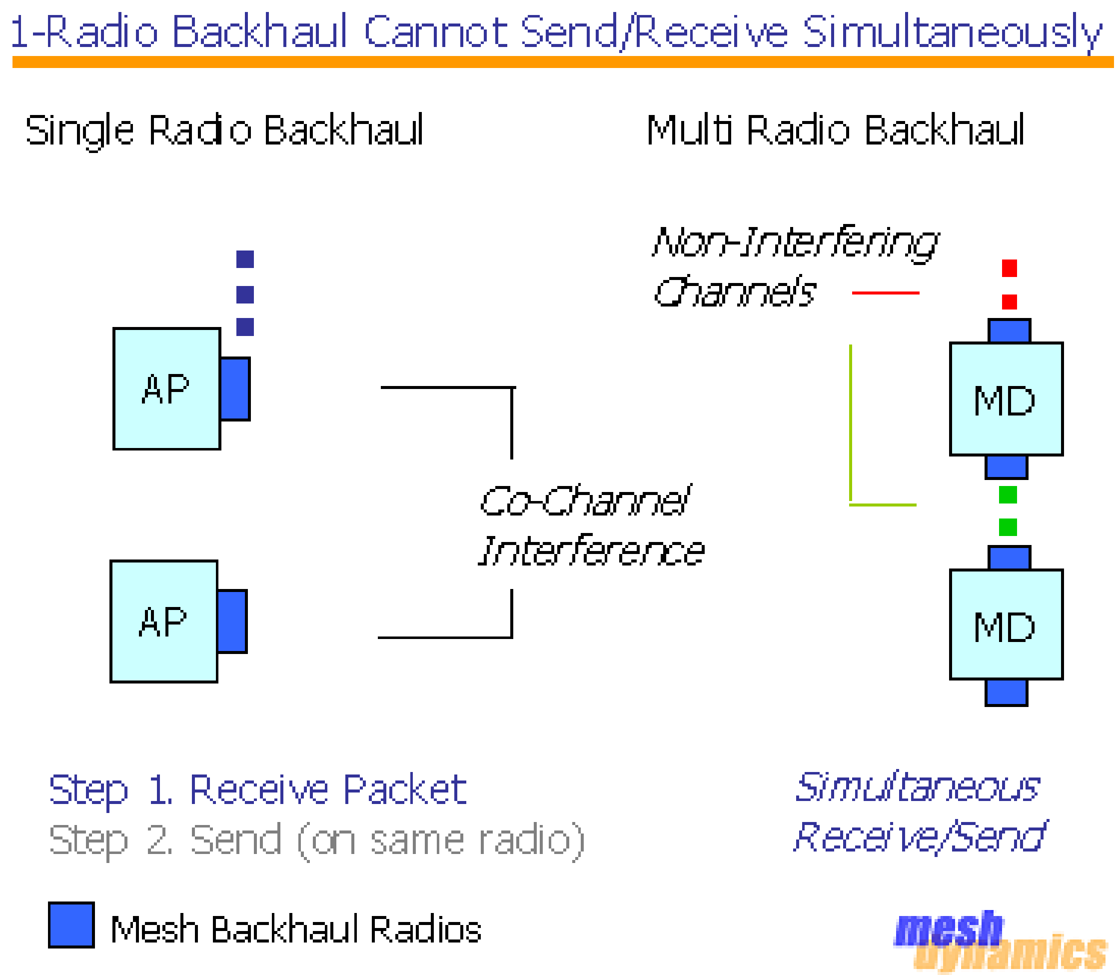
Applications

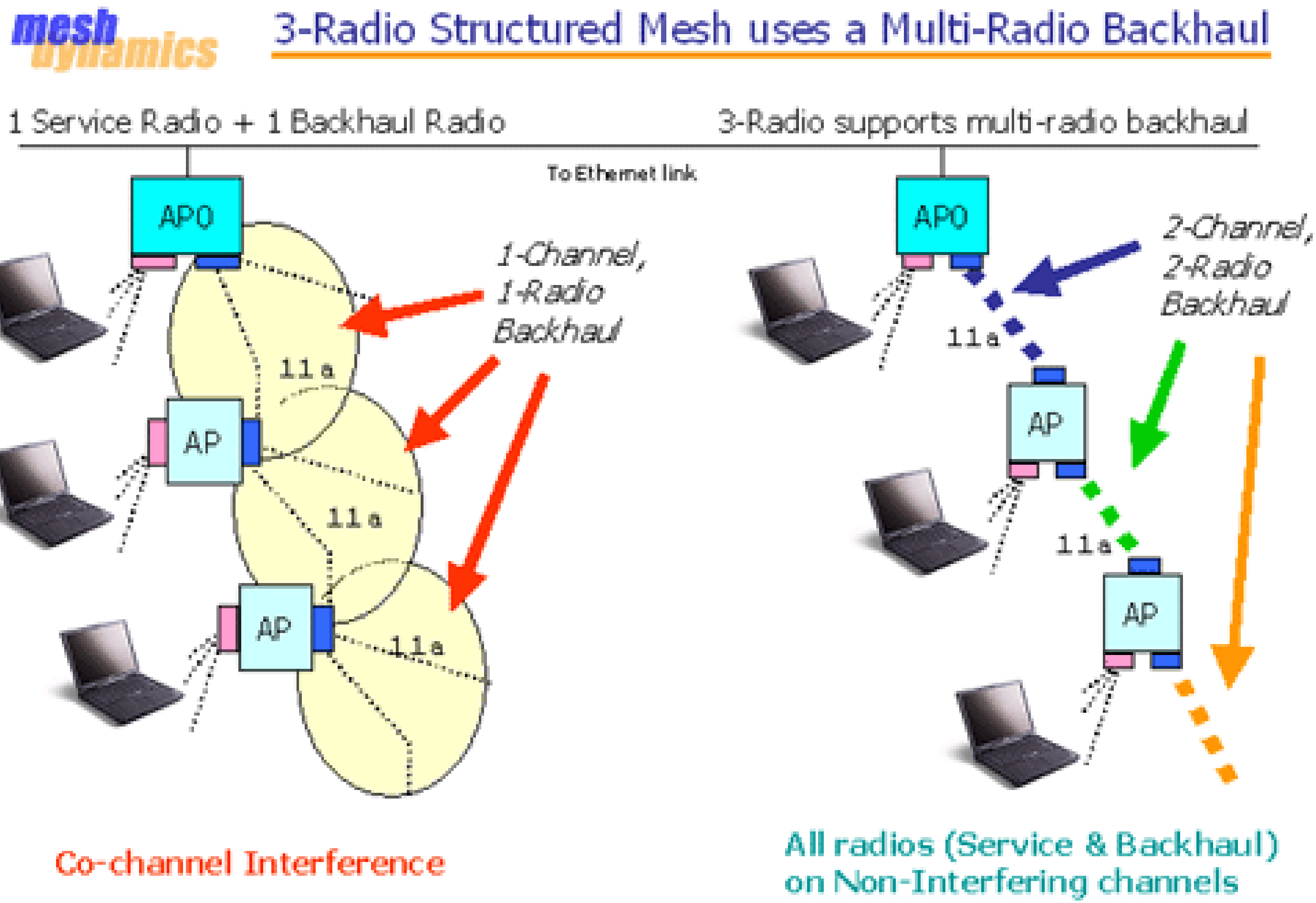
- broadband home networking
- community and neighborhood networking
- enterprise networking
- automation inside a building
- transportation systems
- health and medical systems
- security surveillance systems
- …

Multi-Channel Multi-Radio System

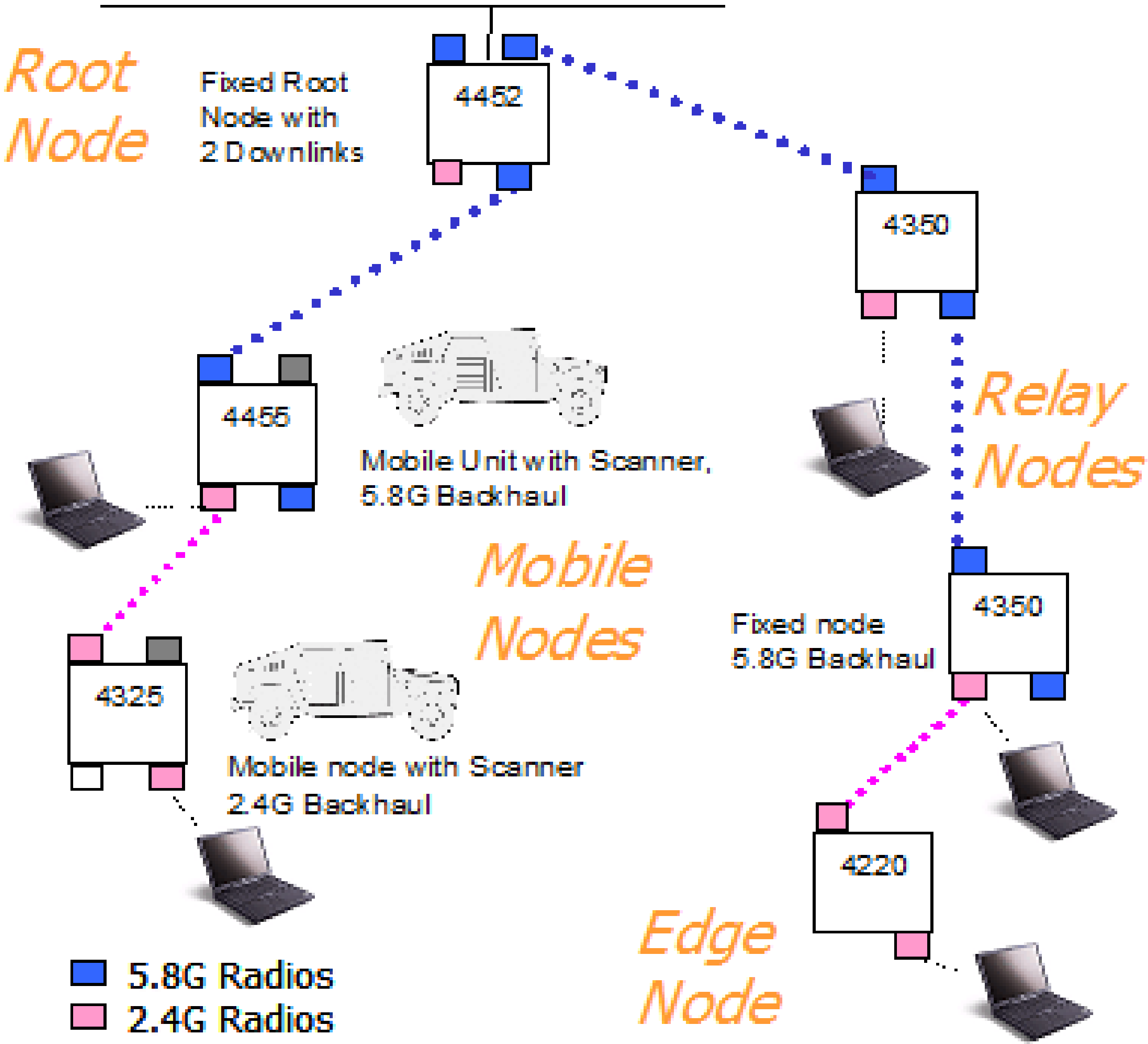
- There are multiple non-overlapping channels
  - IEEE 802.11b/a standards offer 3 and 8 non-overlapping channels, respectively.
- Each node is equipped with multiple radios
  - interference reduction
  - communicate with more than one neighbor simultaneously
  - full duplex operation
  - throughput improvement

1-Radio vs. 2-Radios




mesh dynamics
3-Radio Structured Mesh uses a Multi-Radio Backhaul
1 Service Radio + 1 Backhaul Radio
3-Radio supports multi-radio backhaul
To Ethernet link
AP0
AP
11a
1-Channel, 1-Radio Backhaul
2-Channel, 2-Radio Backhaul
Co-channel Interference
All radios (Service & Backhaul) on Non-Interfering channels

Serving both Mobile Users and Downlink



Topology Control in WMNs

- A topology consists of a set of nodes and links, and it describes the connectivity information of the network
- Links in topology are the result of controlled parameters, such as transmission power and channel assignment
- A good topology is critical to network performance
  - too dense → energy consumption & interference↑ throughput↓
  - too sparse → long path, disconnected network
- Reducing energy consumption and connectivity may be conflicting goals
  - We focus on topology control for reducing interference

Topology Control: Power adjustment and Channel assignment

- Topology control in WMNs includes two steps:
  - Power adjustment
  - Channel assignment
- Power adjustment
  - Define the physical topology of network
  - A link between two nodes if they are within each other's transmission range
- Channel assignment
  - Define the logical topology on the top of the physical topology
  - A link between two nodes if they are within each other's transmission range and use the same channel

Physical Topology

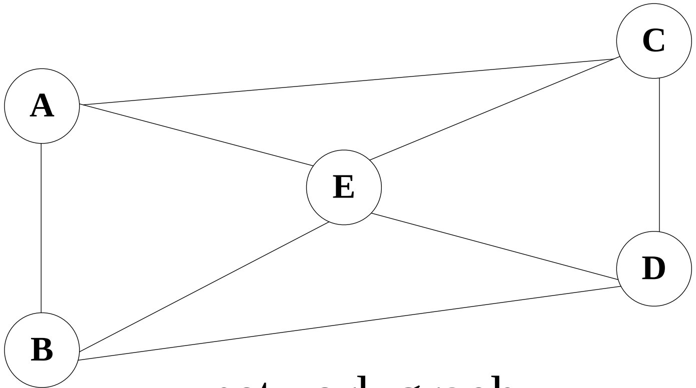
V : set of nodes, representing wireless devices in a region
$p_{max}(v)$: max transmission power of node v
$p(u, v)$: least required power to transmit data from u to v

- $G(V, E)$: network graph, any link $e = (u, v) \in E$ iff $p_{max}(u) \geq p(u,v)$ // reachable by max power
- $G_P(V, E_P)$: physical topology, $E_P \subseteq E$, G_P is a subgraph of G, obtained by removing some long-distance links through reducing transmission power

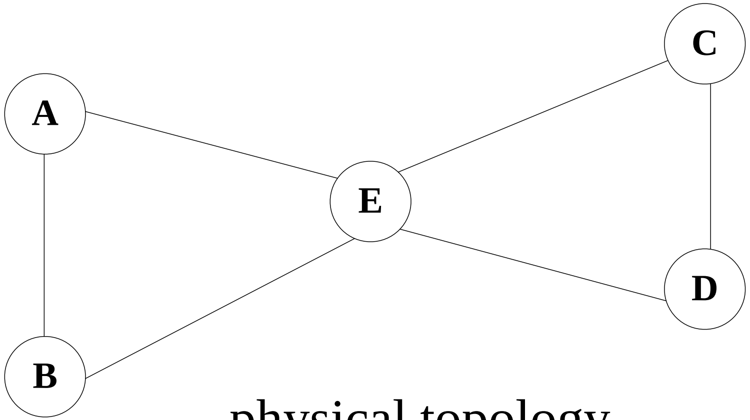
Logical Topology

- C: number of available channels in the system
- $Q(v)$: number of radios on node v, typically $Q(v) < C$
- $A(v)$: set of channels assigned to v, $|A(v)| = Q(v)$
- $G_L(V, E_L)$: logical topology, $E_L \subseteq E_P$
  - a logical link $e = (u, v; k) \in E_L$ iff $(u, v) \in E_P$ and $k \in A(u) \cap A(v)$
- There could be multiple logical links between a pair of nodes in G_L
  - it is a multi-graph

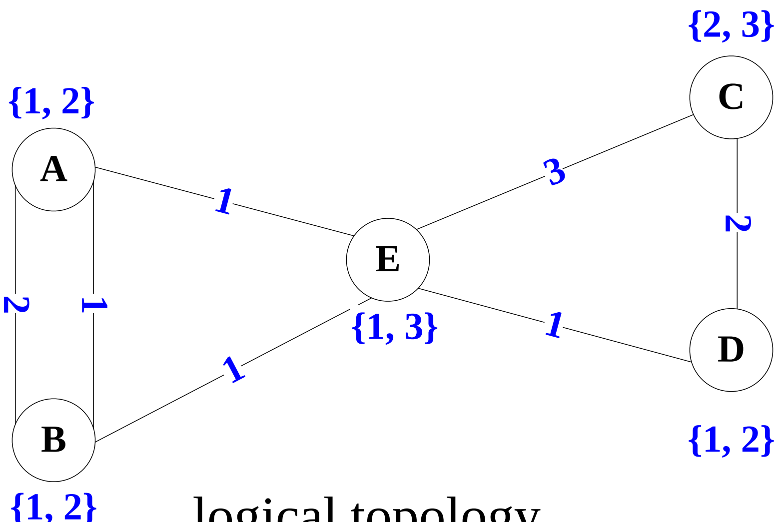
Example of physical & logical topologies



network graph



physical topology



logical topology

SNR Model

- Interference model specifies conditions where a signal can be successfully received
- Physical Model
  - transmission from *u* to *v* (SNR: signal-to-noise ratio, SS: signal strength)

$$SNR_{uv} = \frac{SS_{uv}}{N + \sum_{\substack{k \in V \\ k \text{ is transmitting} \\ k \neq u}} SS_{kv}} \geq SNR_{threshold}$$

Interference Models

- Protocol Model (transmission from u to v)
  - $p(u) \geq p(u, v)$, and
  - no other transmitter w within range $(1 + \Delta)d(u, v)$:
    $d(w, v) \leq (1 + \Delta)d(u, v)$, $\Delta > 0$ // $d(w,v)$: distance

- Physical Interference Model
  - Based on SNR level at receiver side

- IEEE 802.11 MAC protocol
  - RTS-CTS
  - Symmetrical communication: Both sender and receiver should be free from interference for a successful transmission (bi-direction of data and ACK)

Objectives of Interference Reduction

- Interference vs. network connectivity
  - Achieving required network connectivity
  - MIN interference while keeping certain network properties, such as k-connectivity

- Interference vs. network throughput
  - Network planning and routing by considering link load and interference
  - MAX network throughput

Power Adjustment

- Reduce interference by reducing transmitting power

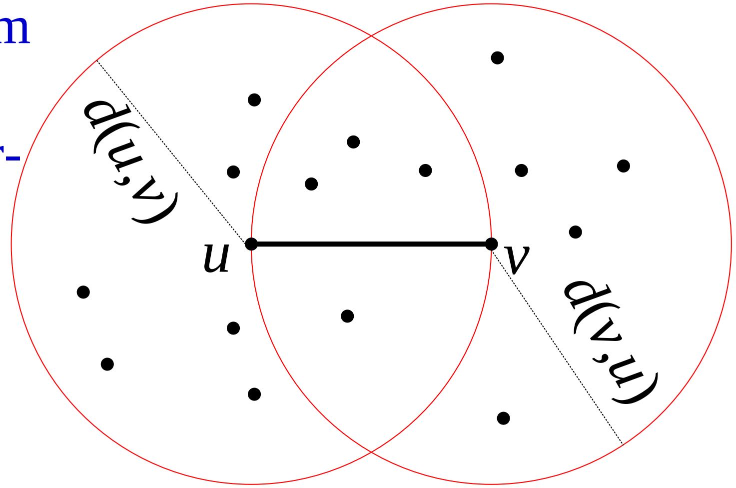
- Link Interference Reduction
  - define the interference of a link

- Node Interference Reduction
  - define the interference of a node

Link Interference Reduction

- Minimize the number of nodes that are within the interference range of a link
  - Set of nodes interfered by link $e = (u,v)$:

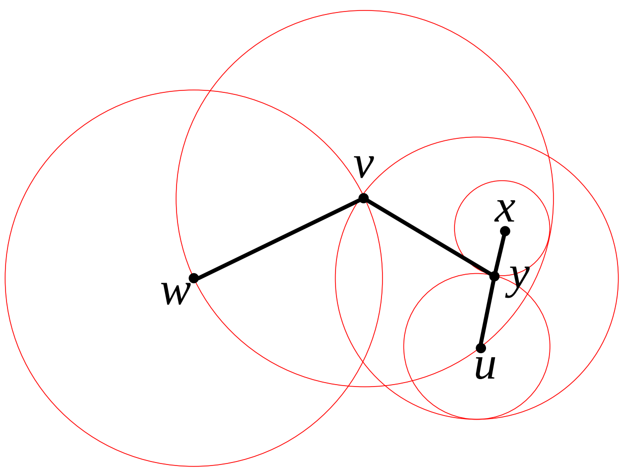
    $I(e) = \{w \in V \mid d(u, w) \leq d(u, v)\} \cup \{ w \in V \mid d(v, w) \leq d(v, u)\}$
  - The network interference can be defined as the maximum (or total) number of nodes interfered by any (or all) links in the physical topology
  - MST is the optimal solution to the problem of MinMax link interference in a physical topology while keeping the topology inter-connected (i.e., $\mathrm{MinMax}_{e \in E}\, I(e)$)



Node Interference Reduction

- Minimize the number of nodes that are within the interference range of a node
  - $r(u)$: interference range (radius) of u
  - Set of nodes interfered by node u:

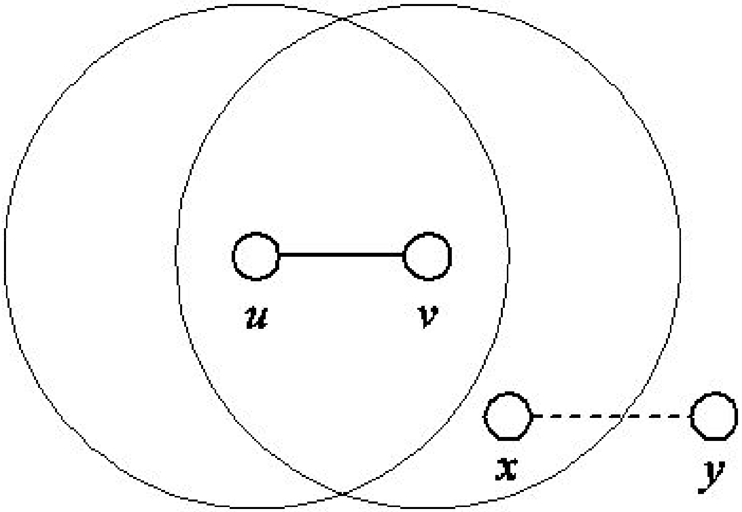
    $I(u) = \{v \mid d(u,v) \le r(u)\}$
  - Minimize the total/max node interference while keeping the network connected (or k-connected)
  - Is MST still the optimal solution?



$I(v) = 4$
$I(u) = 1$

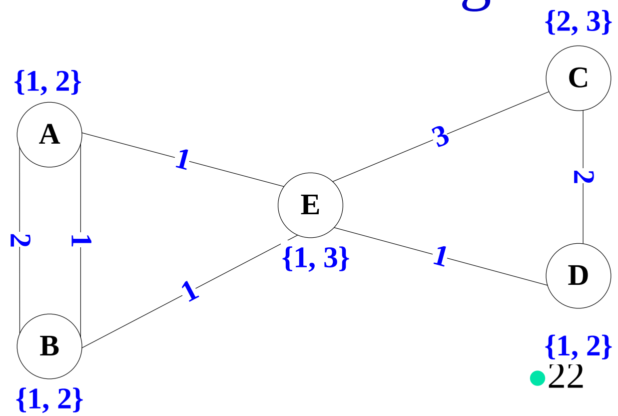
Channel Assignment

- Number of channels assigned to a node must be equal to the number of radios equipped with the node
  - Assuming channels are non-overlapping
  - Channels are more scarce resources in wireless networks
- Efficient channel assignment can reduce network interference
- Two links interfere with each other *iff* one node of a link is within the interference range of the other link and both links use the same channel



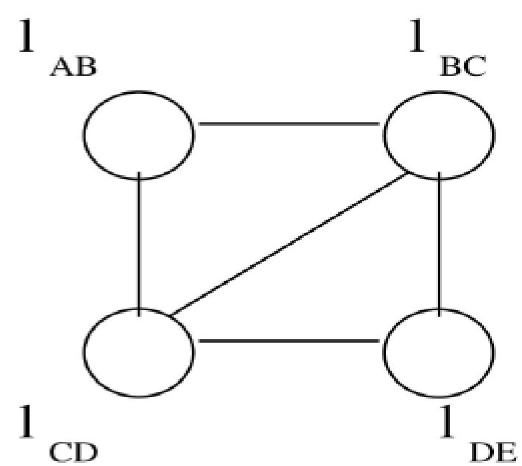
Channel Assignment Methods

- Two channel assignment strategies
  - dynamic assignment: assign channels to transceivers at flow setup time (or even at packet level)
    - Efficient use of channel resources
    - Require channel switching at high speed
    - Difficult for two end-nodes of an edge to agree on the same channel (particularly at packet switching level)
  - static assignment: assign channels to all links statically
    - No need of coordination between two nodes of an edge at transmission time
    - Channels are not fully utilized



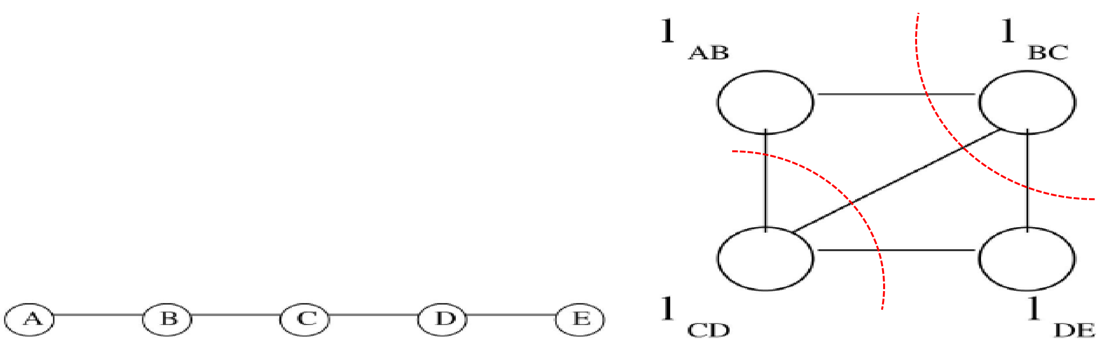
Static Channel Assignment: conflict graph

- Given network graph $G(V,E)$, its Conflict Graph $G_c(V_c,E_c)$ is constructed as follows:
  - $V_c = E$
  - Each $e(l_{ij}, l_{ab}) \in E_c$ *iff* links l_{ij} and l_{ab} ($l_{ij}, l_{ab} \in E$) interfere with each other in network G
  - Note: ~~conflict graph is independent from interference model~~ (conflict graph is a general tool)



Static Channel Assignment Algorithm

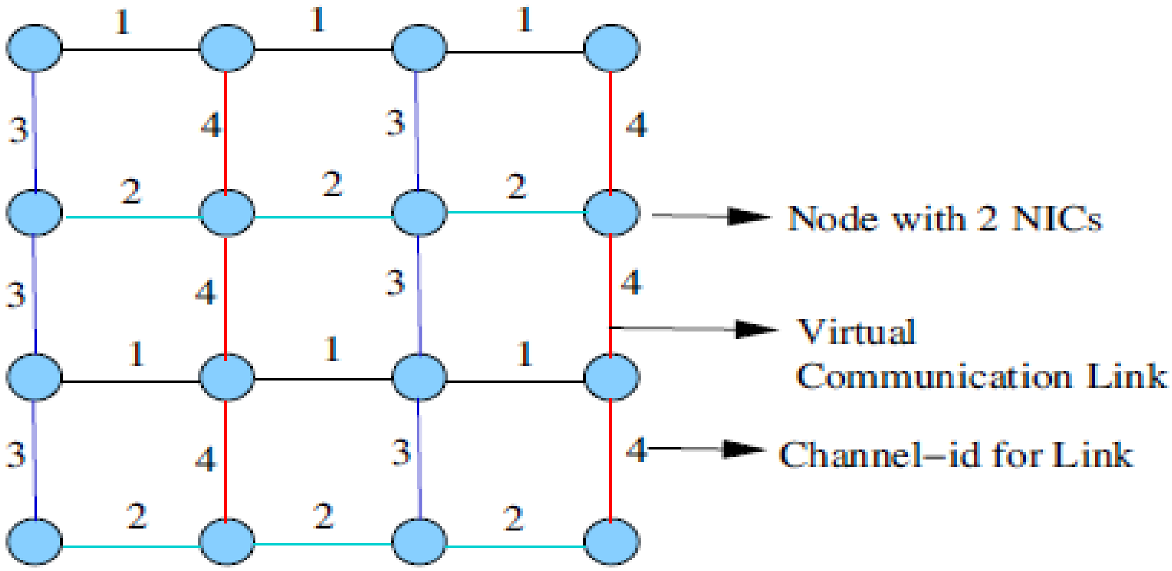
- Goal of channel assignment: assign channels to links such as the total number of interfering links (after channel assignment) is minimized
  - Two links will not interfere with each other if they are assigned with different channels
- Given conflict graph $G_c(V_c,E_c)$ and K channels, Max-K cut problem: partition V_c into K partitions, aiming to maximize the number of edges whose end-points lie in different partitions
- Channel assignment problem for minimizing total interference is equivalent to Max-K cut problem of the conflict graph
- Why?



A Distributed Channel Assignment Method

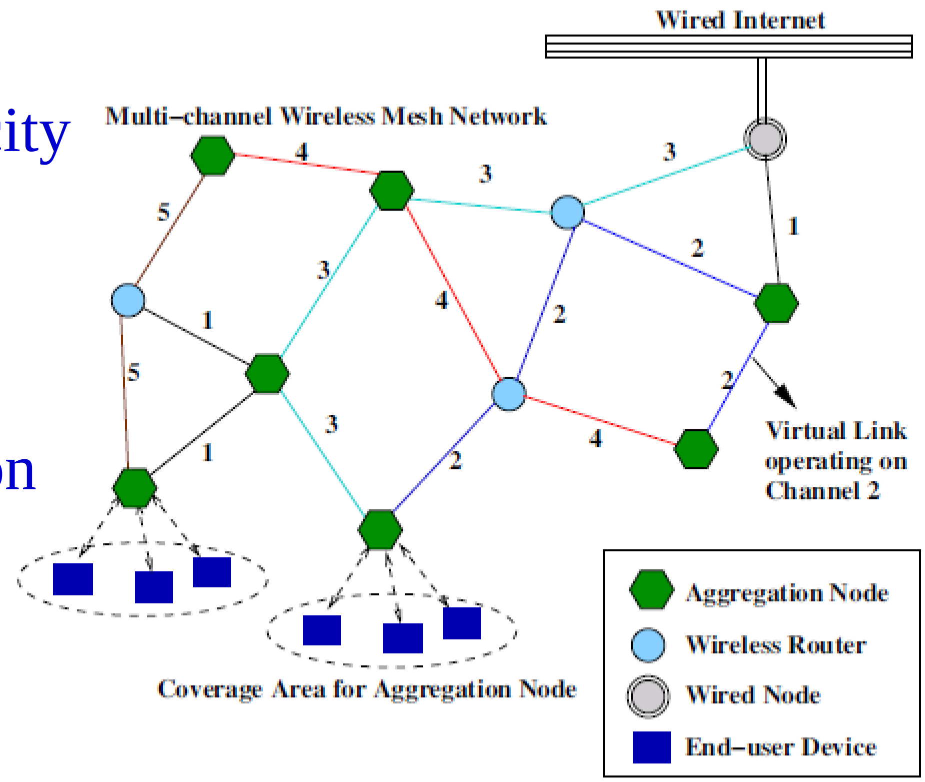
- Starting from any node (with *r* radios) in a graph, partition its neighbors into *r* groups and assign one channel to each group
- Choose one of the previous node's neighbor to continue the above process, while maintaining the channels already assigned by the previous node
- Repeat the above process until all nodes have channels assigned
- No consideration of traffic load on links…

Example of a grid network, *r* = 2, # of channels = 4



Joint Channel Assignment & Routing

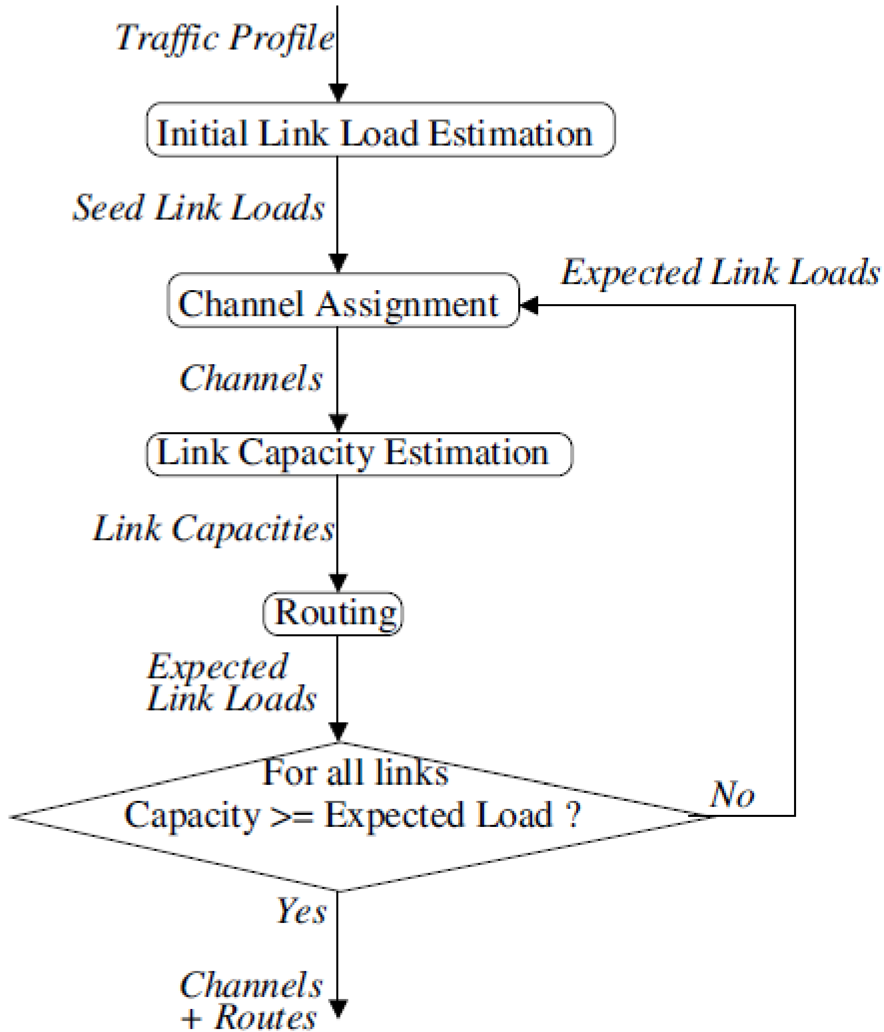
- Cyclic Dependency Problem:
  Given traffic demand from each node, cyclic dependency between routing and channel assignment
  - Routing depends on link capacity
  - Link capacity depends on channel assignment due to interference of links
  - Channel assignment depends on traffic load on links, which depends on routing
- How to break this cycle?



Iterative Method of Channel Assignment & Routing

Iterative Improvement Method:

1. Start with initial link load estimation without regard of channels
2. Assign channel to each radio (of nodes) according to link traffic load (aim: max link-throughput)
3. Do the routing again based on the actual link capacity after the channel assignment
4. Goto step 2) until all link traffic load is less than the capacity or the throughput cannot be further increase



Summary

- What's WMN and why
- Topology control
  - Physical network topology
  - Logical network topology
- Interference and network topology
  - Protocol interference model (RTS/CTS model)
  - SNR interference model
- Channel assignment
  - Dynamic and static channel assignment
  - Joint channel assignment and routing

Exercise and research issues

- There are two interference models: protocol model and physical model
  - Which model is closer to the real system situation?
  - Which model has easier algorithm solutions? Why?
- Most of the topology control algorithms aim to minimize interference. However, network engineers care more about network throughput:

  Is Min interference ≡ Max throughput?
- Channel assignment often uses Conflict Graph to model interference between links
  - Is conflict graph for protocol model or physical model?
  - Why channel assignment problem is equivalent to Max K-cut problem?