Distance-1 Constrained Channel Assignment in Single Radio Wireless Mesh Networks

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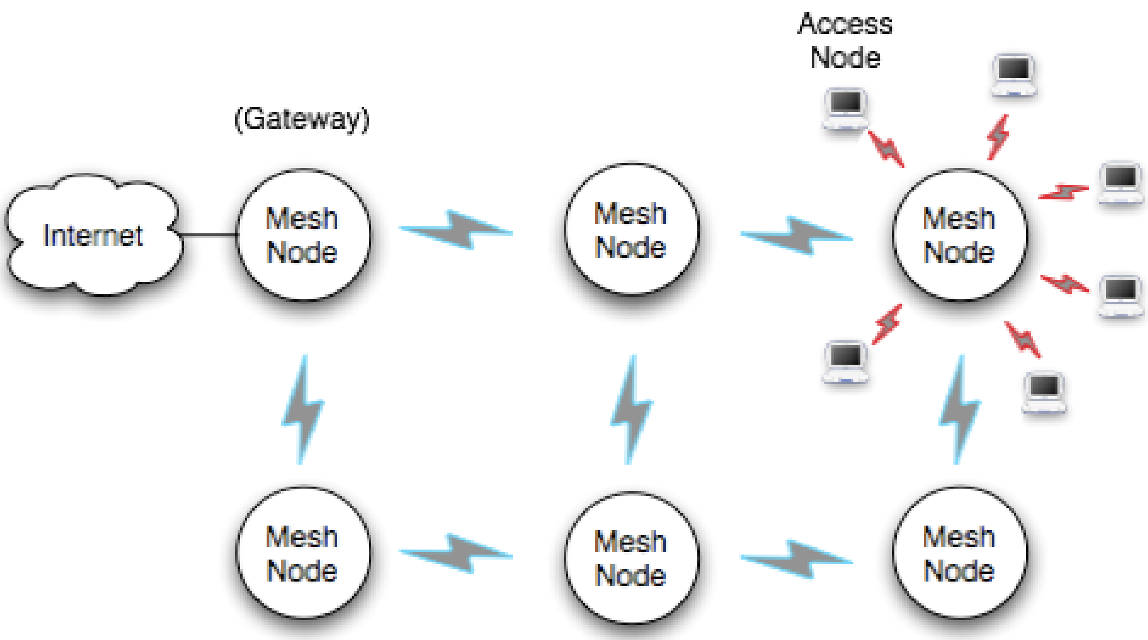
Motivation: Mesh Networks

- City-wide mesh network deployments
  - e.g.
  - Philadelphia
  - Tempe
  - Washington DC
  - San Francisco
  - Houston



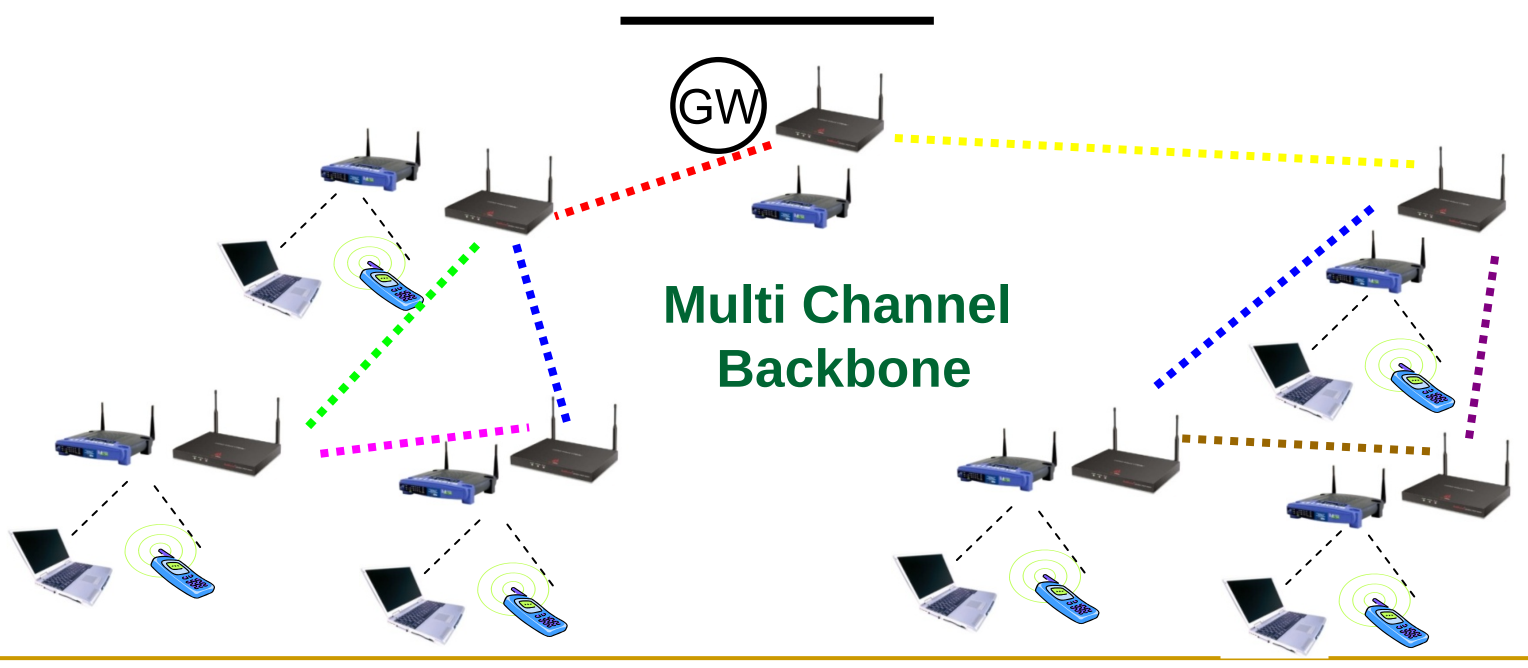
- Two-Tier Mesh Architecture
  - Access tier – clients (homes and mobiles) to mesh nodes
  - Backhaul tier - mesh nodes wirelessly hop to gateway
  - Gateways - Limited number of nodes connected to wired internet

System Model

- Two-tier mesh architecture
- Single half-duplex Radio for backhaul-tier
- K orthogonal frequency channels
  - Single Radio for access tier
  - Multiple channels for backhaul tier
- Predetermined data forwarding links by an existing routing protocol
- Bidirectional links selected by the routing protocol

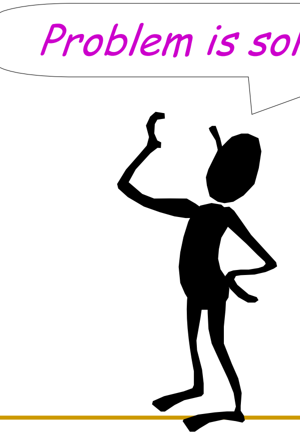
Objective

- Low channel utilization and high throughput imbalance are well known problems in single channel mesh
- Our objective: Design a single radio channel allocation architecture that maintains high channel utilization while keeping fair bandwidth allocation between flows



State of the art:
Transceiver based assignment schemes

- Transceivers dynamically select channel for data transmission based on local channel Information
  - Example: DCA’00, MMAC’04, AMCP’06, …
  - Considered by 802.11s multi-channel mesh standard proposals



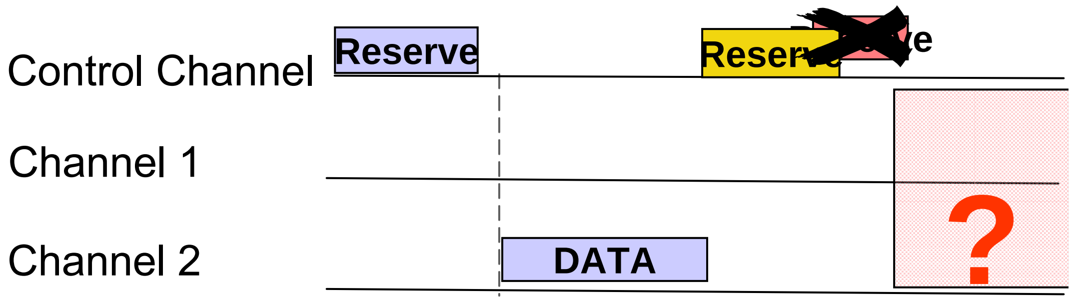
Why Change?

If it is not broken,

why mess with it?

Inherent limitations within transceiver based channel assignment schemes:

- Inaccurate channel availability:
  - Corrupted reception of control packets due to collisions
  - Loss of reception when tuned to a different channel



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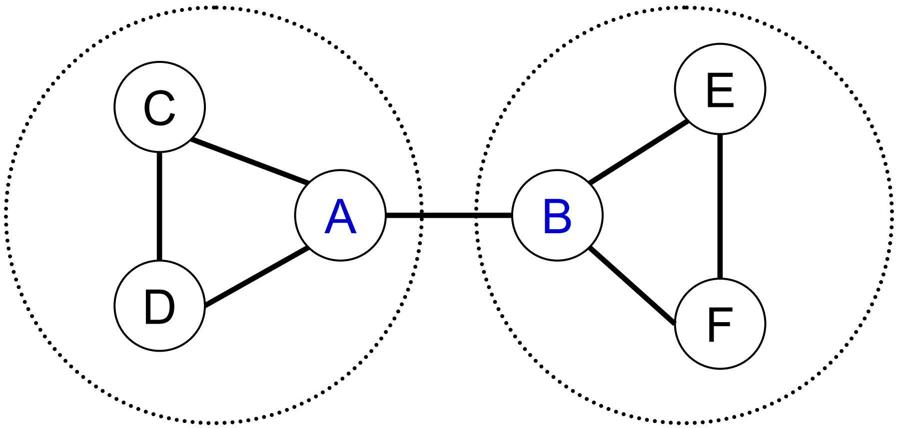
- Inconsistent topology seen by neighboring nodes
  - Unique to multihop, as in single hop all nodes are within transmission range



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$\Rightarrow$ Local greedy channel selection can lead to poor channel utilization with severe throughput imbalance between flows

Why Change?

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- Inaccurate channel availability:
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  - Loss of reception when tuned to a different channel
- Inconsistent topology seen by neighboring nodes
  - Unique to multihop, as in single hop all nodes are within transmission range

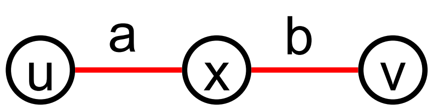
⟹ In contrast to prior work we used one of the nodes as a central point to compute static channel assignment

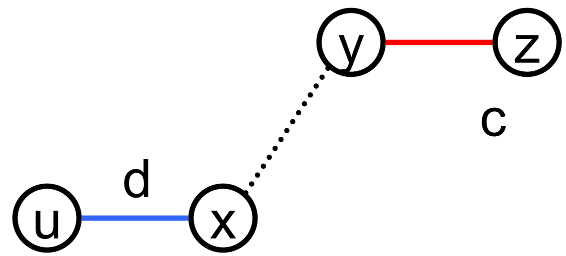
Channel Assignment Protocol

- A Network Controller allocates channels to all active links
  - This procedure is run only once during network setup and is updated based on deployment of new nodes or node failures.
- Each active link is notified of:
  - the channel assigned to the link
  - the number of interfering links
- Medium access algorithm mechanism which coordinates between each sender and receiver to schedule transmission

Channel Assignment Objective

Assigning different channels to any two links that can be active at the same time only if their transmission occurs on two different channels



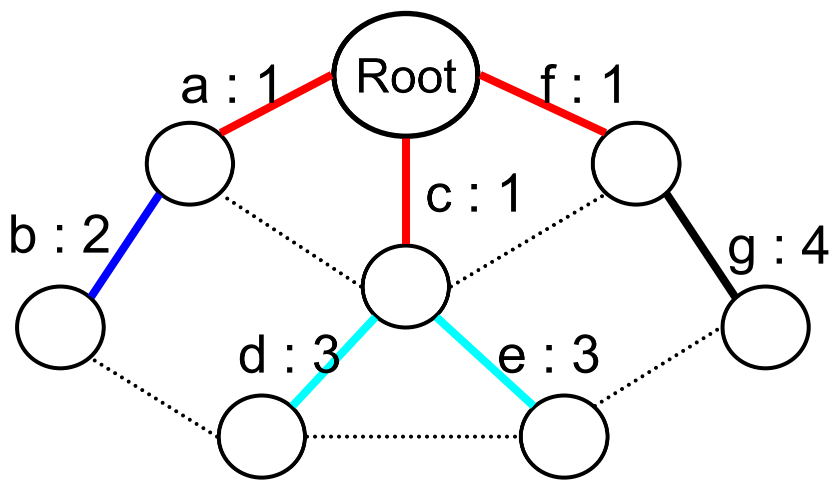


Remark: With this assignment any set of links that form a matching can be active at the same time

- Define Distance-1 as the distance between links that do not share a common node but still interfere with each other, e.g., links *u-x* and *y-z* are Distance-1 apart

Distance-1 Edge Coloring Problem

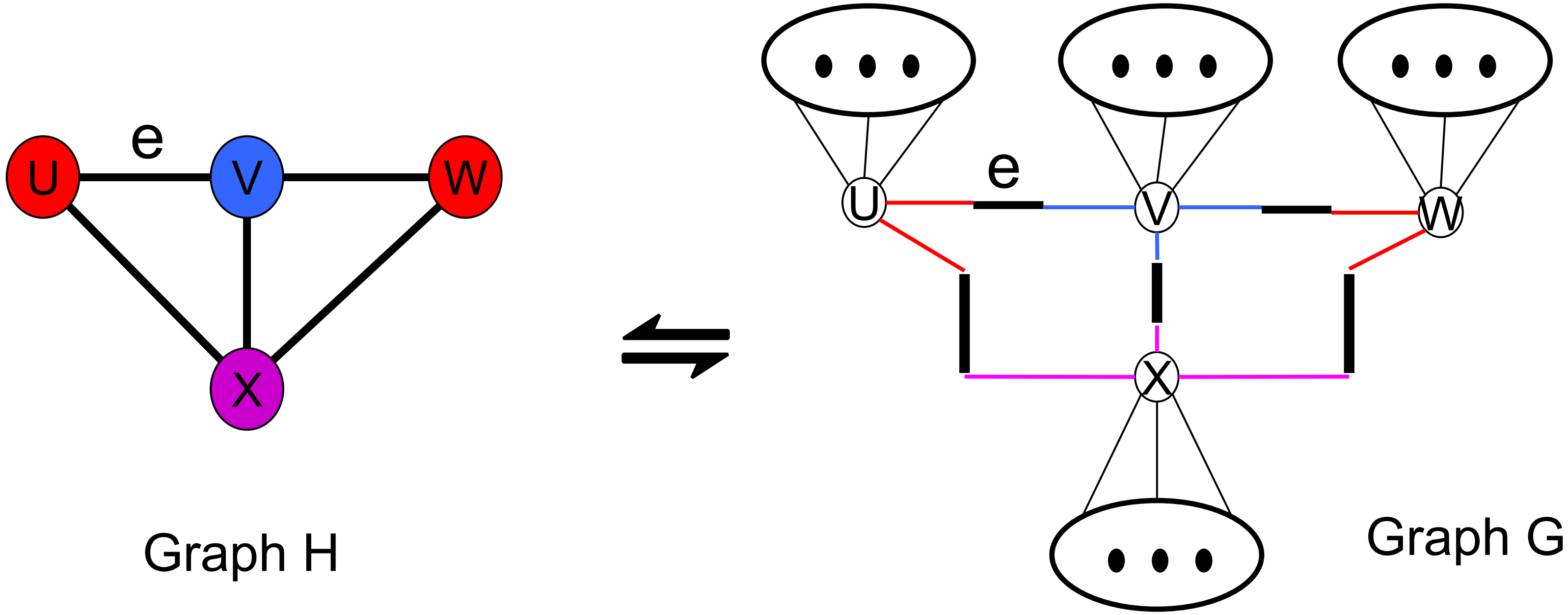
- *Definition (D1EC Problem)* : Given a physical graph G and a selected subgraph $A \in G$, the distance-1 edge coloring problem seeks a mapping of colors to links in A such that any two links that are at distance-1 with respect to G are assigned different colors.



Minimum required number of channels

- Theorem 1: The decision problem whether k colors are sufficient to have a valid D1EC is NP-complete

Basic proof idea: Reduction from graph K colorability.



Upper bounds for typical topologies

- Theorem 3 : For a geometric graph of maximum degree Δ, K_{D1EC} is upper bounded by 18 X (Δ + 1)

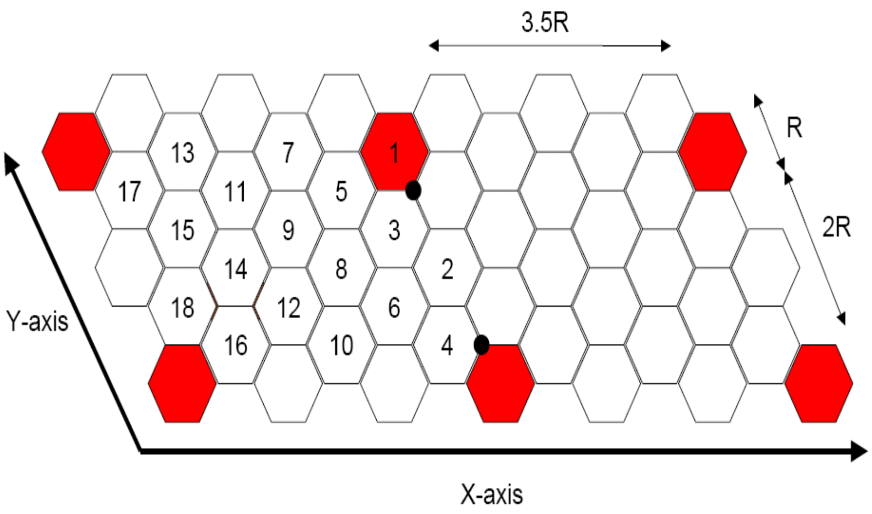
Basic proof idea:

1: Physical graph division into cells

2: Assign channel pools to each cell

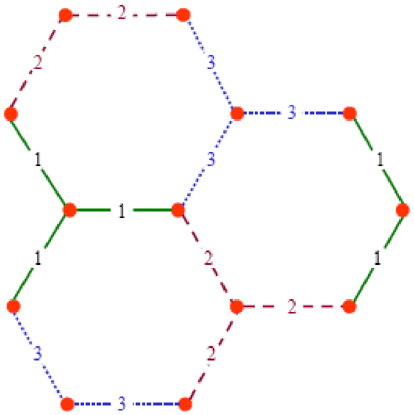
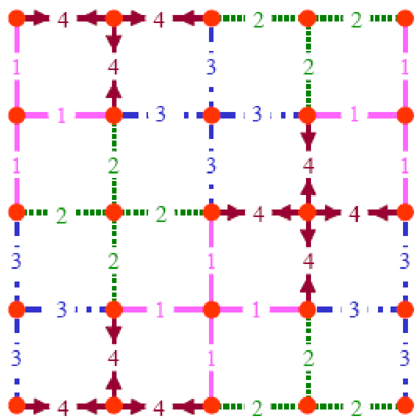
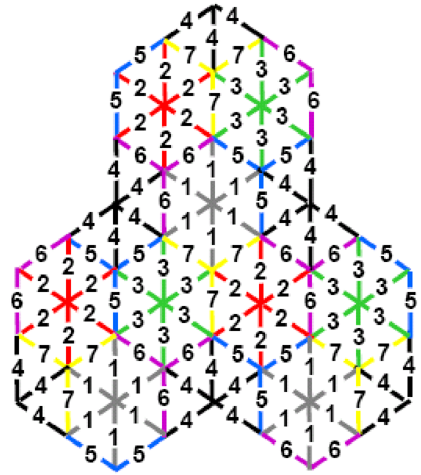
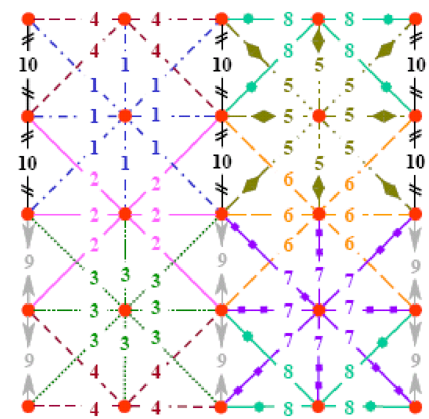
3: Reuse pools at appropriate distances

4: Good bound depends on the shape and size of cell



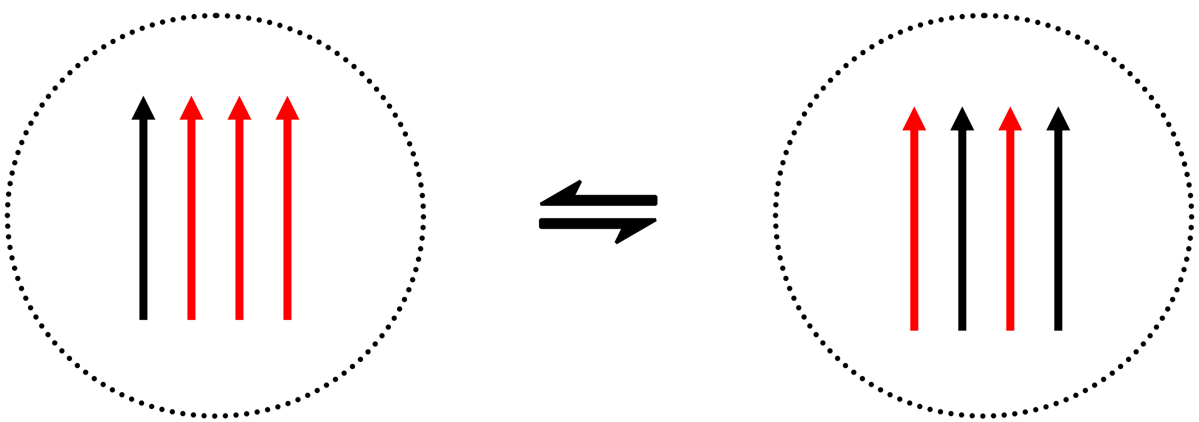
Upper bounds for typical topologies

- Theorem 4: minimum number of colors to have a valid D1EC of links in typical grid topologies such as Δ = 3,4,6,8 is upper bounded by 3,4,7,10, respectively

Minimum required number of channels exceeds the number of available channels

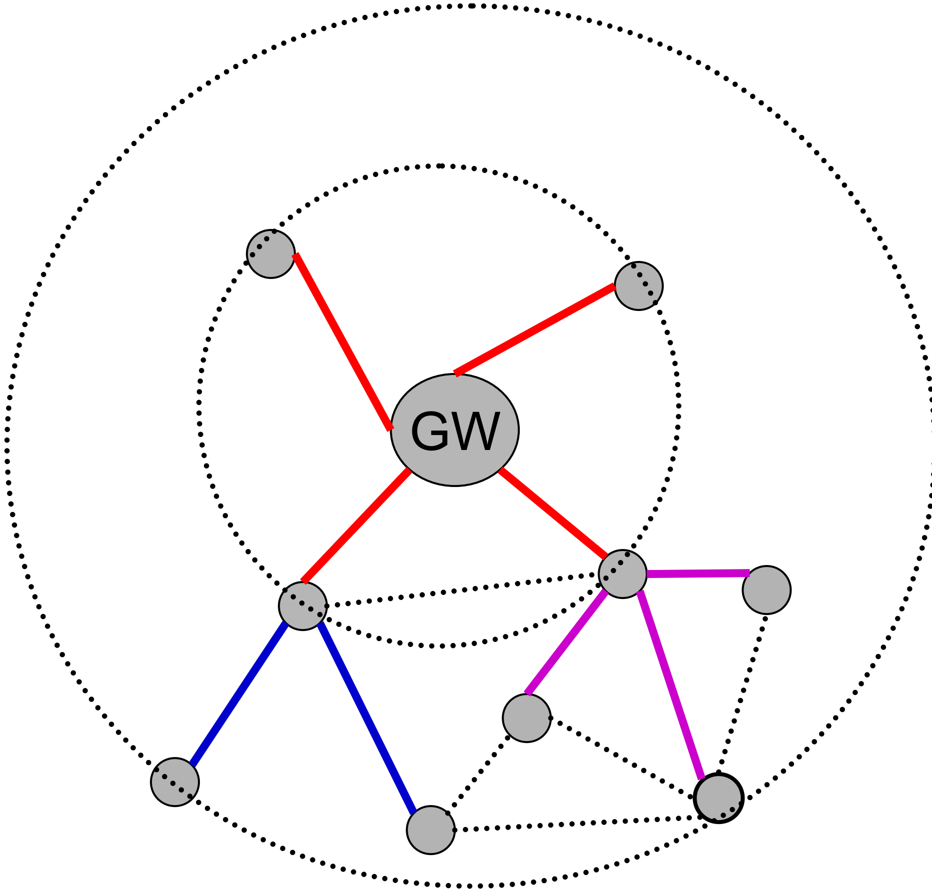
- Interference-free links can communicate whenever sender and receiver pairs are available
- Interference on interfering links should be balanced



Channel Assignment Algorithm for MESH Network

- Basic Algorithm Steps:
  - Visiting nodes vs. edges
  - Reserve interference-free links for gateway nodes
  - Greedy assignment for all links

Theorem 6: Under geometric graph model, if the number of channels is *C1* times the number of channels needed to have a valid D1EC coloring the suggested algorithm guaranty to find a conflict free coloring



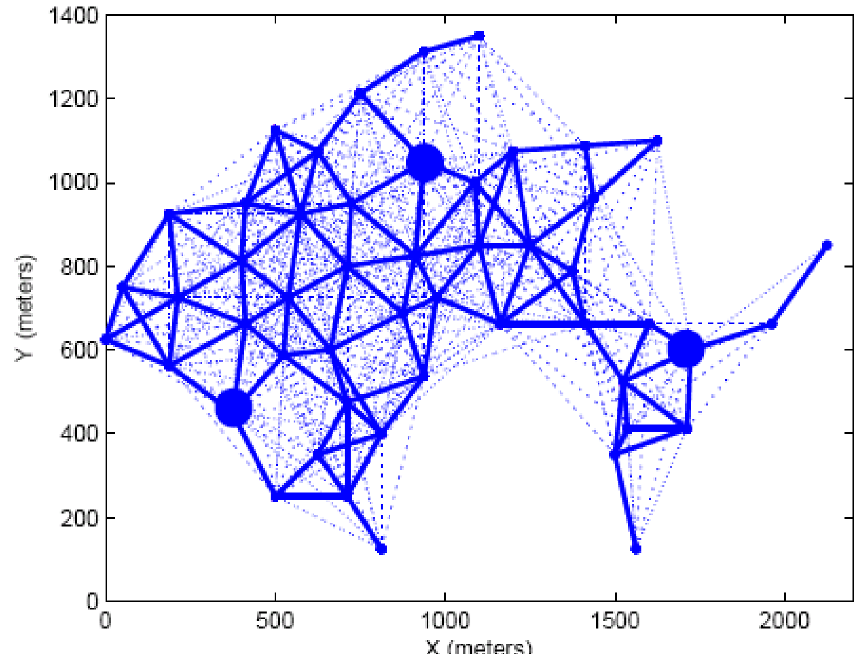
Common Channel Reference MAC

- Two common problems in Multi-Channel MAC protocols
  - Contaminated channel availability data base
  - Mutual deafness deadlock

- Basic MAC properties:
  - Separate control channel
  - Use information provided by network controller for medium access

Simulation Results: Setup

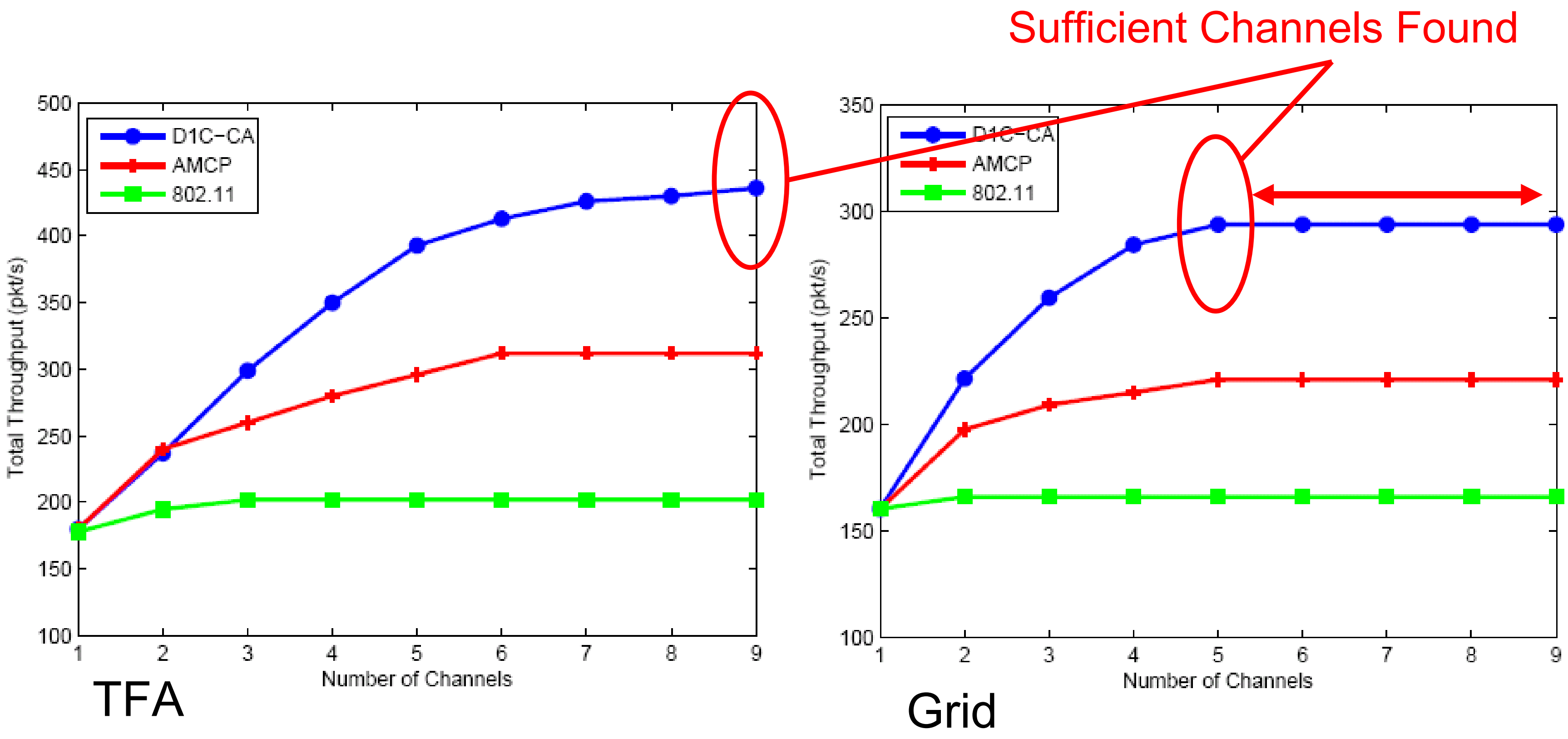
- Setup:
  - NS-2 Simulator
  - Rice TFA topology + Grid
  - Number of channels 1 to 9
  - 25 flows, CBR over UDP
  - Switching delay, 80 μsec
  - Routing: Shortest Path
  - Competitors:
    - AMCP: Leading scheme
    - One channel per gateway 802.11



Rice TFA Topology

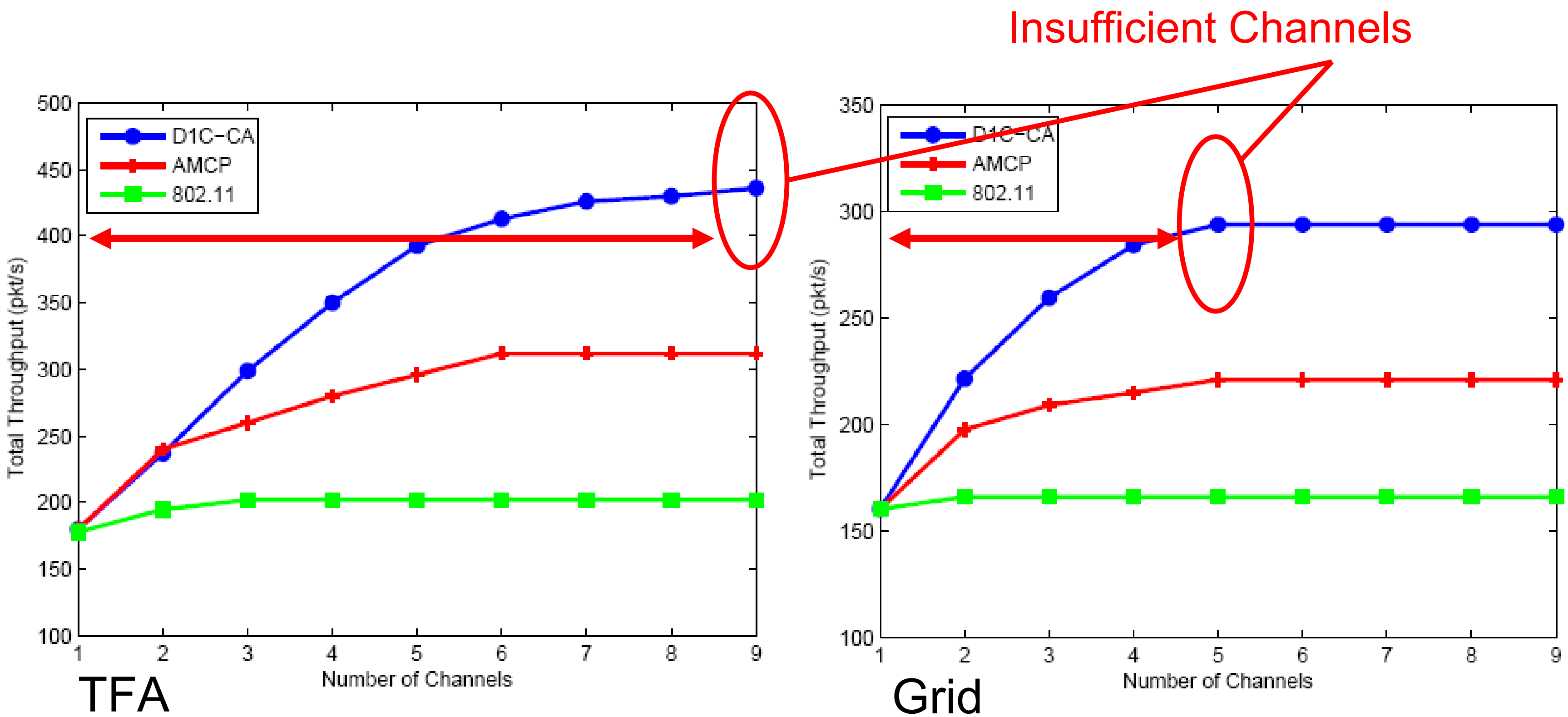
- Metric
  - Aggregate Throughput (pkt/sec)
  - Per flow Throughput

Simulation Results: Aggregate Upload



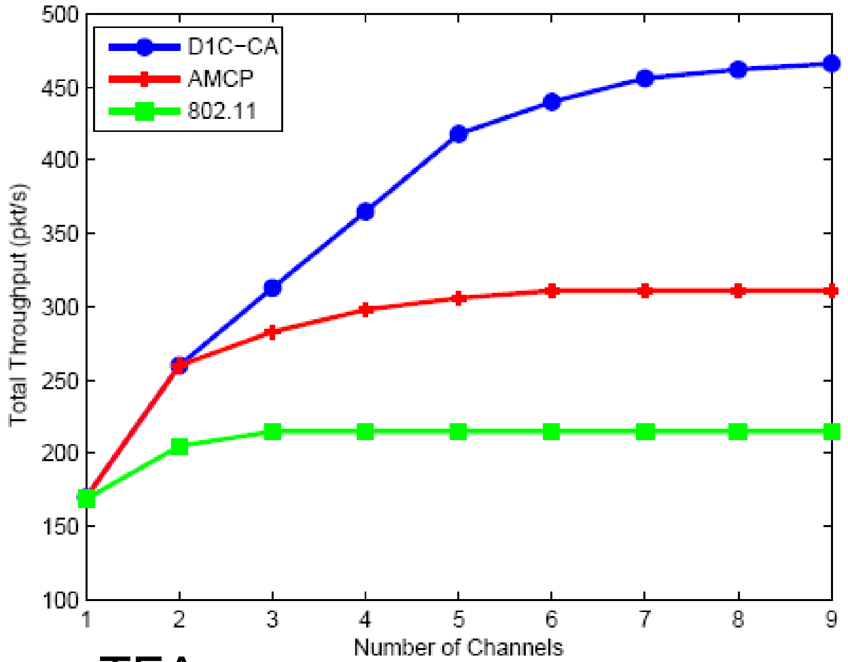
- Maximum throughput of a link in isolation = 184 pkt/sec
- Maximum achieved throughput = 150 pkt/sec

Simulation Results: Aggregate Upload

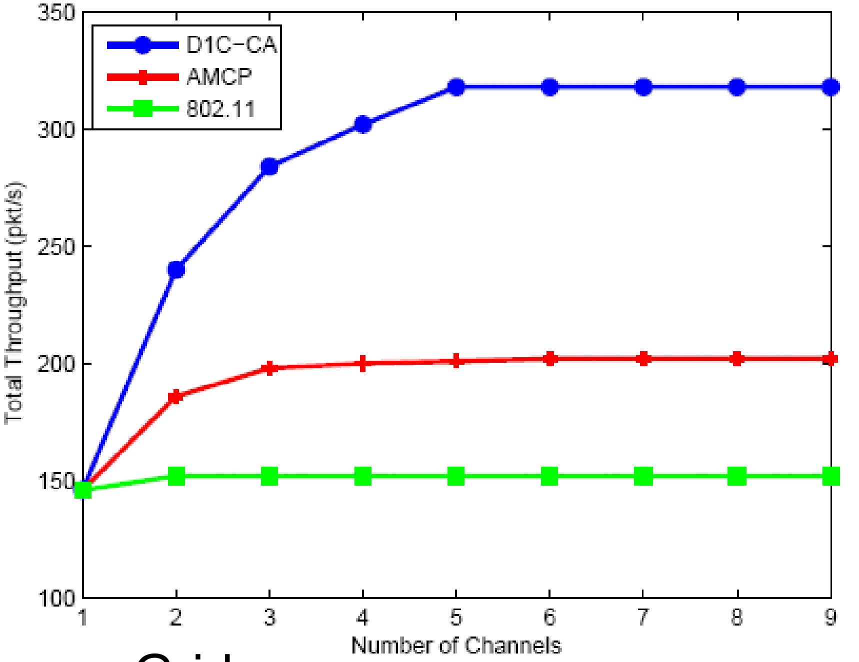


- D1C-CA efficiently utilizes additional increase in number of channels
- Packet selection schemes do not efficiently utilize additional increase in channels and saturate with small channels
- 802.11: High interference within each subnetwork

Simulation Results: Aggregate download



TFA



Grid

- Gateway node becomes heavy bottleneck for download in AMCP
- Two channels are sufficient to guarantee a high performance in our scheme due to gateway bottleneck removal

Summary

- Introduced and investigated distance-1 channel assignment coloring problem
- Designed an efficient channel assignment algorithm for mesh networks based on D1EC
- Designed a random access MAC protocol that exploits the channel assignment

Thank You

Questions

?

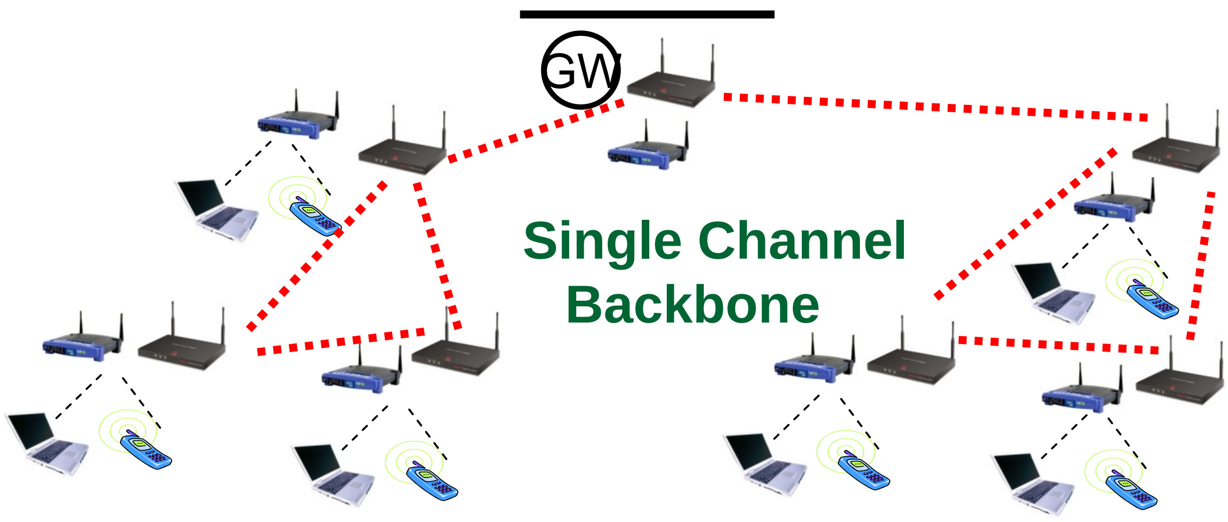
BACKUP

Motivation

Single-channel ⇒ Link interference ⇒

Low channel utilization and high throughput imbalance

e.g., Garreto05, Garreto06



IEEE 802.11 supports multiple channels

e.g., 802.11a – 12 orthogonal channels , 802.11b – 3 orthogonal channels

In contrast to prior work

We propose quasi-static link based channel assignment that minimizes interference among links

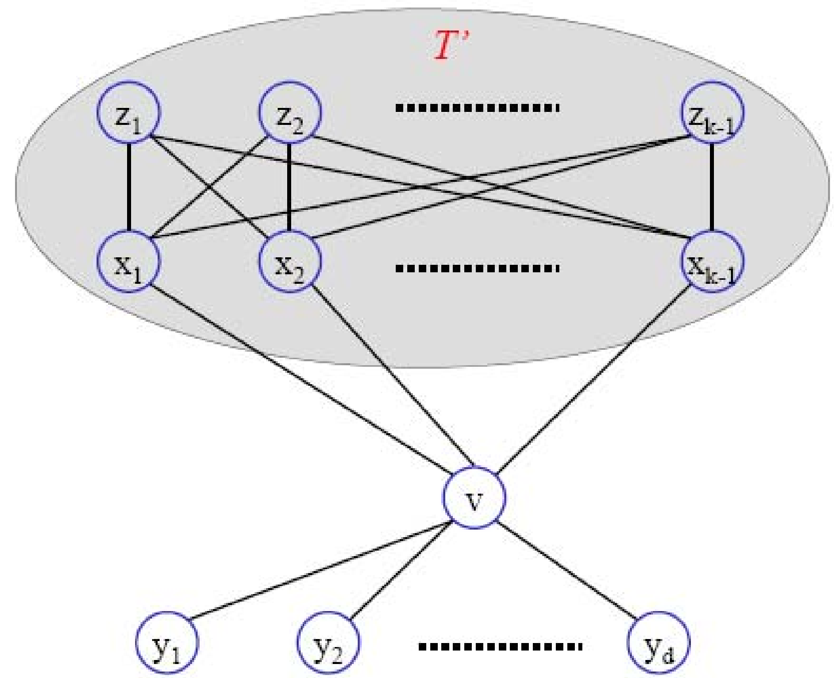
- The gateway node has global information about network topology and can be used as a central point to compute channel assignment

Minimum needed number of channels

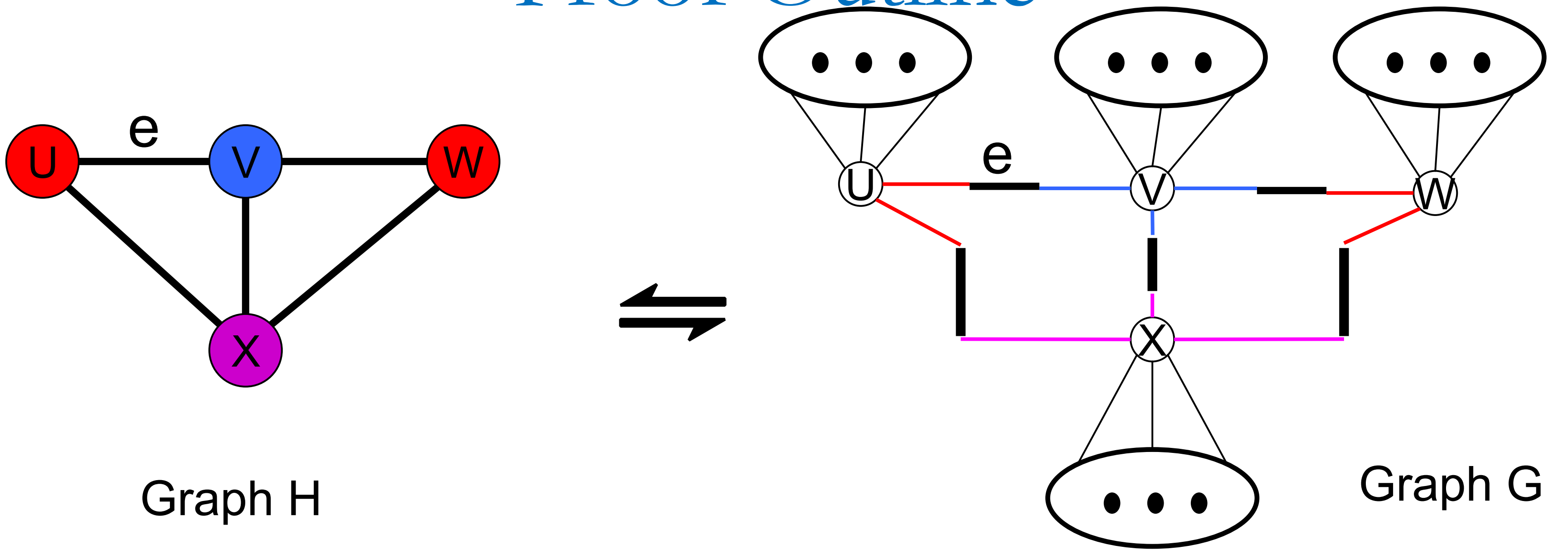
- Theorem 1: The decision problem whether k colors are sufficient to have a valid D1EC is NP-complete

  Basic proof idea: Reduction from graph K colorability: For every graph H, we construct another graph G such that H is K-colorable if and only if G has a D1EC with K colors.

- Lemma 1 : In any distance-1 edge coloring of $T_{K,d}$ with K colors, the colors of all vy_j edges is the same.



Proof Outline



- Construction of *G* from *H*: Corresponding of each vertex *v* of degree *d* in *H*, we put a copy C_v of $T_{K,d}$ in *G*. Each head of C_v corresponds to one of the edges incident to *v*
- If two vertices *u* and *v* in *H* are joined by an edge *e*, their corresponding heads in *Cu* and *Cv* are connected through *e* in the resulting graph *G*

Upper bounds on K_{D1EC}: Geometric Graphs

- Geometric Graph Model: All nodes have the same transmission and interference range

- Theorem 3 : For a geometric graph of maximum degree Δ, K_{D1EC} is upper bounded by 18 X (Δ + 1)

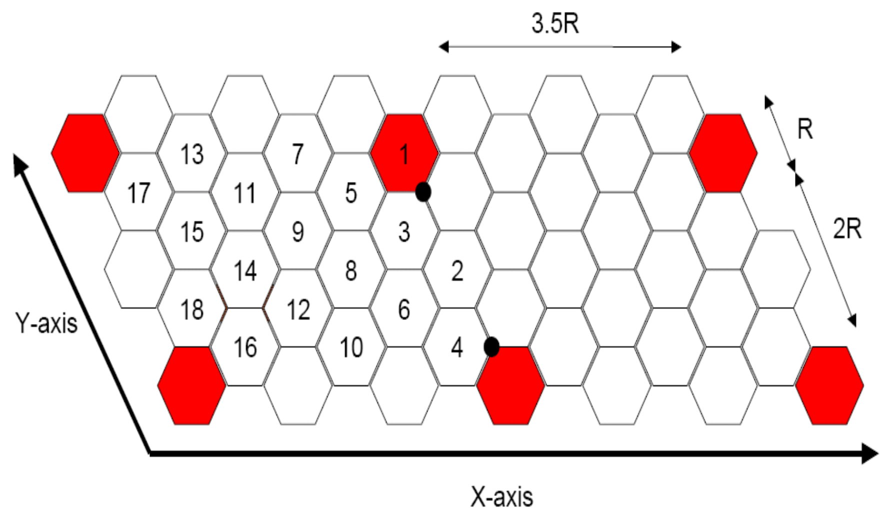
Basic proof idea:

1: Physical graph division into cells

2: Assign channel pools to each cell

3: Reuse pools at appropriate distances

4: Good bound depends on the shape and size of cell



Preview: Context

- Channel assignment in multi-channel wireless networks can increase achievable throughputs
- Multi-channel, multi-hop wireless mesh networks with single radio for backhaul tier
- Channel assignment: For each node, which channel should we operate at any given point in time?

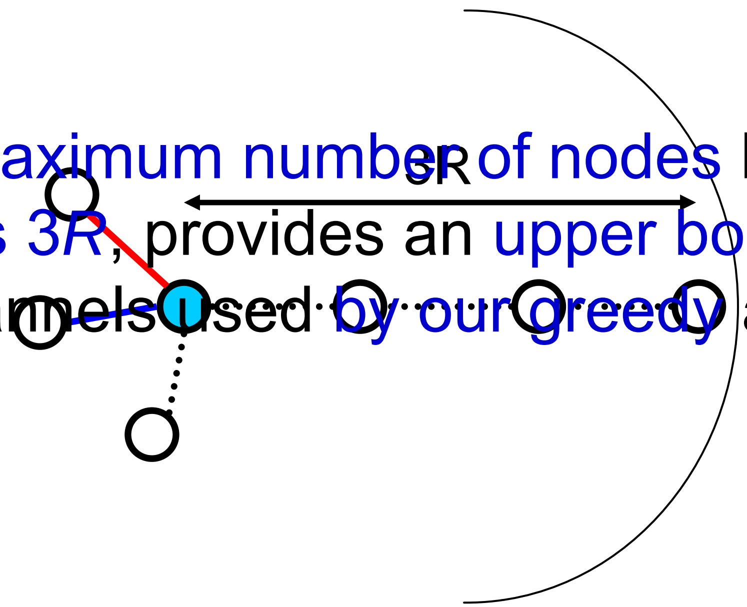
Algorithm Performance Analysis

- Theorem 6: Under geometric graph model, algorithm D1C-CA needs at most $C_1 . OPT(K_{D1EC})$ channels for all links to have a valid D1EC coloring
  - $OPT(K_{D1EC})$: Minimum number of channels used by an optimum algorithm

- Theorem 7: Under geometric graph model, algorithm D1C-CA's maximum contention degree is at most $C_2 . OPT_{min (Co)}$ as $\Delta \rightarrow \infty$
  - $OPT_{min (Co)}$: Minimum contention degree found by an optimal algorithm
  - C_2 depends on the number of available channels

Algorithm Performance Analysis

- Two main properties of the algorithm that provide constant approximation:
  - Looking at nodes instead of edges
  - Greedy channel assignment behavior



Conclusion: Maximum number of nodes bounded in a circle of radius 3*R*, provides an upper bound on the number of channels used by our greedy algorithm

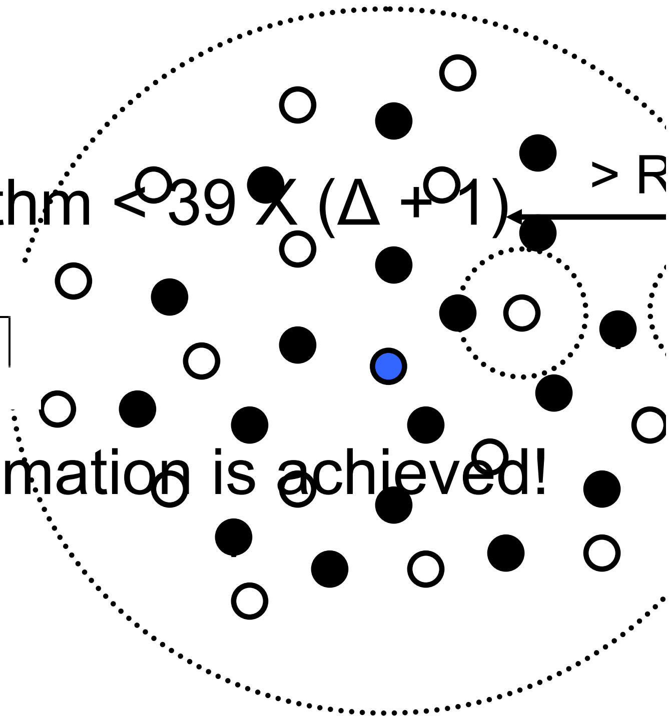
Algorithm Performance Analysis

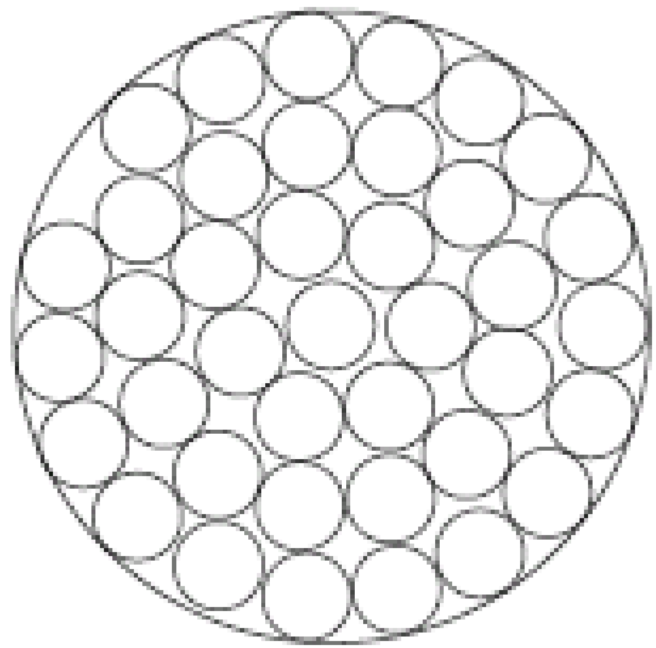
Definition: An **independent set** is a set of vertices in a graph no two of which are adjacent.

colors of algorithm < 39 X (Δ + 1)

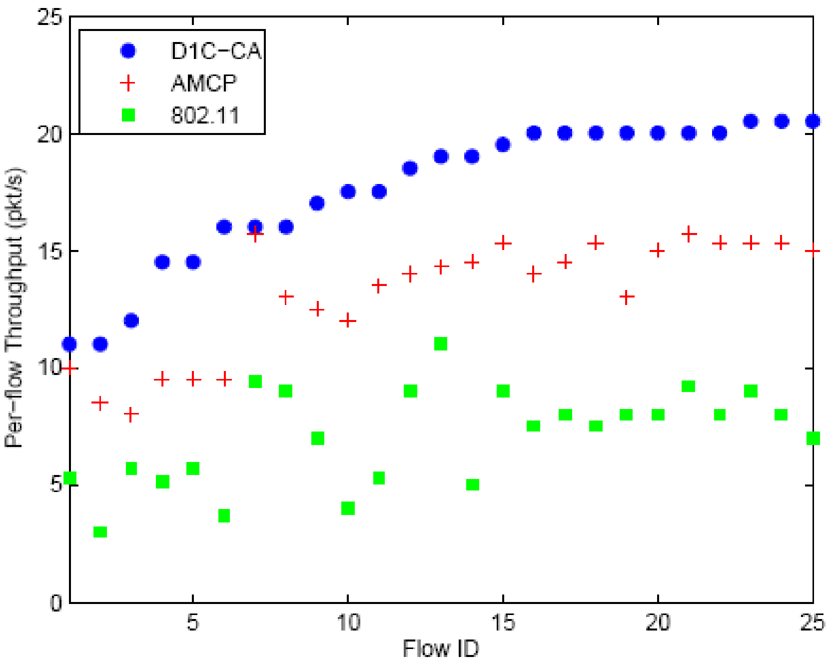
$$OPT(K_{D1EC}) \geq \lceil \frac{\Delta}{6} \rceil$$

Constant approximation is achieved!

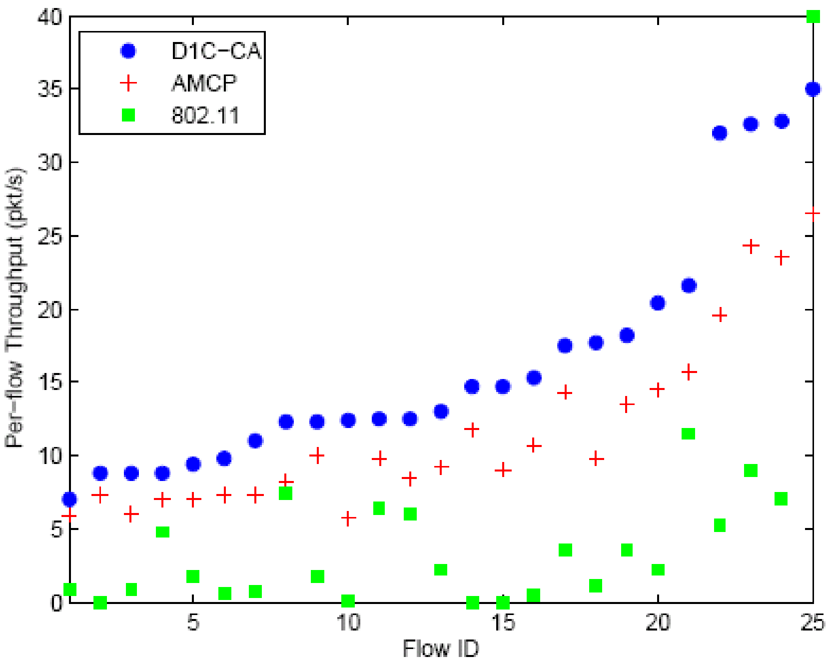




Simulation Results: Per-flow Throughput



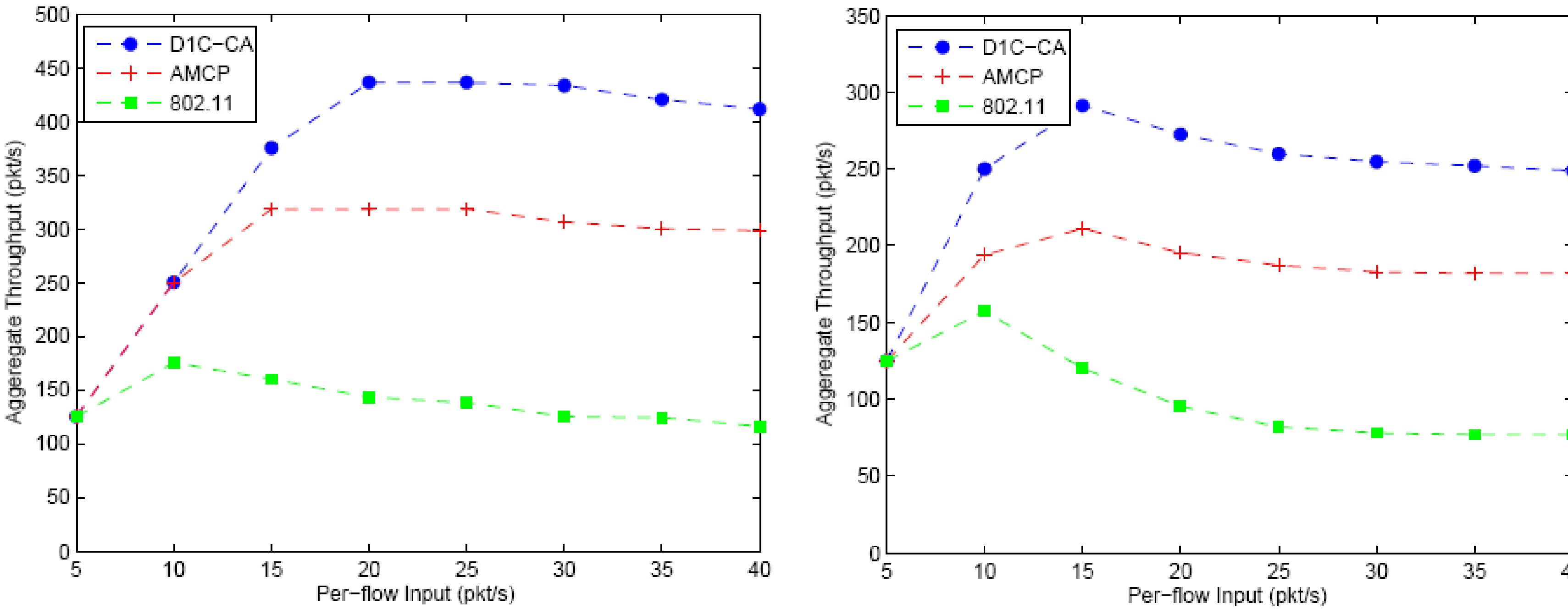
Saturation Region



Fully Backlogged Flows

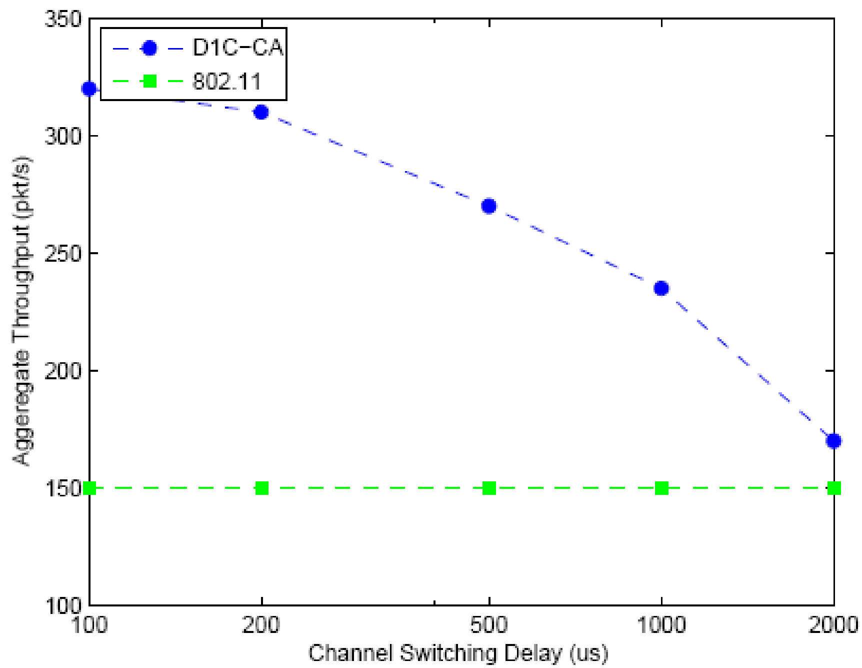
- Same performance irrespective of topology and number of channels
- Starvation in 802.11 with fully backlogged flows
- Sufficient number of channels guarantees minimum rate in other schemes
- With insufficient channels starvation may occur in other schemes

Simulation Results: Effect of Traffic Load



- Same performance irrespective of number of channels
- With small load all approaches handle traffic
- Severe throughput degradation in 802.11 with increased traffic due to hidden terminals

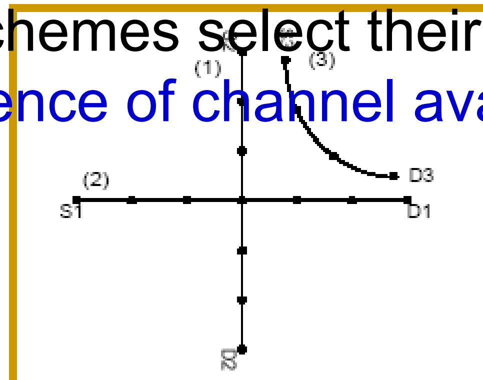
Simulation Results: Effect of Channel Switching Delay



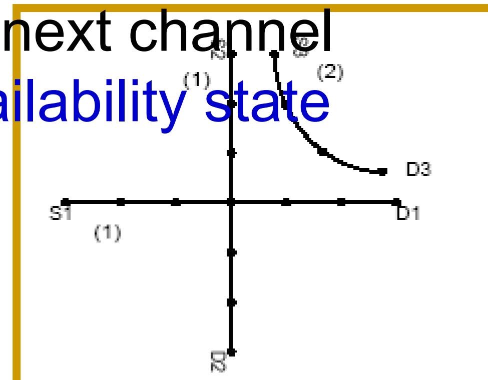
- Low throughput degradation up to 200 μsec: switching delay is small compared to packet transmission time
- Big switching delay can be compensated by sending multiple back to back packets

Preview: Context (contd)

- Granularity of Assignment
  - Packet: Channel assignment on a per-packet [DCA'00,MMAC'04,AMCP'06,802.11s Multi-Channel Mesh,…]
  - Flow: All links in a flow are sent along the same channel [MCP'05]
  - Component: Channel assignment on a component basis [COM'07]
- In a single gateway mesh, Component and Flow level assignments have same or worse performance compared to single channel 802.11
- Packet level assignment schemes select their next channel purely based on local inference of channel availability state



(ii) Flow Based Channel Assignment



(iii) Component Based Channel Assignment

Commercial Technologies

Vendor	Product	Radios for client access	Radios for backhaul
BelAir Networks	BelAir 200	1 802.11b/g	Up to 3 proprietary 5GHz
Cisco	Aironet 1500	1 802.11b/g	1 802.11a
Firetide	HotPort 3203	1 802.11a/b/g	Same as for client access
Nortel	Wireless AP 7220	1 802.11b	1 802.11a
Strix Systems	OWS 3600	Up to 3 802.11b/g	Up to 3 802.11a
Tropos Networks	5210 MetroMesh Router	1 802.11b/g	Same as for client access

Source: Network World

Channel Assignment with Insufficient Number of Channels

- Definition: Suppose A is a subset of the network graph G, and a channel assignment C to the links of A is given. The contention degree of a link e in A; Co(e); is the maximum cardinality matching of a set M with the following properties: M is a subgraph of A containing e and the following set $\{l \in A|\ Color(l) = Color(e), d(l, e)_G = 1\}$

Related Work: Graph Theoretic Techniques

Graph Theory Based Coloring

- L(h, k) labeling problem
- List Coloring Problem

Graph Theory Based Channel Assignment

- Unified Framework and Algorithm for Channel Assignment in Wireless Networks
  - Including several time, code and frequency assignments

D1EC Problem

- First to introduce and investigate the problem
- Study also includes the case of insufficient channels

Related Work: Protocols to Exploit Frequency Diversity

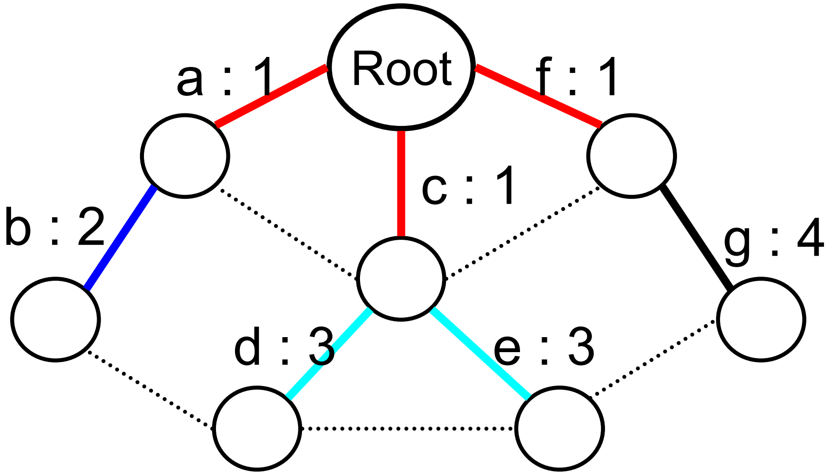
- Single radio protocols:
  - Packet based: [AMCP’06, MMAC’04, DCA’00, 802.11s, …]
  - Flow based: [MCP’05]
  - Component based: [Comp’07]

- Multiple radio protocols
  - MAC modified: [xRDT’07, DAS’01, …]
  - Unmodified MAC: Load balancing, Topology control, External Interference [DAS’05, RAM’06, ASH’05, ASH’06]

Distance-1 Edge Coloring Problem

- *Definition (D1EC Problem)* : Given a physical graph G and a selected subgraph of it $A \in G$, the distance-1 edge coloring problem seeks a mapping of colors to links in A such that any two links that are at distance-1 with respect to G are assigned different colors.

- *Definition* : The distance-1 chromatic index, K_{D1EC}, of a subgraph $A \in G$, is the minimum number of colors to have a valid D1EC of links in A.



Minimum required number of channels

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  Basic proof idea: Reduction from graph K cc
  graph H, we construct another graph G su
  that H is K-colorable if and only if G has a
  D1EC with K colors.

- For any graph with maximum degree Δ:

$$k_{D1EC} \leq min\{|V|, 2 \times (\Delta - 1)^2 + 1\}$$

- For arbitrary graphs, K_{D1EC} can be lower bounded with a function of square degree of Δ:

$$K_{D1EC} \geq \frac{(\Delta + 2)^2}{4}$$