Wireless Mesh Networks Challenges and Opportunities

Mihail L. Sichitiu
Electrical and Computer Eng. Dept.
NC State University,
Raleigh, NC, USA

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Outline

- Overview of the technology
- Opportunities
- (Research) Challenges
- Current state of the art
- Conclusion

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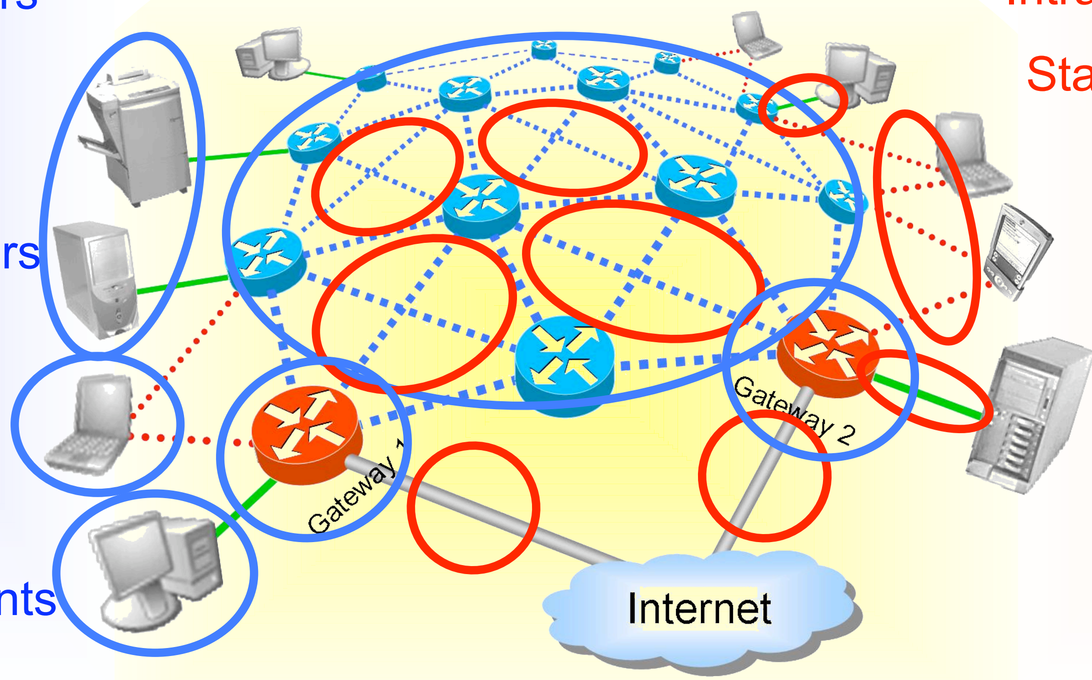
Overview

Node Types

- Wireless routers
- Gateways
- Printers, servers
- Mobile clients
- Stationary clients

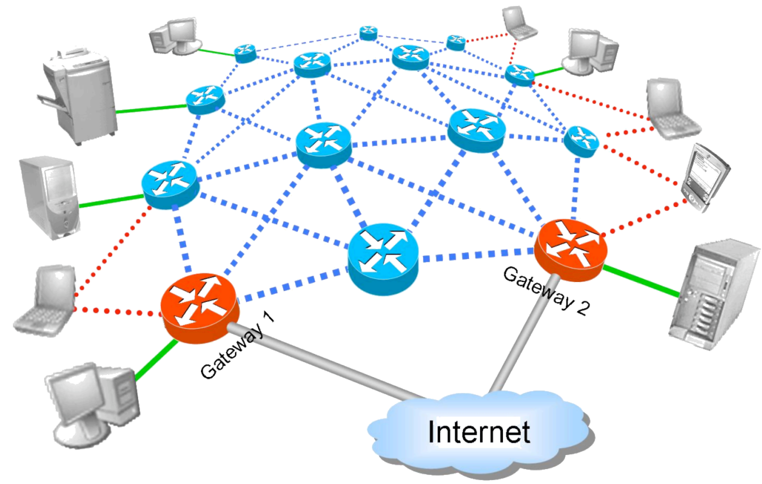


Link Types

- Intra-mesh wireless links
- Stationary client access
- Mobile client access
- Internet access links

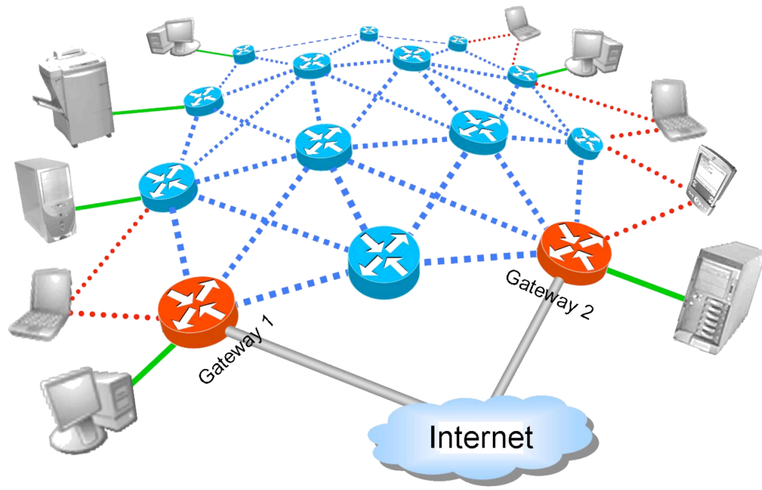
Gateways

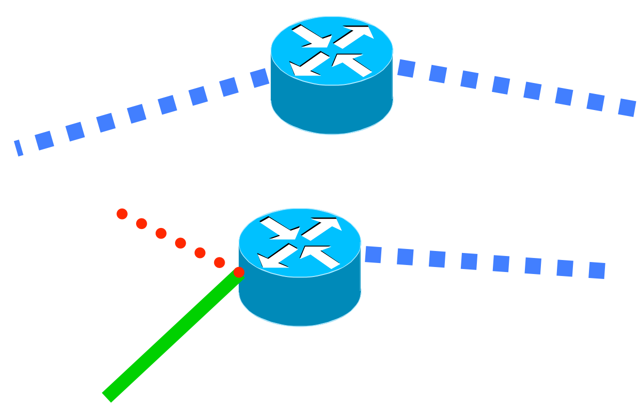
- Multiple interfaces (wired & wireless)
- Mobility
  - Stationary (e.g. rooftop) – most common case
  - Mobile (e.g., airplane, busses/subway)
- Serve as (multi-hop) "access points" to user nodes
- Relatively few are needed, (can be expensive)



Wireless Routers

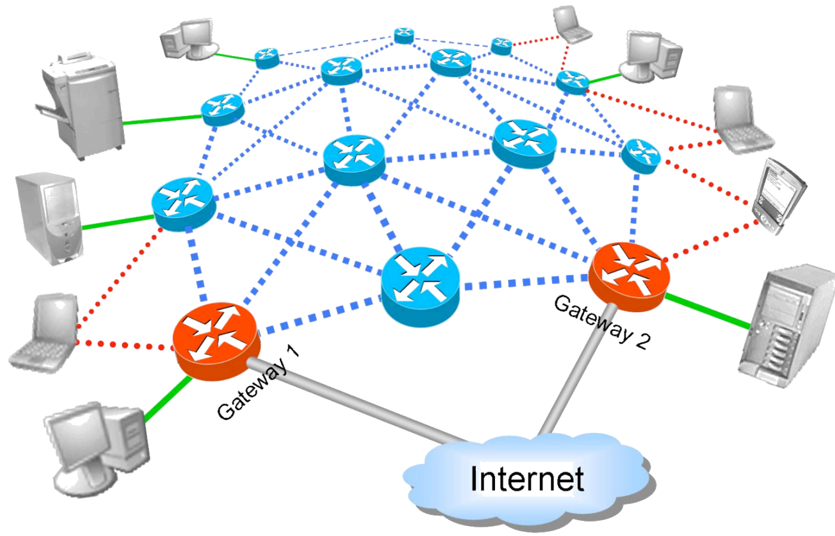
- At least one wireless interface.
- Mobility
  - Stationary (e.g. rooftop)
  - Mobile (e.g., airplane, busses/subway).
- Provide coverage (acts as a mini-cell-tower).
- Do not originate/terminate data flows
- Many needed for wide areas, hence, cost can be an issue.





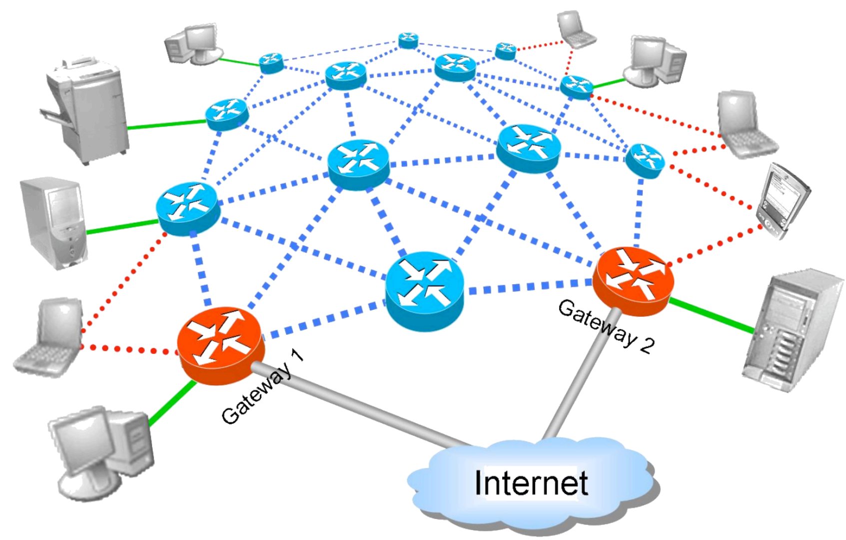
Users

- Typically one interface.
- Mobility
  - Stationary
  - Mobile
- Connected to the mesh network through wireless routers (or directly to gateways)
- The only sources/destinations for data traffic flows in the network.



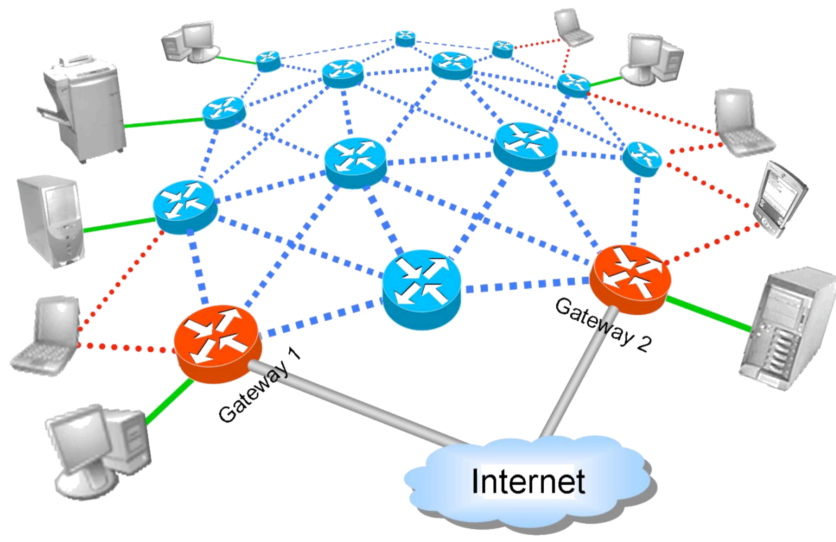
User – Wireless Router Links

- Wired
  - Bus (PCI, PCMCIA, USB)
  - Ethernet, Firewire, etc.
- Wireless
  - 802.11x
  - Bluetooth
  - Proprietary
- Point-to-Point or Point-to-Multipoint
- If properly designed is not a bottleneck.
- If different from router-to-router links we'll call them access links



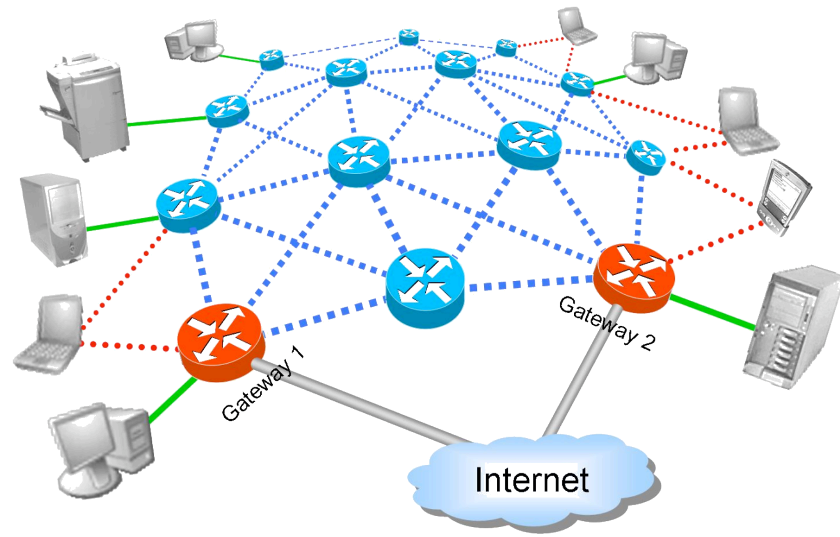
Router to Router Links

- Wireless
  - 802.11x
  - Proprietary
- Usually multipoint to multipoint
  - Sometimes a collection of point to point
- Often the bottleneck
- If different from router-to-user links we'll call them backbone links



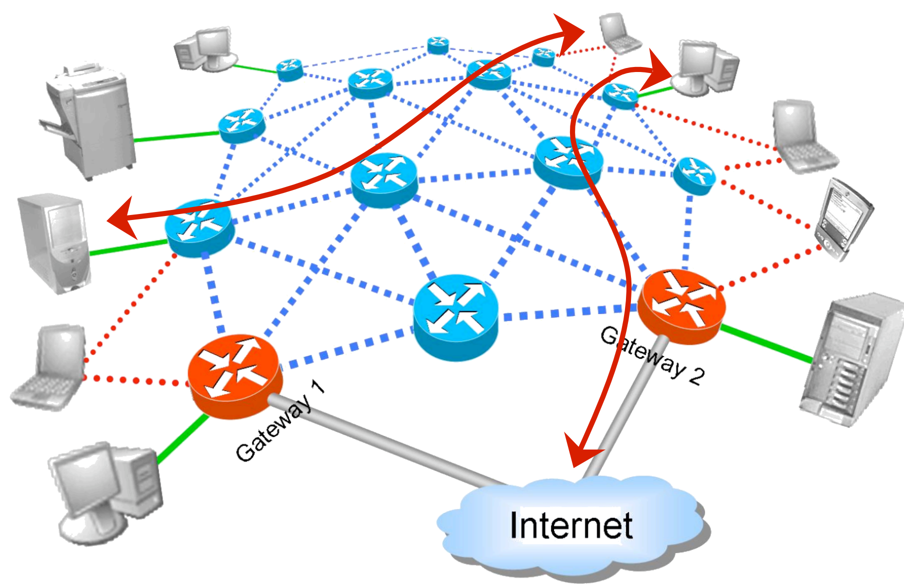
Gateway to Internet Links

- Wired
  - Ethernet, TV Cable, Power Lines
- Wireless
  - 802.16
  - Proprietary
- Point to Point or Point-to-Multipoint
- We'll call them backhaul links
- If properly designed, not the bottleneck

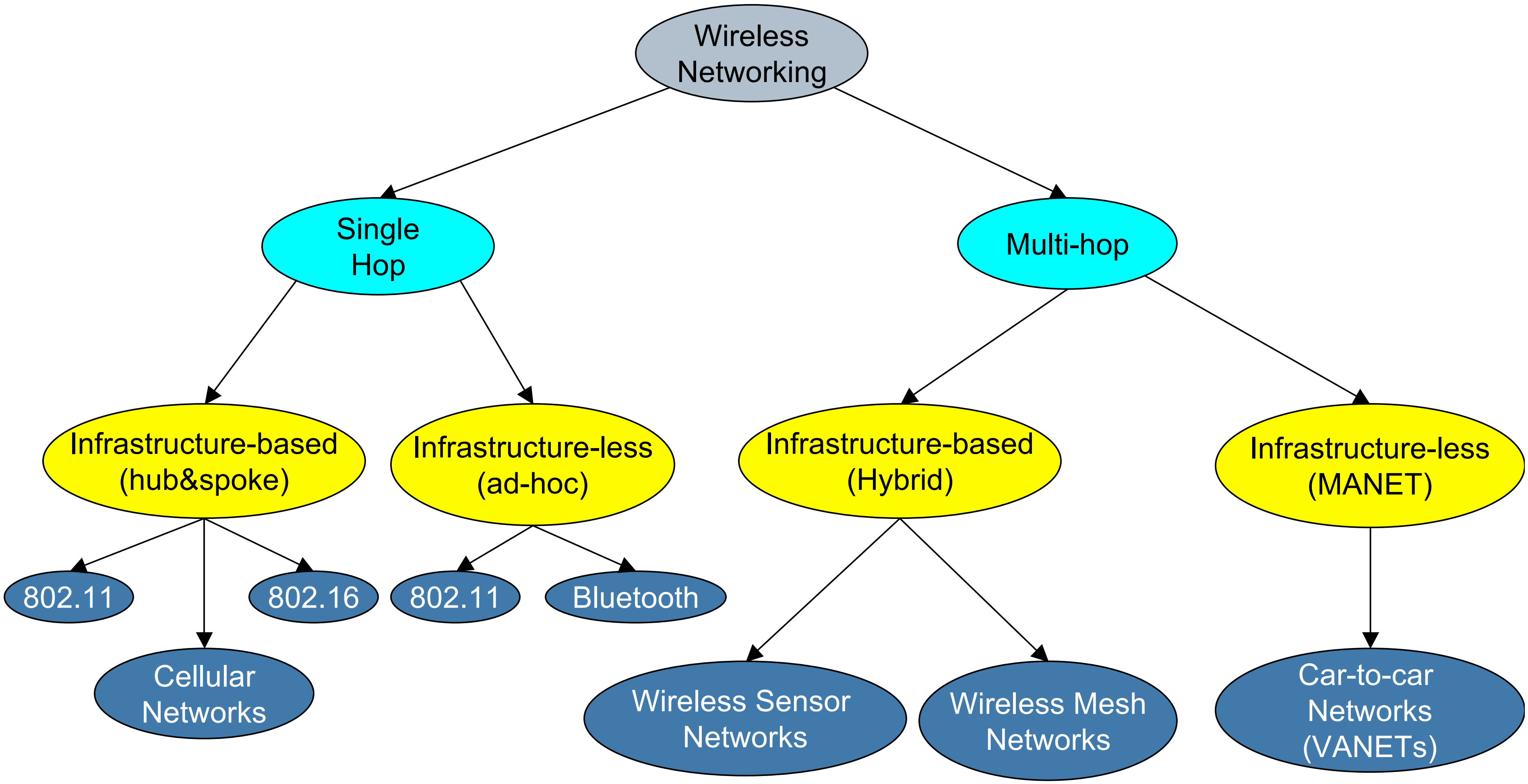


How it Works

- User-Internet Data Flows
  - In most applications the main data flows
- User-User Data Flows
  - In most applications a small percentage of data flows



Taxonomy


Wireless Networking
Single Hop
Multi-hop
Infrastructure-based (hub&spoke)
Infrastructure-less (ad-hoc)
Infrastructure-based (Hybrid)
Infrastructure-less (MANET)
802.11
802.16
Cellular Networks
802.11
Bluetooth
Wireless Sensor Networks
Wireless Mesh Networks
Car-to-car Networks (VANETs)

Mesh vs. Ad-Hoc Networks

Ad-Hoc Networks

- Multihop
- Nodes are wireless, possibly mobile
- May rely on infrastructure
- Most traffic is user-to-user

Wireless Mesh Networks

- Multihop
- Nodes are wireless, some mobile, some fixed
- It relies on infrastructure
- Most traffic is user-to-gateway

Mesh vs. Sensor Networks

Wireless Sensor Networks

- Bandwidth is limited (tens of kbps)
- In most applications, fixed nodes
- Energy efficiency is an issue
- Resource constrained
- Most traffic is user-to-gateway

Wireless Mesh Networks

- Bandwidth is generous (>1Mbps)
- Some nodes mobile, some fixed
- Normally not energy limited
- Resources are not an issue
- Most traffic is user-to-gateway

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  - Comparison with existing technologies
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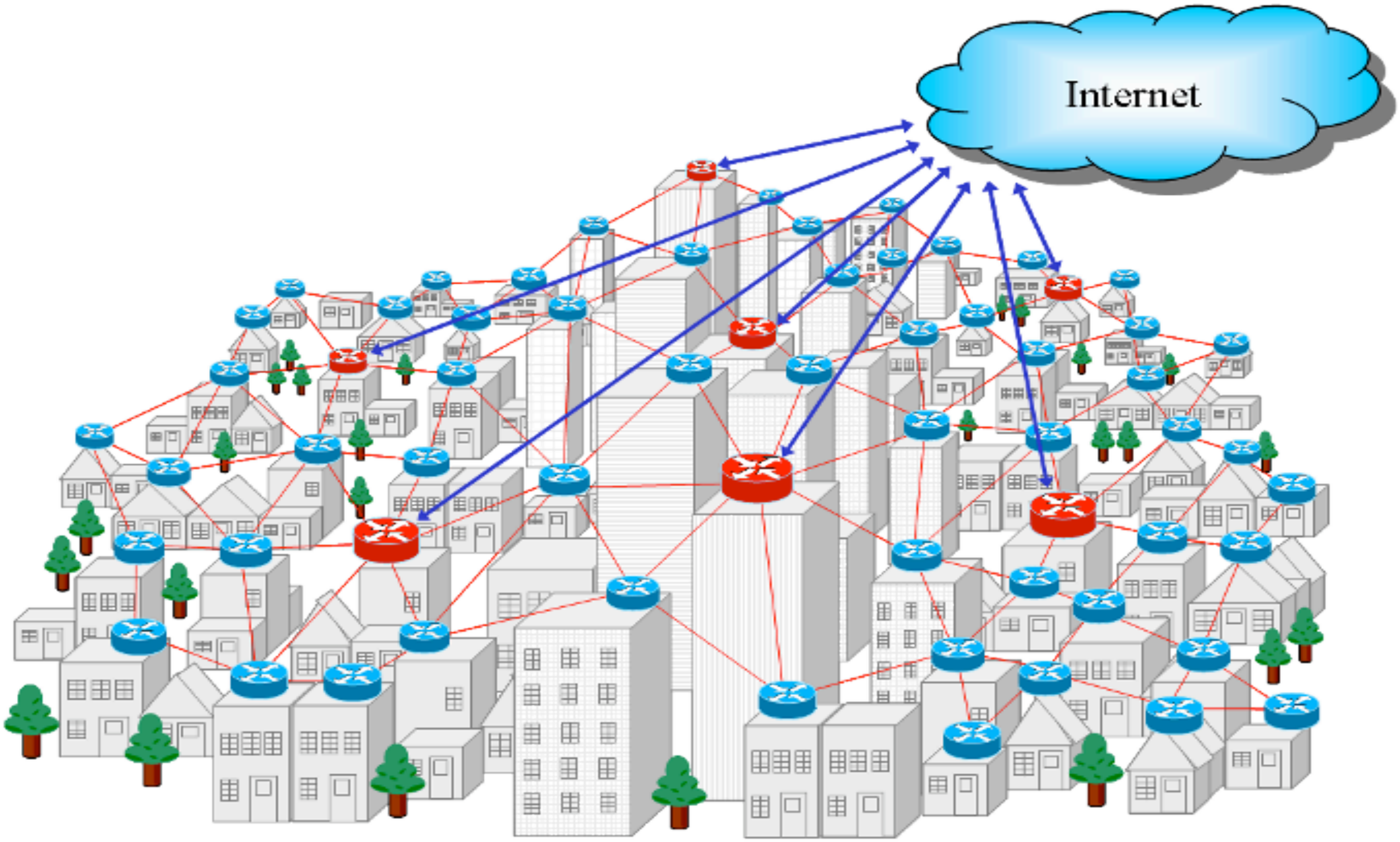
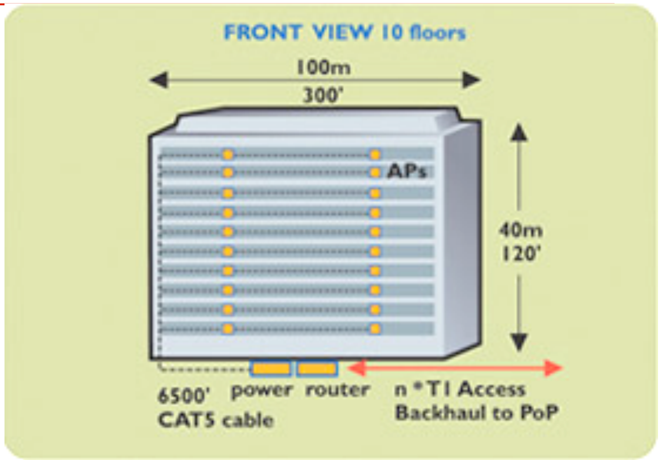
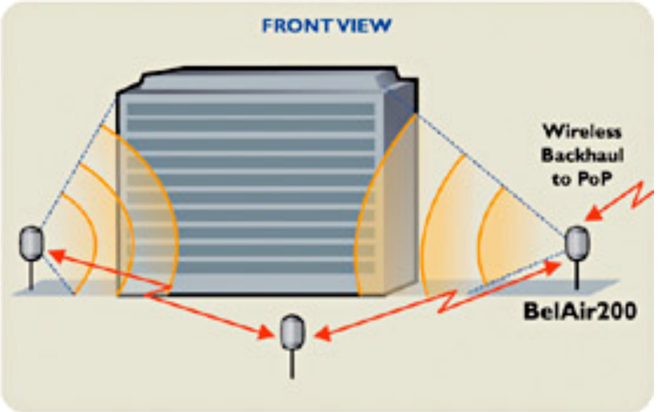
Broadband Internet Access



Extend WLAN Coverage

Source: www.meshdynamics.com





Source: www.belair.com

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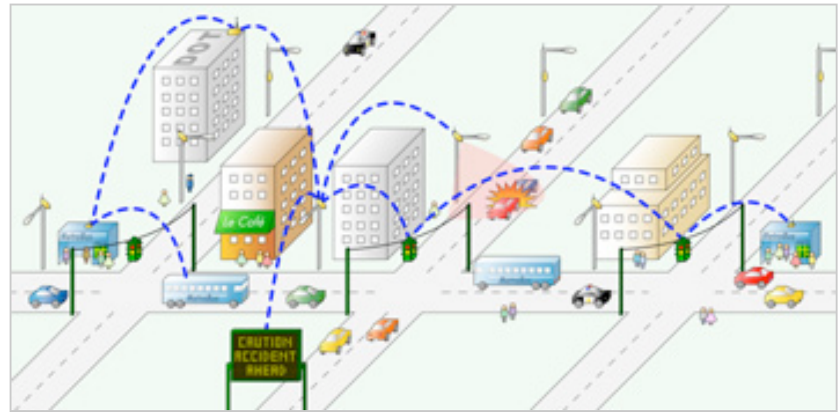
Mobile Internet Access

- Direct competition with G2.5 and G3 cellular systems.

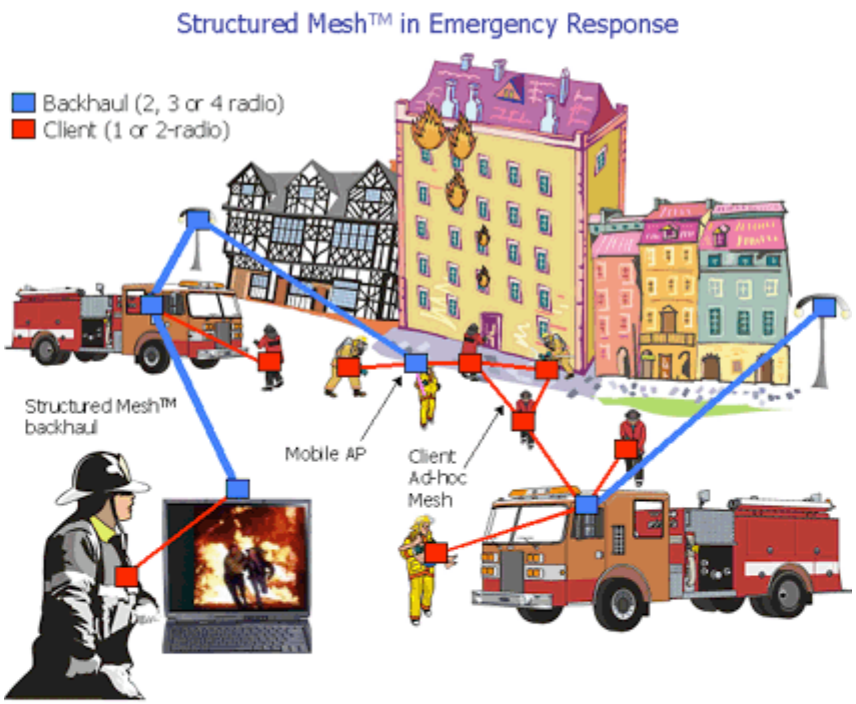


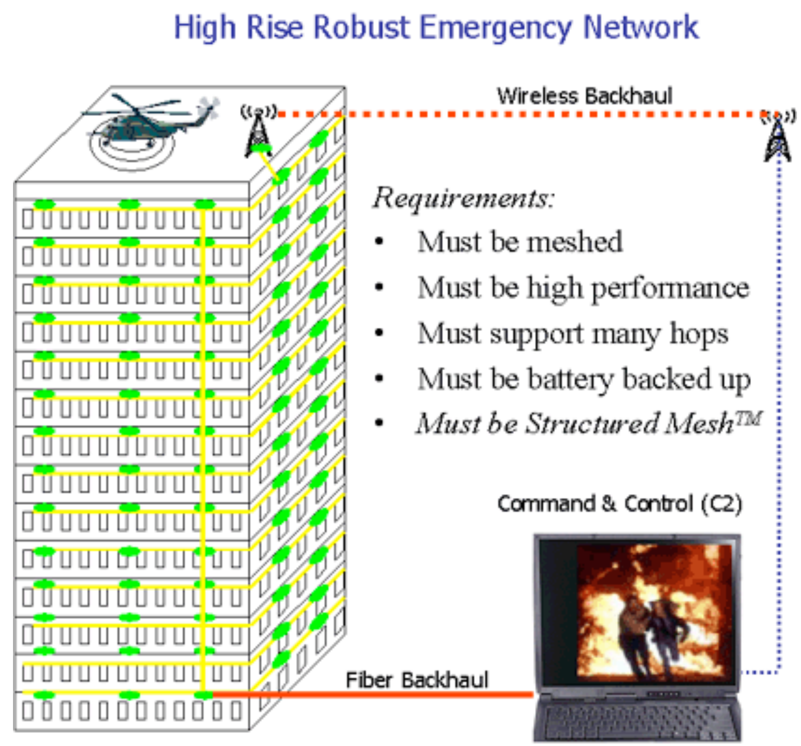
Law enforcement

Intelligent transportation

Source: www.meshnetworks.com (now www.motorola.com).

Emergency Response

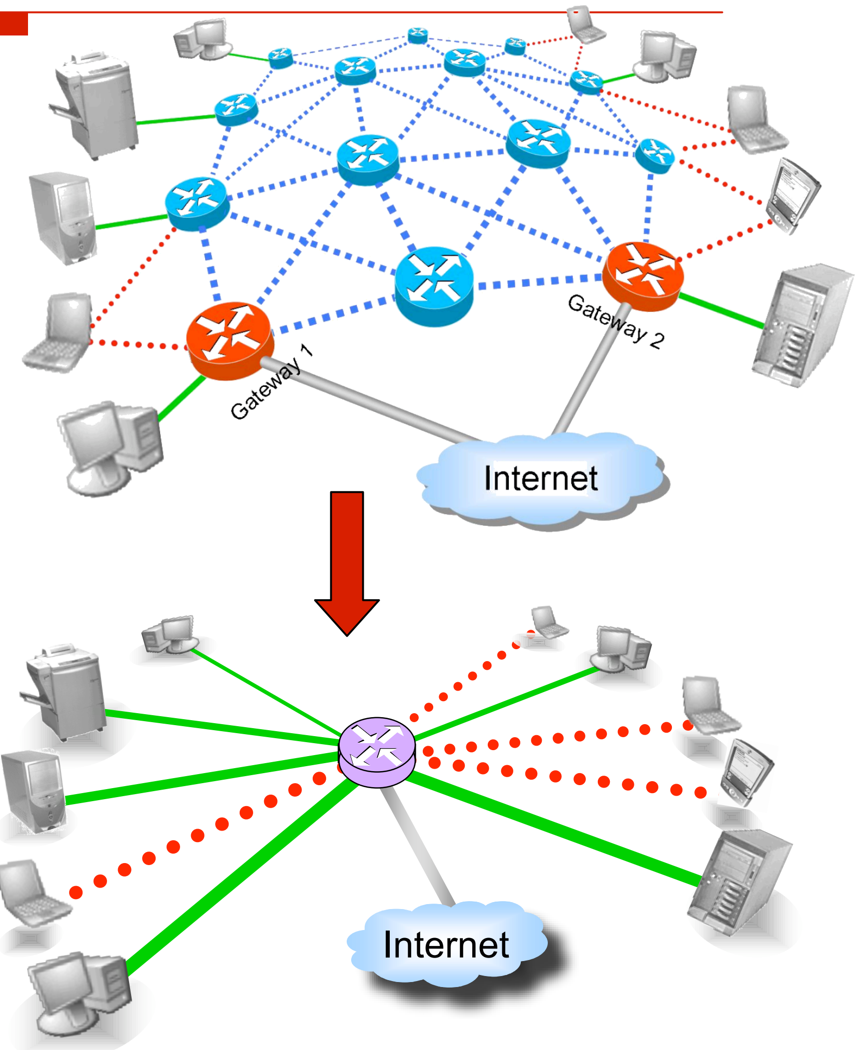




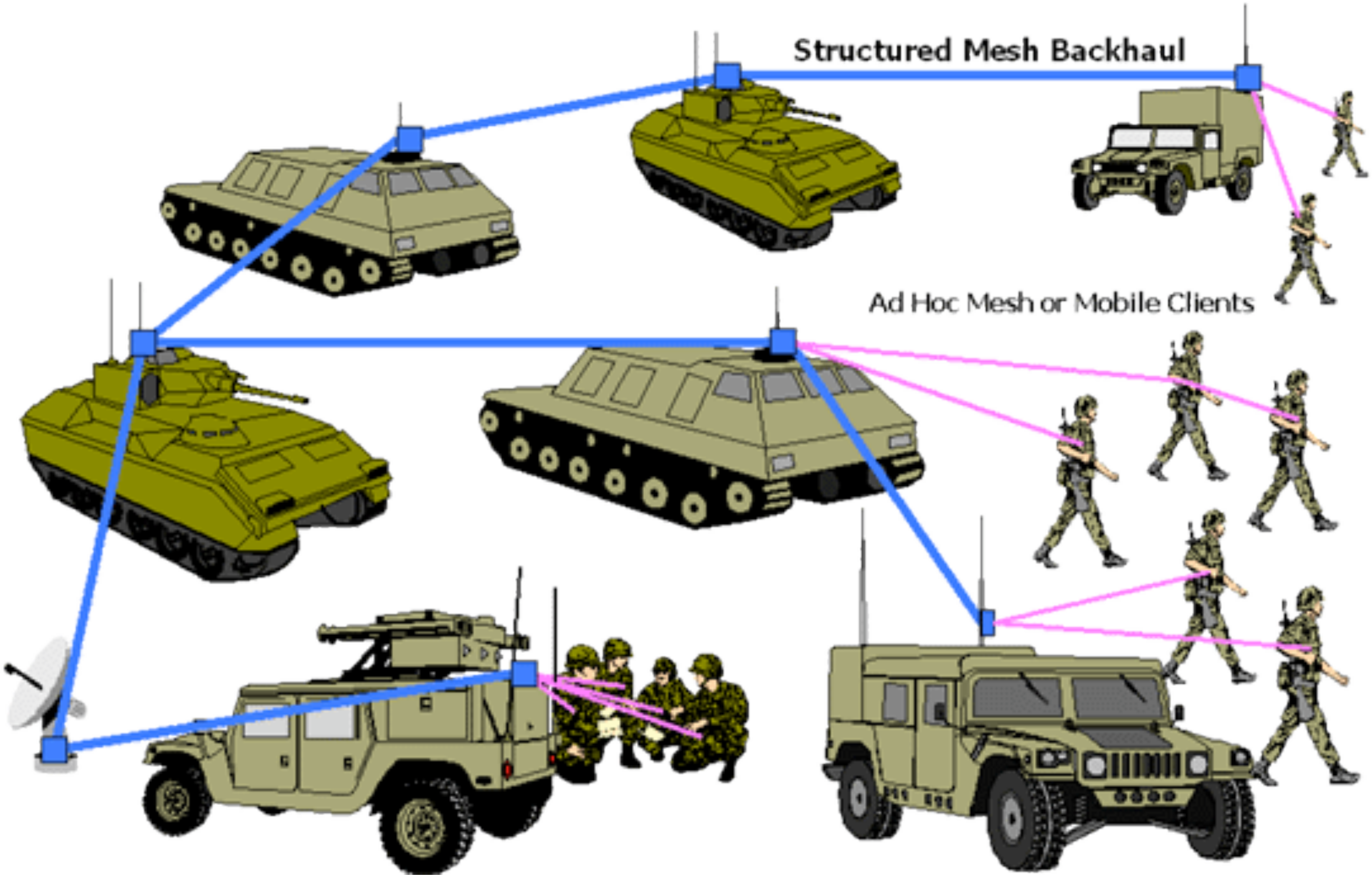
Source: www.meshdynamics.com

Layer 2 Connectivity

- The entire wireless mesh cloud becomes one (giant) Ethernet switch
- Simple, fast installation
  - Short-term events (e.g., conferences, conventions, shows)
  - Where wires are not desired (e.g., hotels, airports)
  - Where wires are impossible (e.g., historic buildings)



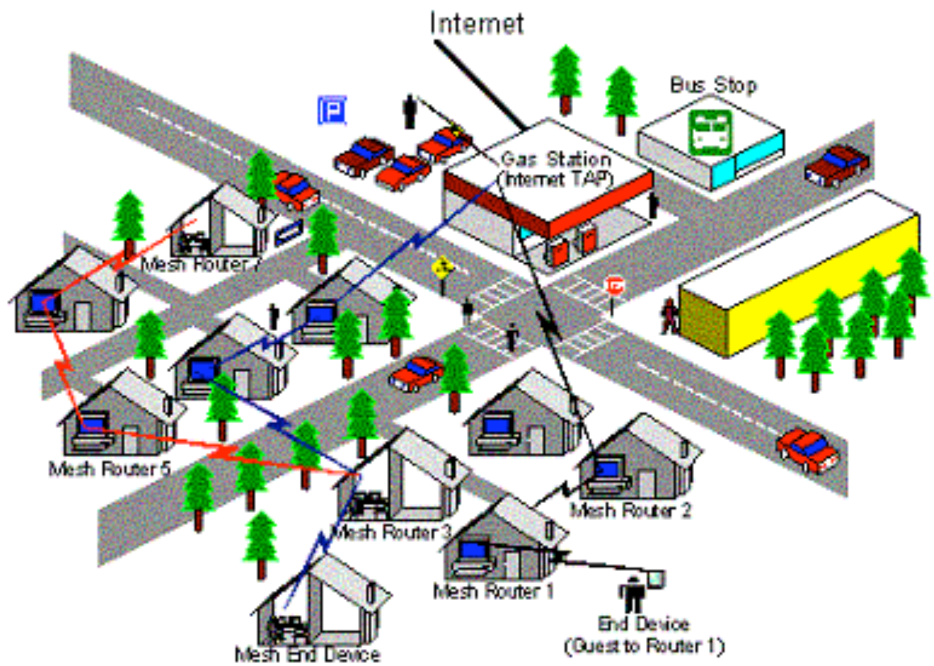
Military Communications



Source: www.meshdynamics.com

Community Networks

- Grass-roots broadband Internet Access
- Several neighbors may share their broadband connections with many other neighbors
- Not run by ISPs
- Possibly in the disadvantage of the ISPs



Source: research.microsoft.com/mesh/

Many Other Applications

- Remote monitoring and control
- Public transportation Internet access
- Multimedia home networking

Source: www.meshnetworks.com

(now www.motorola.com).

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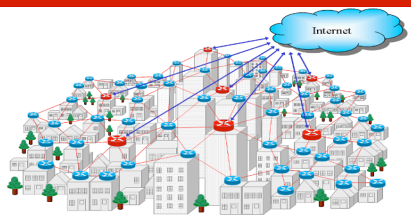
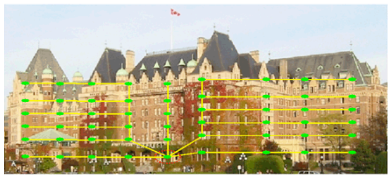
Broadband Internet Access

	Cable DSL	WMAN (802.16)	Cellular (2.5-3G)	WMN
Bandwidth	Very Good	Very Good	Limited	Good
Upfront Investments	Very High	High	High	Low
Total Investments	Very High	High	High	Moderate
Market Coverage	Good	Modest	Good	Good

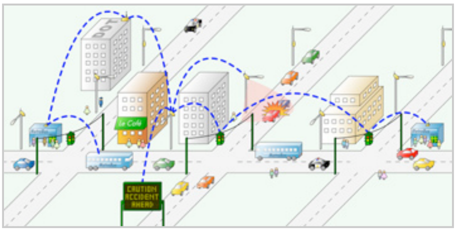
WLAN Coverage

Hotel HotZone with MeshDynamics All Wireless Switch Stacks



Source: www.meshdynamics.com	802.11	WMN
Wiring Costs	High	Low
Bandwidth	Very Good	Good
Number of APs	As needed	Twice as many
Cost of APs	Low	High

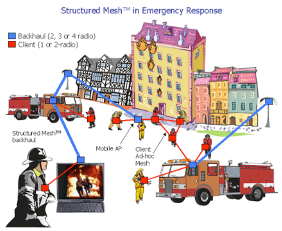
Mobile Internet Access



Source: www.meshnetworks.com
(now www.motorola.com).

	Cellular 2.5 – 3G	WMN
Upfront Investments	High	Low
Bandwidth	Limited	Good
Geolocation	Limited	Good
Upgrade Cost	High	Low

Emergency Response

 Source: www.meshdynamics.com	Cellular 2.5 – 3G	Walkie Talkie	WMN
Availability	Reasonable	Good	Good
Bandwidth	Limited	Poor	Good
Geolocation	Poor	Poor	Limited

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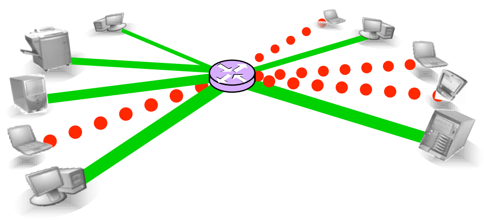
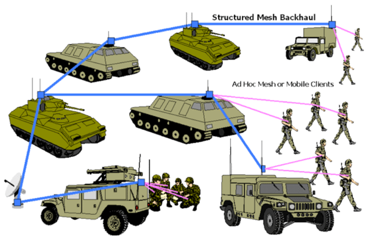
Layer 2 Connectivity

	Ethernet	WMN
Speed/Ease of Deployment	Slow/Difficult	Fast/Easy
Bandwidth	Very Good	Good
Mobile Users	802.11 needed	Good
Total Cost	Low	Moderate

Military Communications



Source: www.meshdynamics.com

	Existing System(s)	WMNs
Coverage	Very Good	Good
Bandwidth	Poor	Good
Voice Support	Very Good	Good
Covertness	Poor	Better
Power efficiency	Reasonable	Good

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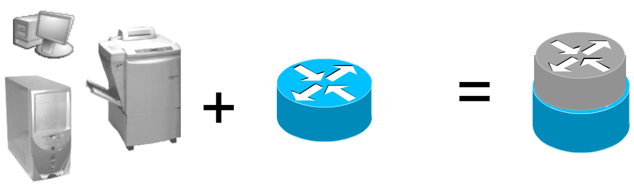
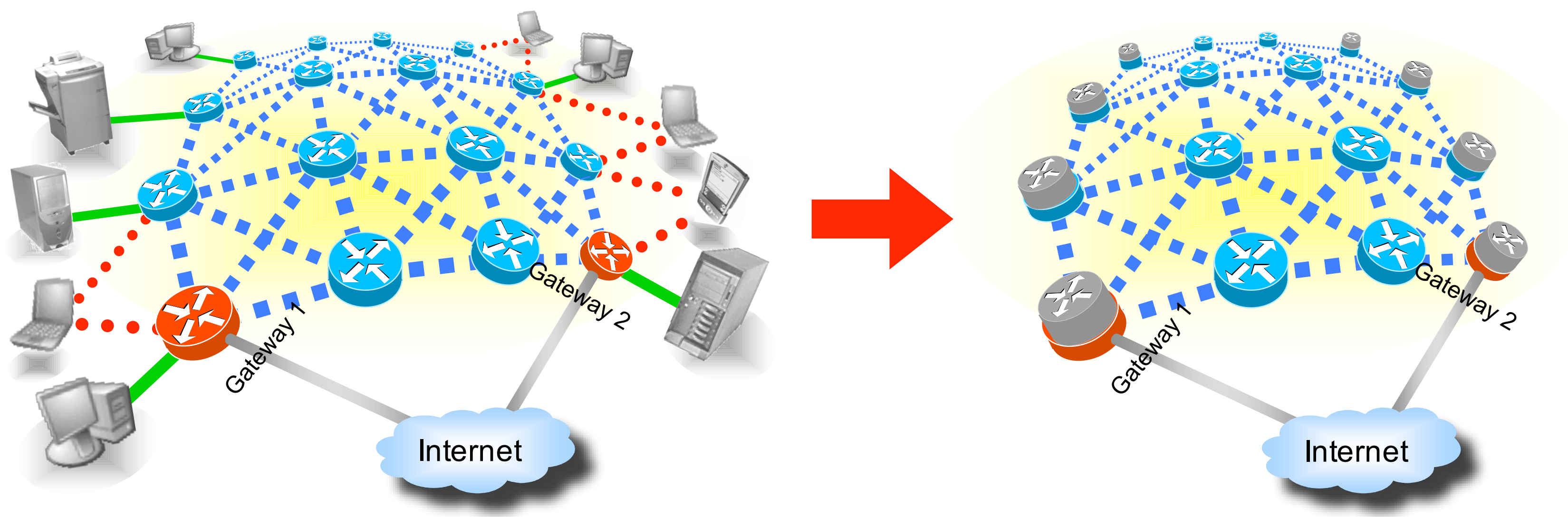
Abstraction

- Users + routers = nodes
- Nodes have two functions:
  - Generate/terminate traffic
  - Route traffic for other nodes





Overview of Research Topics

- Physical Layer
  - Smart Antennas
  - Transmission Power Control
- MAC Layer
  - Multiple Channels
- Network Layer
  - Routing
  - Fairness and QoS
- Transport Layer
- Provisioning
- Security
- Network Management
- Geo-location

Physical Layer (PHY) Wish list

- Performance
  - Bandwidth
  - Robust modulation
  - Sensitivity
  - Short preamble
  - Fast switch between channels
  - Fast switch from Tx/Rx and back
- Extras
  - Mobility (potentially high-speed)
  - Link adaptation
  - Variable transmission power (details shortly)
  - Multiple channels
  - Link quality feedback

PHY - Modulation

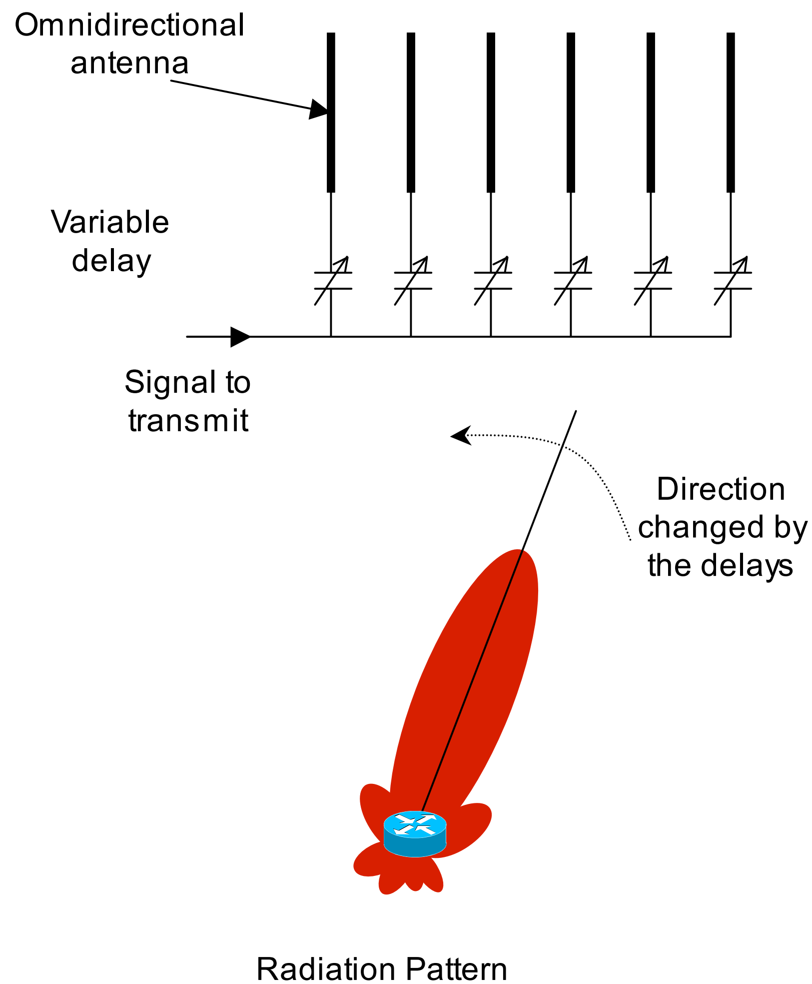
- Existing modulations work well (OFDM, DSSS, FSK, etc.).
- UWB may be an interesting alternative for short distances
- Spread spectrum solutions are preferred as they tend to have better reliability in the face of
  - Fading (very important for mobile applications)
  - Interference (more of a factor than in any other wireless system)

PHY- Licensed vs. Unlicensed Spectrum

	Licensed Spectrum	Unlicensed Spectrum
Cost	Expensive	Free
Controllable medium (i.e., no interference)	Yes	No
Limits on Transmitted Power	Some	Lots

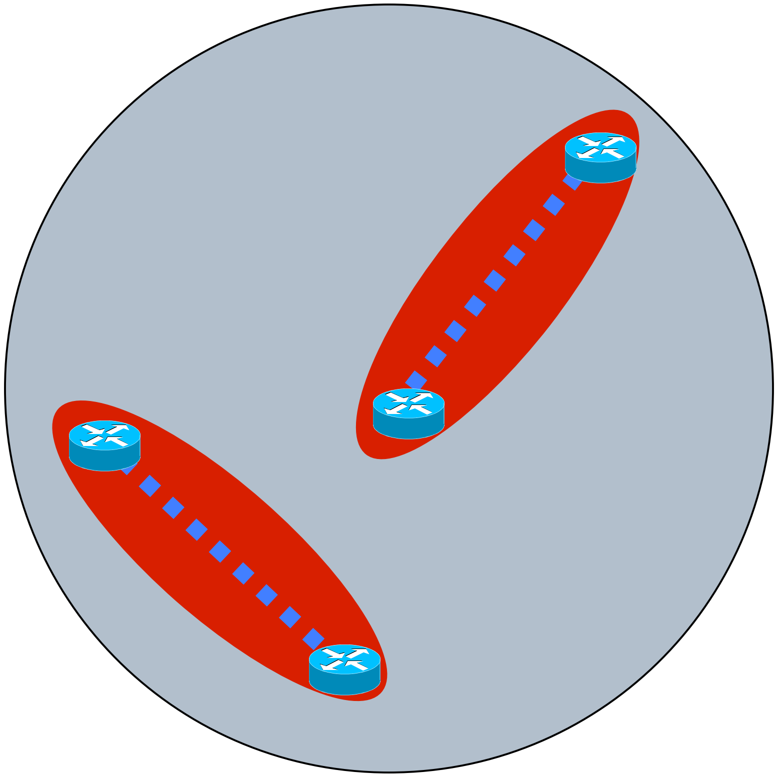
PHY – Smart Antennas

- Background
  - Implemented as an array of omnidirectional antennas
  - By changing the phase, beamforming can be achieved
  - The result is a software steered directional antenna



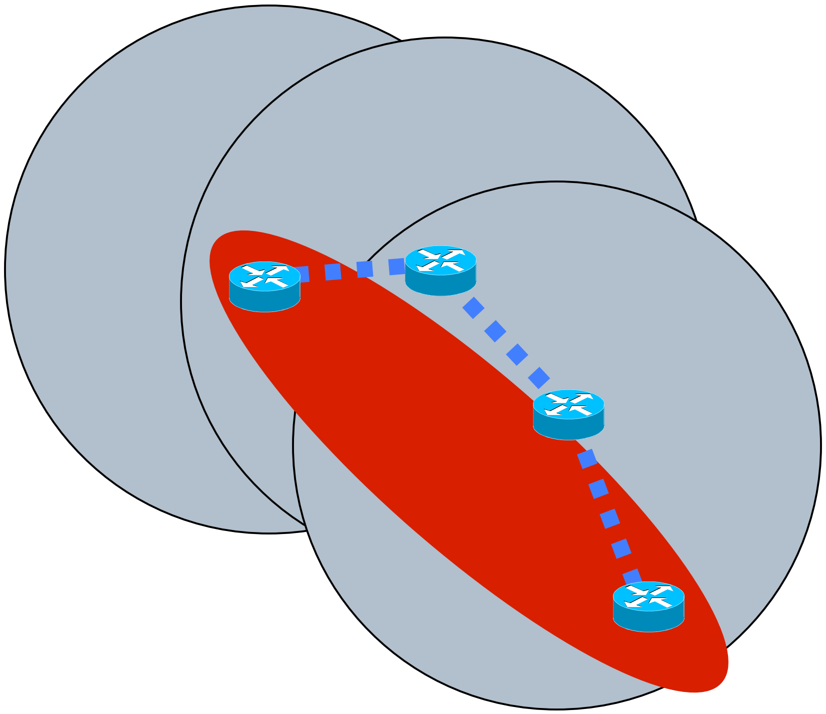
PHY-Smart Antennas Advantages

- Low power transmissions
  - Battery not a big concern in many applications
  - Enables better spatial reuse and, hence, increased network capacity



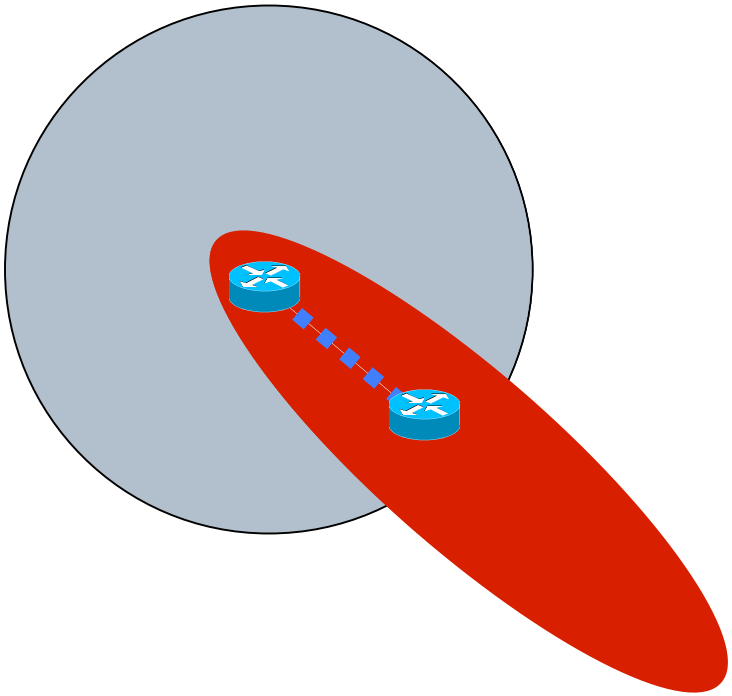
PHY-Smart Antennas Advantages (cont)

- Punch-through links
  - Better delays (?)
  - Less packet loss (?)
  - Better data rates (?)
  - Less power (?)



PHY-Smart Antennas Advantages (cont)

- Better SNR
  - Better data rates
  - Better delays
  - Better error rates



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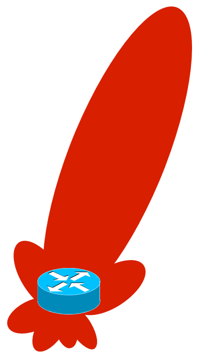
PHY-Smart Antennas Disadvantages

- Specialized hardware
- Specialized MAC (difficult to design)
- Difficult to track mobile data users



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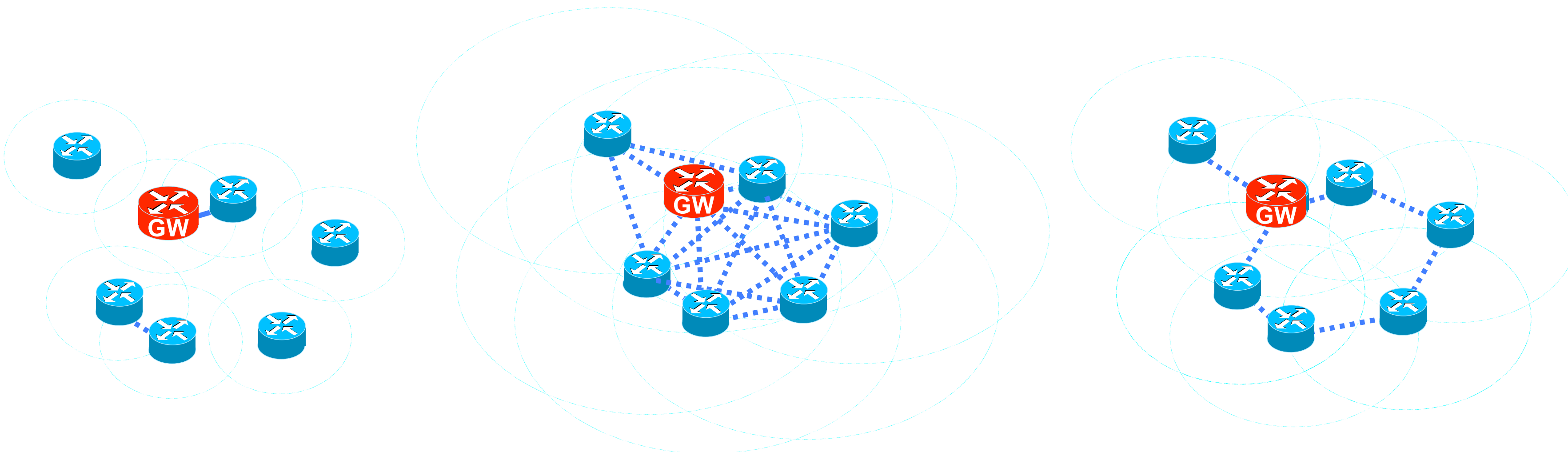
PHY – Transmission Power Control



Too low Too high Just right

PHY – Transmission Power Control (cont)

- Optimization Criteria
  - Network capacity
  - Delay
  - Error rates
  - Power consumption
- The ideal solution will depend on
  - Network topology
  - Traffic load

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- Security
- Network Management
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Medium Access Control (MAC)

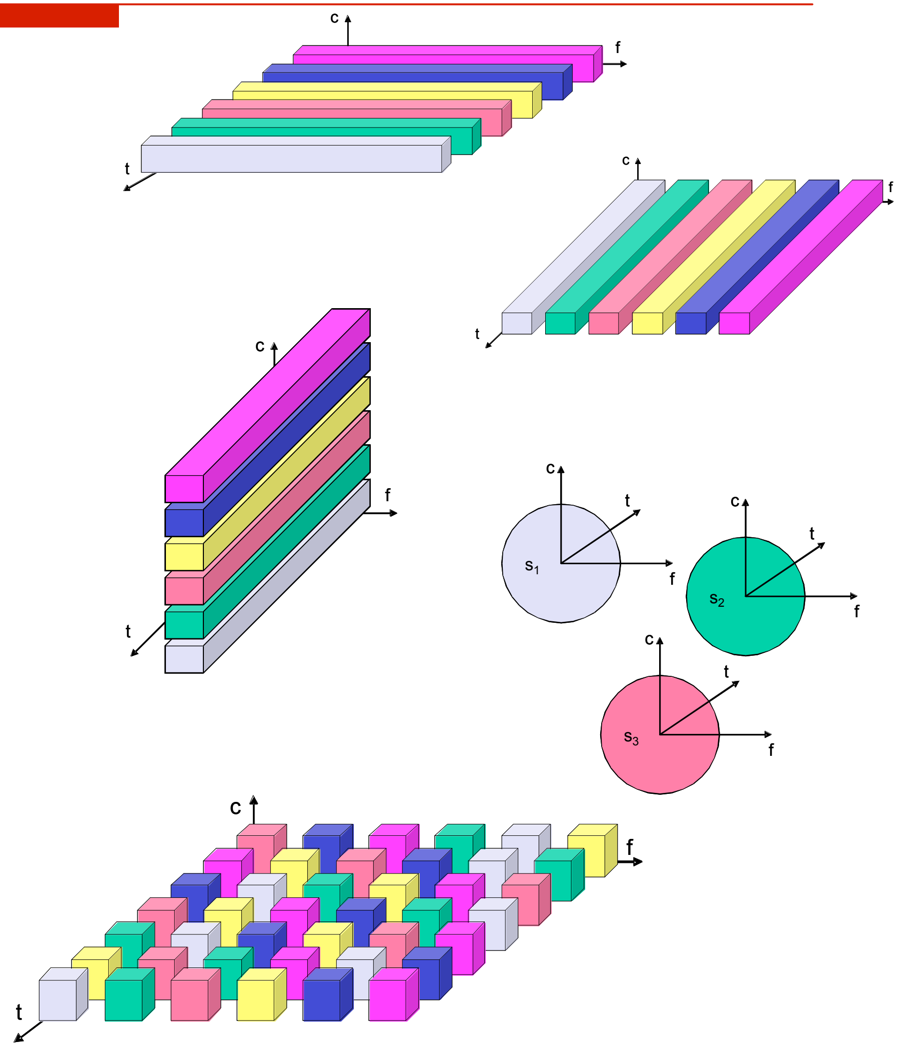
- Scheduled
  - Fix scheduled TDMA
  - Polling
  - Impractical due to lack of:
    - Central coordination point
    - Reasonable time synchronization
- Random Access
  - CSMA – simple and popular
  - RTS/CTS – protects the receiver

802.11 Compatibility

	Proprietary MAC	802.11 Compatible
Flexible PHY/MAC	Yes	No
Ease of upgrade	Hard	Easy
Force clients to buy custom cards	Yes/Yes	No/No

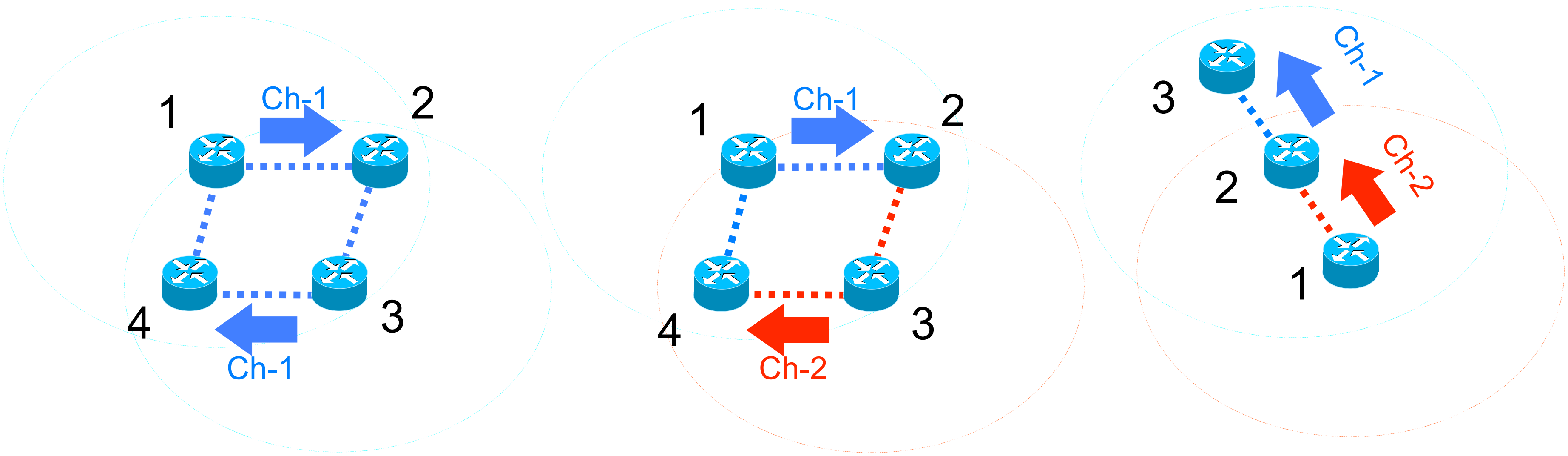
MAC – Multichannel What?

- Channels can be implemented by:
  - TDMA (difficult due to lack of synchronization)
  - FDMA
  - CDMA (code assignment is an issue)
  - SDMA (with directional antennas)
  - Combinations of the above



MAC – Multichannel
Why?

- Increases network capacity



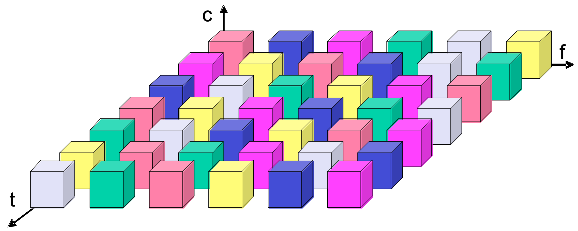
User bandwidth = B/2

User bandwidth = B

Chain bandwidth = B

B = bandwidth of a channel

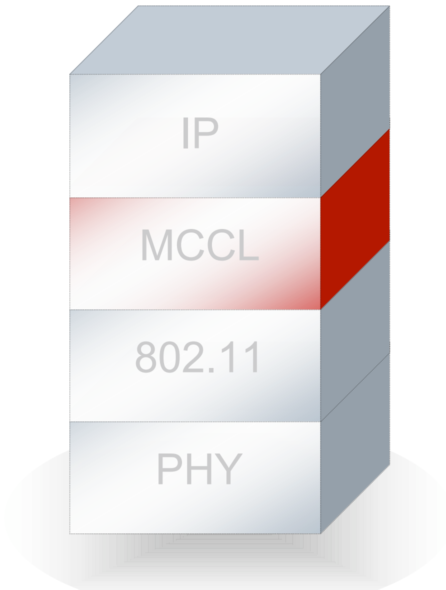
MAC – Multichannel
How?

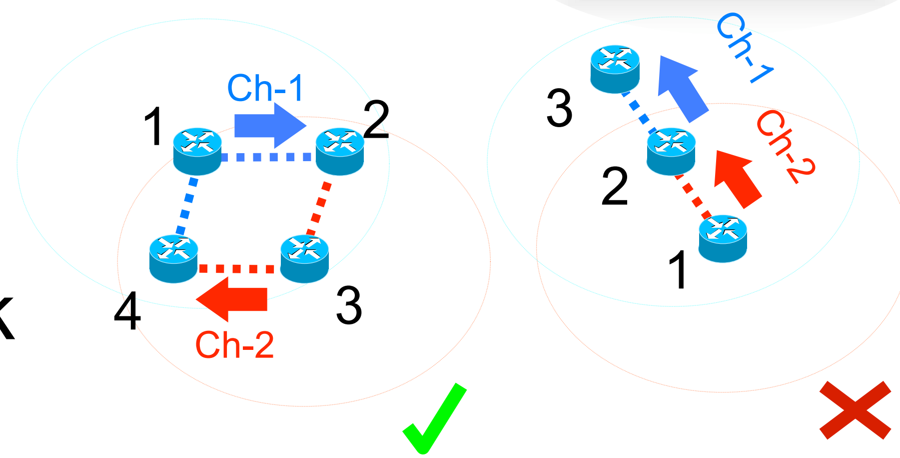


	Standard MAC (e.g.,802.11)	Custom MAC
Single Radio	X	X
Multiple Radios	X	X

MAC – Multichannel
Standard MAC – Single Radio

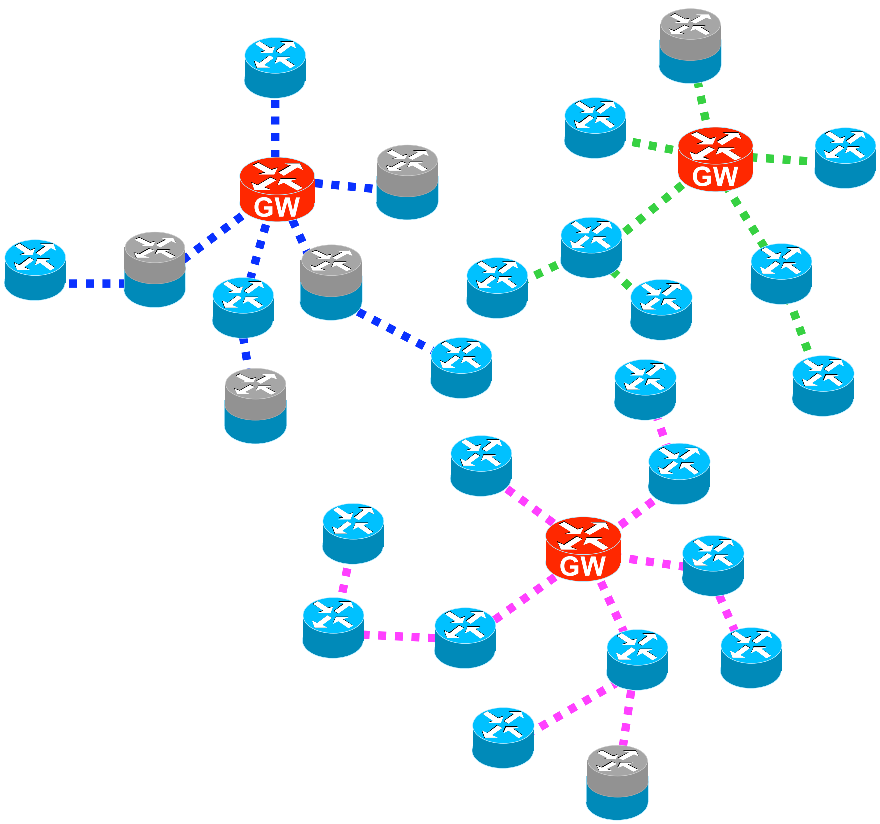
- Can it be done at all?
- Perhaps, if a new Multi-Channel Coordination Layer (MCCL) is introduced between MAC and Network
- Must work within the constraints of 802.11
- May increase the capacity of the network



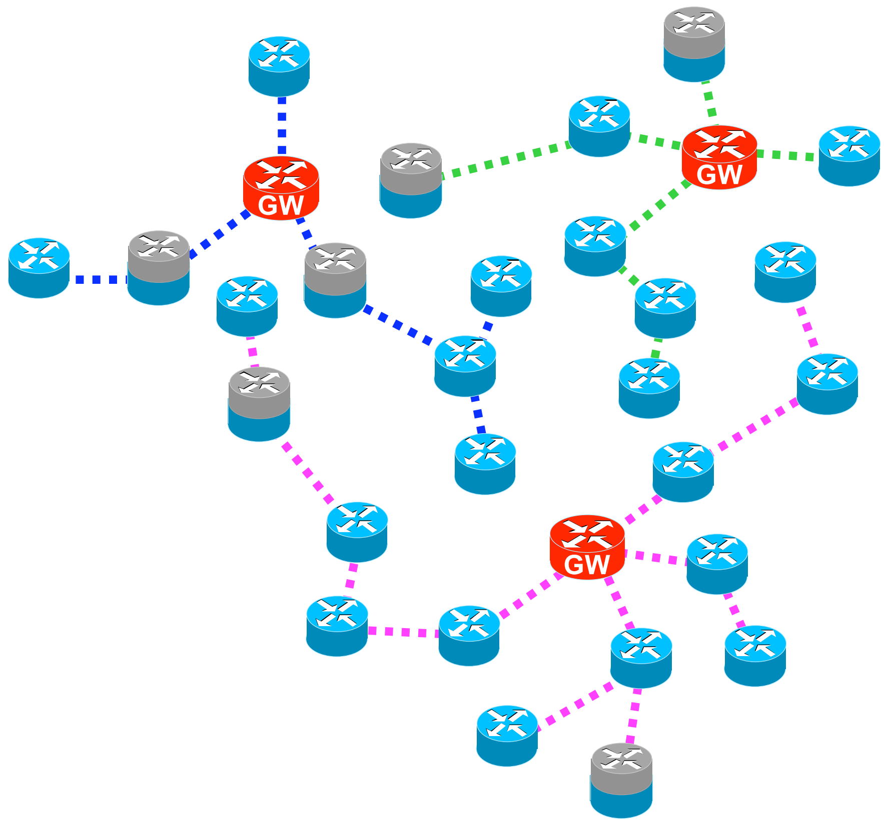


MAC – Multichannel
Standard MAC – Single Radio (cont)

- Channel assignment



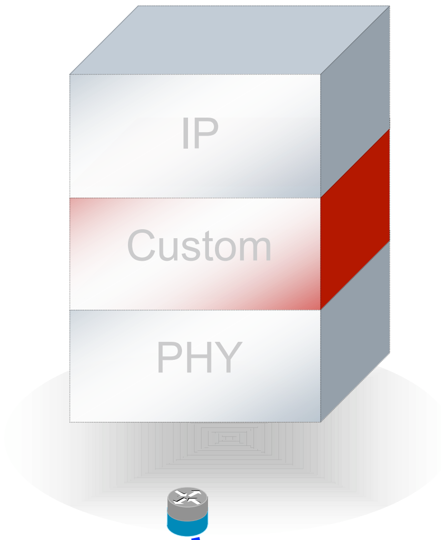
Gateway Loads = 4 : 1 : 1

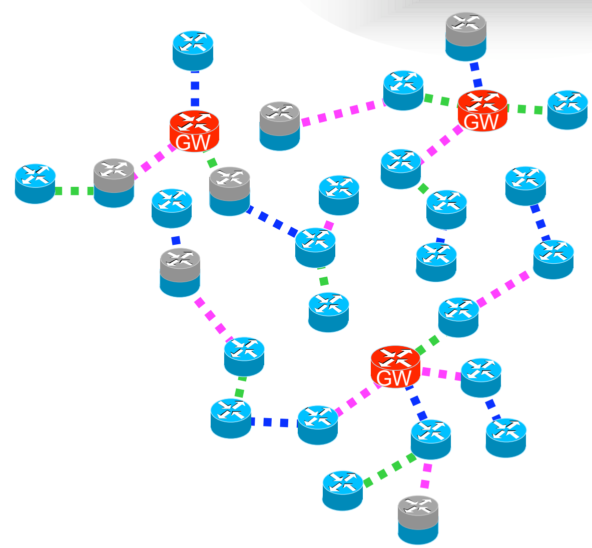


Gateway Loads = 2 : 2 : 2

MAC – Multichannel
Custom MAC – Single Radio

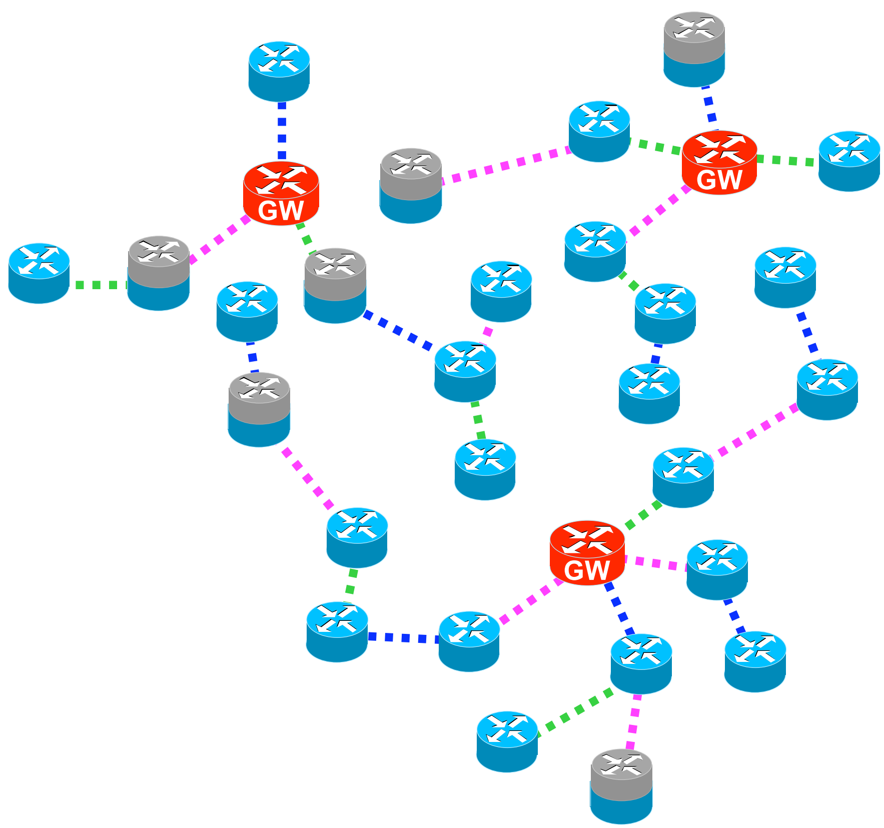
- Easier problem than before
- Common advantages and disadvantages associated with custom MACs
- May further increase the capacity of the network
- The problem of optimal channel assignment remains





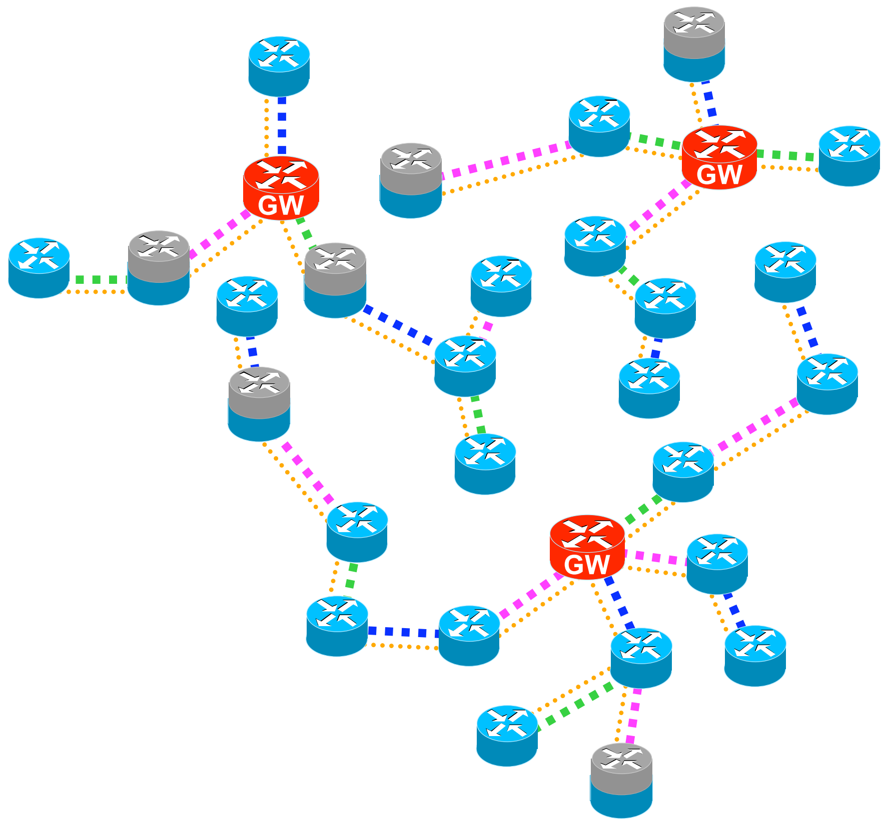
MAC – Multichannel Standard MAC – Multiple Radios

- A node now can receive while transmitting
- Practical problems with antennas separation (carrier sense from nearby channel)
- Optimal assignment – NP complete problem
- Solutions
  - Centralized
  - Distributed



MAC – Multichannel
Custom MAC – Multiple Radios

- Nodes can use a control channel to coordinate and the rest to exchange data.
- In some conditions can be very efficient.
- However the control channel can be:
  - an unacceptable overhead;
  - a bottleneck;



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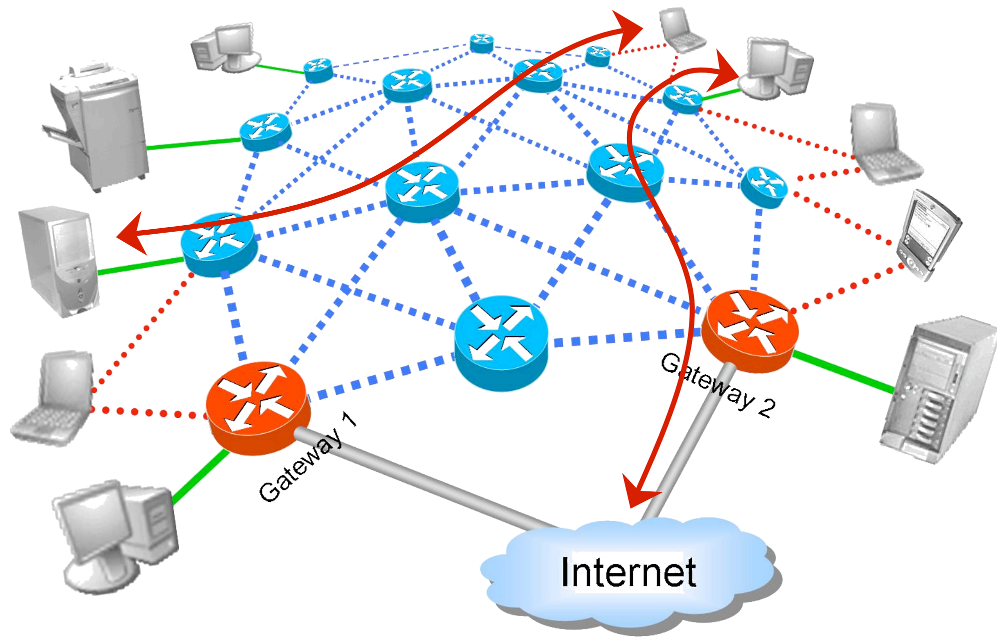
Routing

- Finds and maintains routes for data flows
- The entire performance of the WMN depends on the routing protocol
- May be the main product of a mesh company
- May be missing

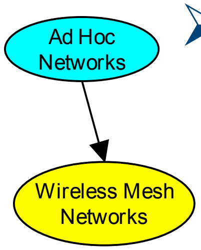


Routing – Wish List

- Scalability
  - Overhead is an issue in mobile WMNs.
- Fast route discovery and rediscovery
  - Essential for reliability.
- Mobile user support
  - Seamless and efficient handover
- Flexibility
  - Work with/without gateways, different topologies
- QoS Support
  - Consider routes satisfying specified criteria
- Multicast
  - Important for some applications (e.g., emergency response)

Existing Routing Protocols

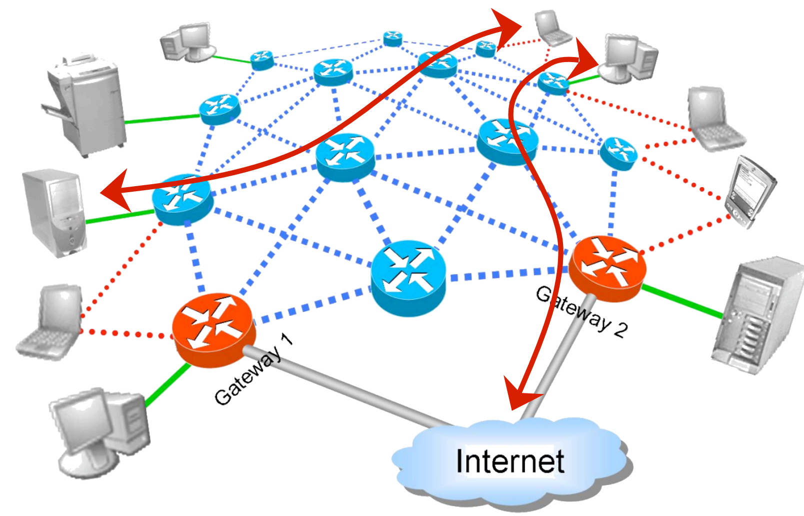
- Internet routing protocols (e.g., OSPF, BGP, RIPv2)
  - Well known and trusted
  - Designed on the assumption of seldom link changes
  - Without significant modifications are unsuitable for WMNs in particular or for ad hoc networks in general.



- Ad-hoc routing protocols (e.g., DSR, AODV, OLSR, TBRPF)
  - Newcomers by comparison with the Internet protocols
  - Designed for high rates of link changes; hence perform well on WMNs
  - May be further optimized to account for WMNs' particularities

Routing - Optimization Criteria

- Minimum Hops
- Minimum Delays
- Maximum Data Rates
- Minimum Error Rates
- Maximum Route Stability
- Minimum ETA
- Power Consumption
- Combinations of the above



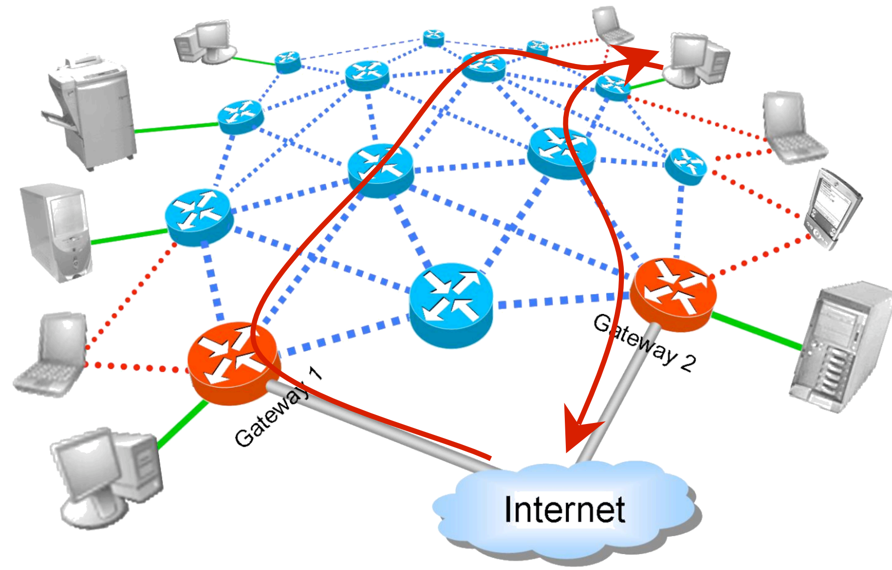
- Use of multiple routes to the same gateway
- Use of multiple gateways

Routing – Cross-Layer Design

- Routing – Physical
  - Link quality feedback is shown often to help in selecting stable, high bandwidth, low error rate routes.
  - Fading signal strength can signal a link about to fail → preemptive route requests.
  - Cross-layer design essential for systems with smart antennas.
- Routing – MAC
  - Feedback on link loads can avoid congested links → enables load balancing.
  - Channel assignment and routing depend on each other.
  - MAC detection of new neighbors and failed routes may significantly improve performance at routing layer.

Routing – Cross-Layer Design (cont)

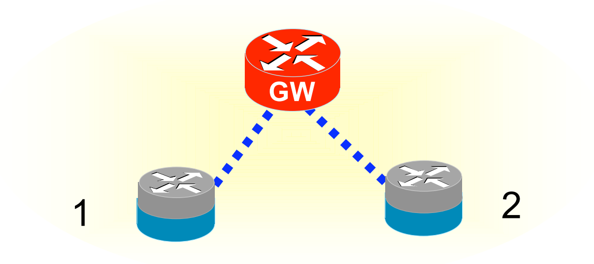
- Routing – Transport
  - Choosing routes with low error rates may improve TCP's throughput.
  - Especially important when multiple routes are used
  - Freezing TCP when a route fails.

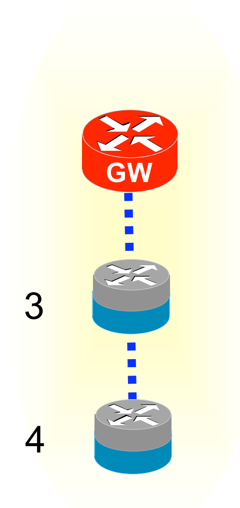


- Routing – Application
  - Especially with respect of satisfying QoS constraints

Network Layer - Fairness

- Fairness
  - Equal share of resources to all participants.
  - Special case of priority based QoS.
- Horizontal – nodes 1, 2
  - The MAC layer's fairness ensures horizontal fairness.
- Vertical – nodes 3, 4
  - MAC layer is no longer sufficient





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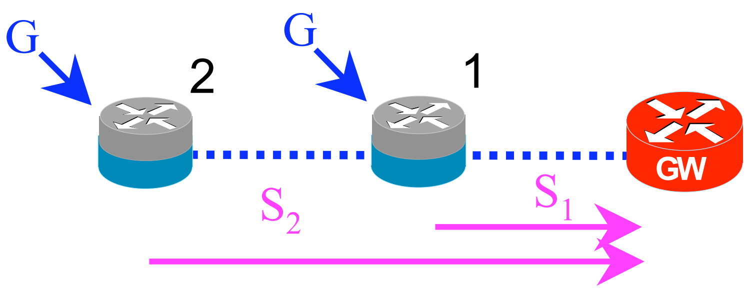
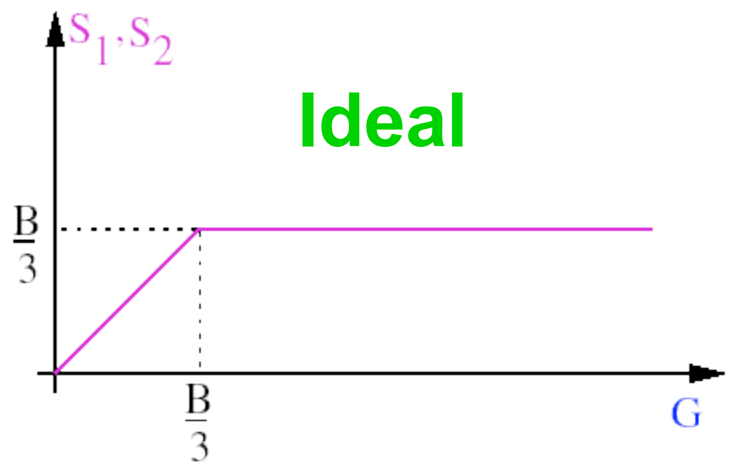
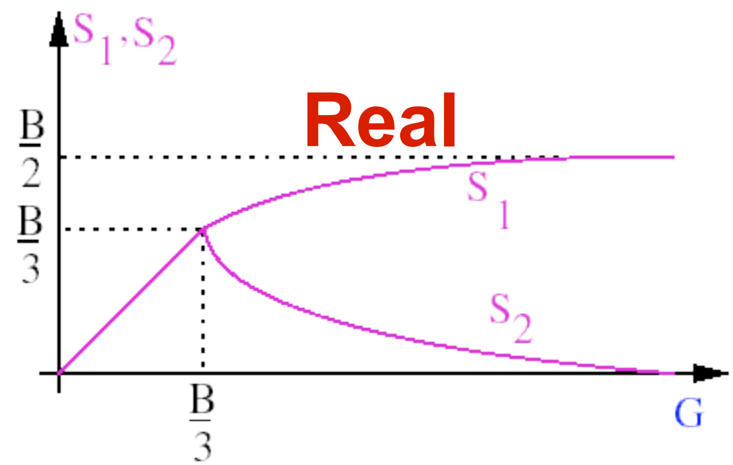
Fairness Problem



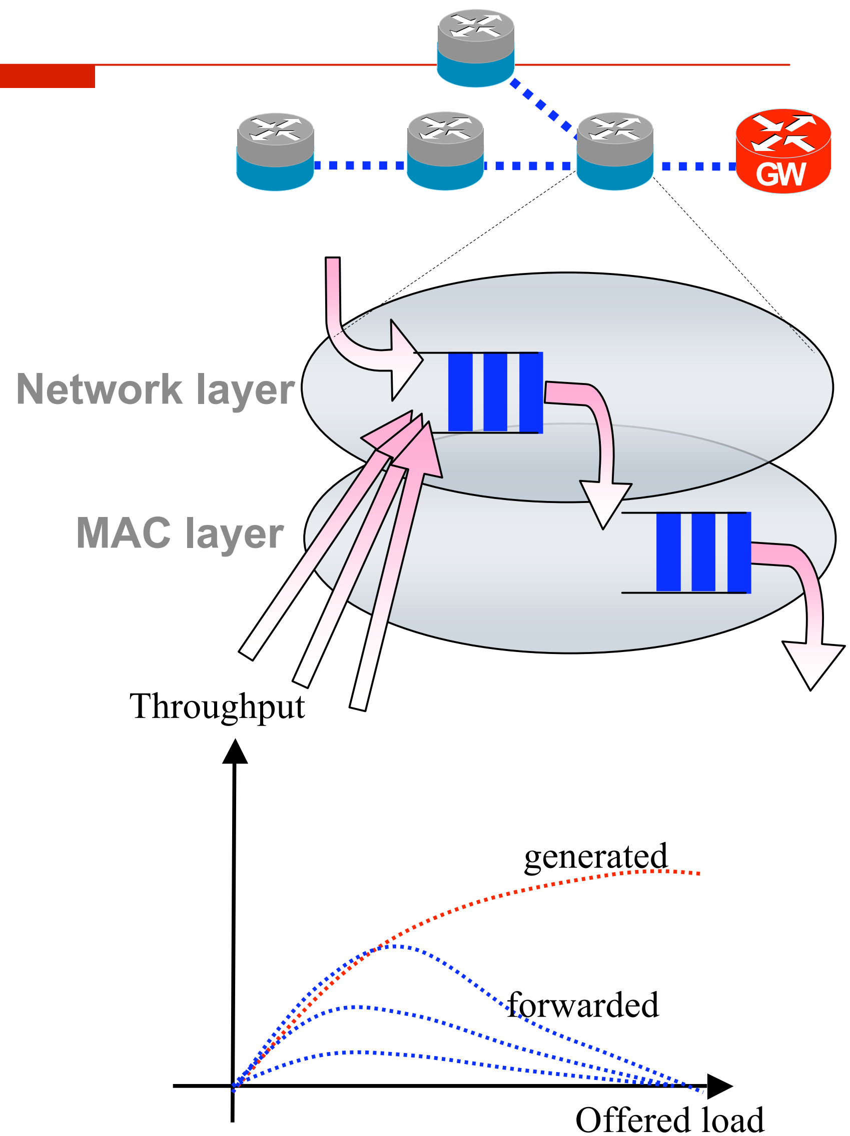
- Unfair
- Inefficient



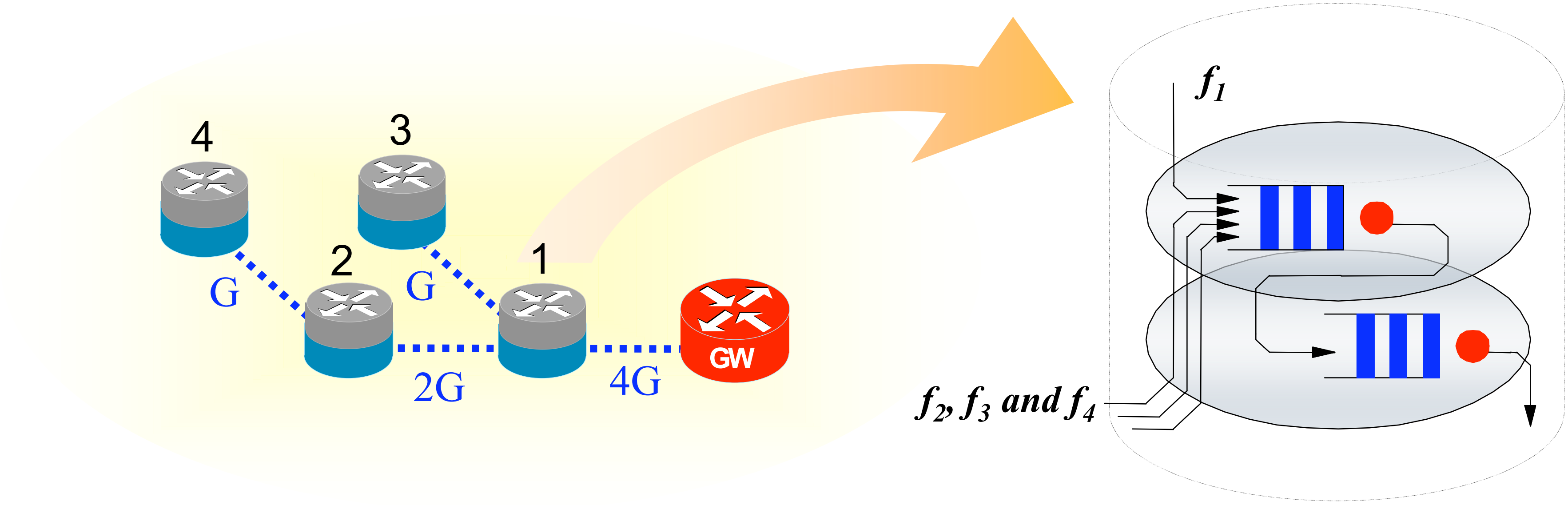


Network – Fairness Problem Source

- Conflict between locally generated traffic and forwarded traffic.
- At high loads the network layer queue fills up with local traffic and traffic to be forwarded arrives to a full queue.
- Consequence:
  - no fairness
  - poor efficiency
- Solutions:
  - Compute the fair share for each user and enforce it
  - Local information based solution presented next

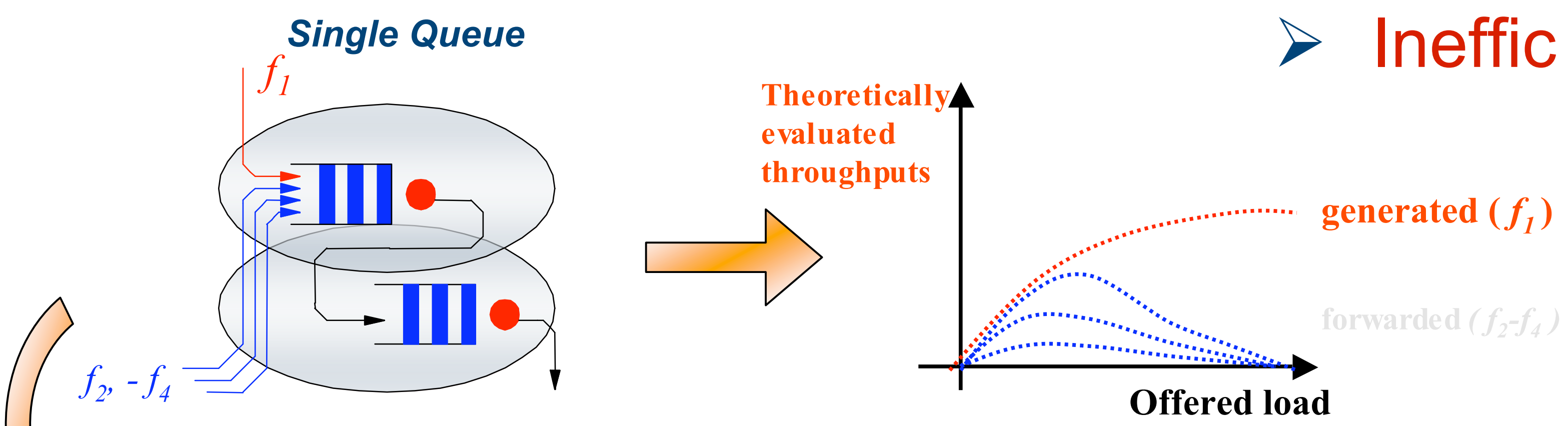


Fairness
Considered Topology and Node Model

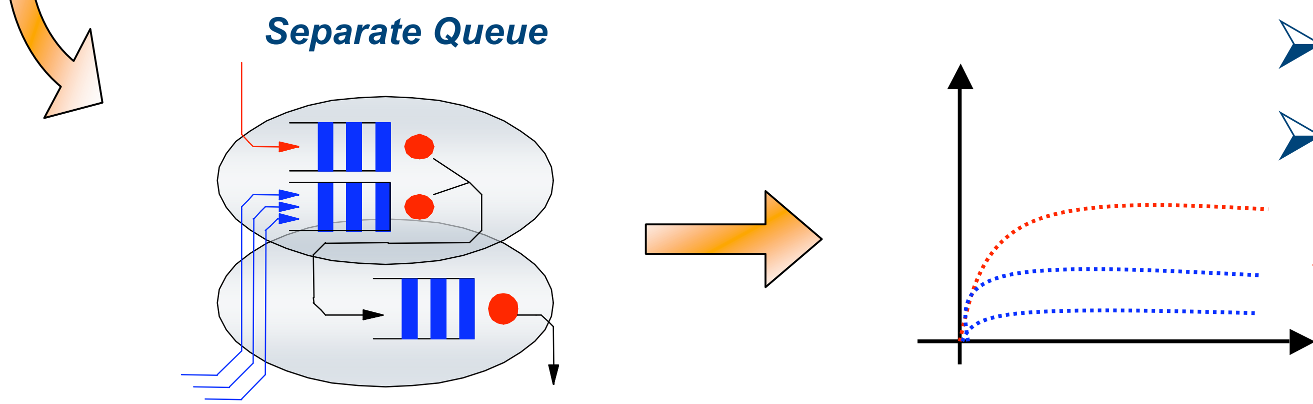


- Capacity of the network: G = B/8
- Assume unidirectional traffic for the clarity of explanation.

Fairness
Separate Queue for Local Traffic



- Unfair
- Inefficient



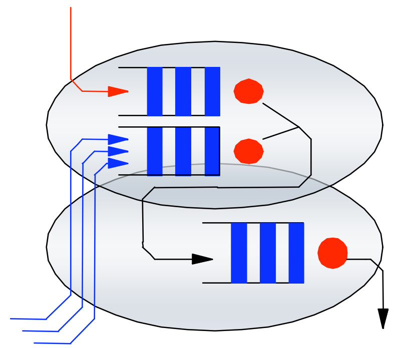
- Unfair
- Inefficient

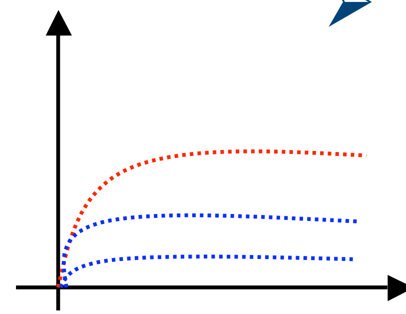
$f_1:f_2:f_3:f_4 = 4:1:2:1$

Fairness

Weighted Queue for Local Traffic

Separate Queue

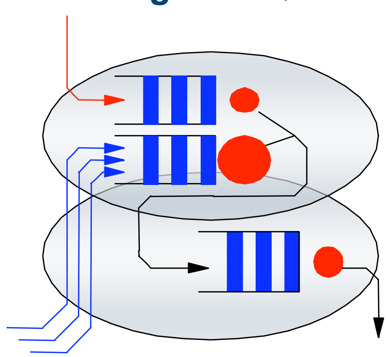


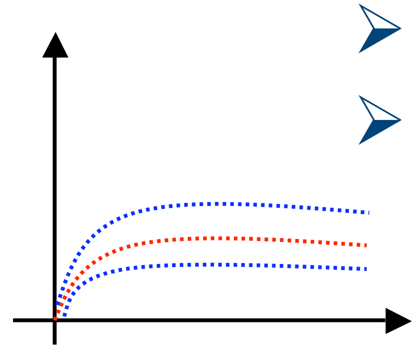


- Unfair
- Inefficient

$f_1:f_2:f_3:f_4 = 4:1:2:1$

Weighted Queue

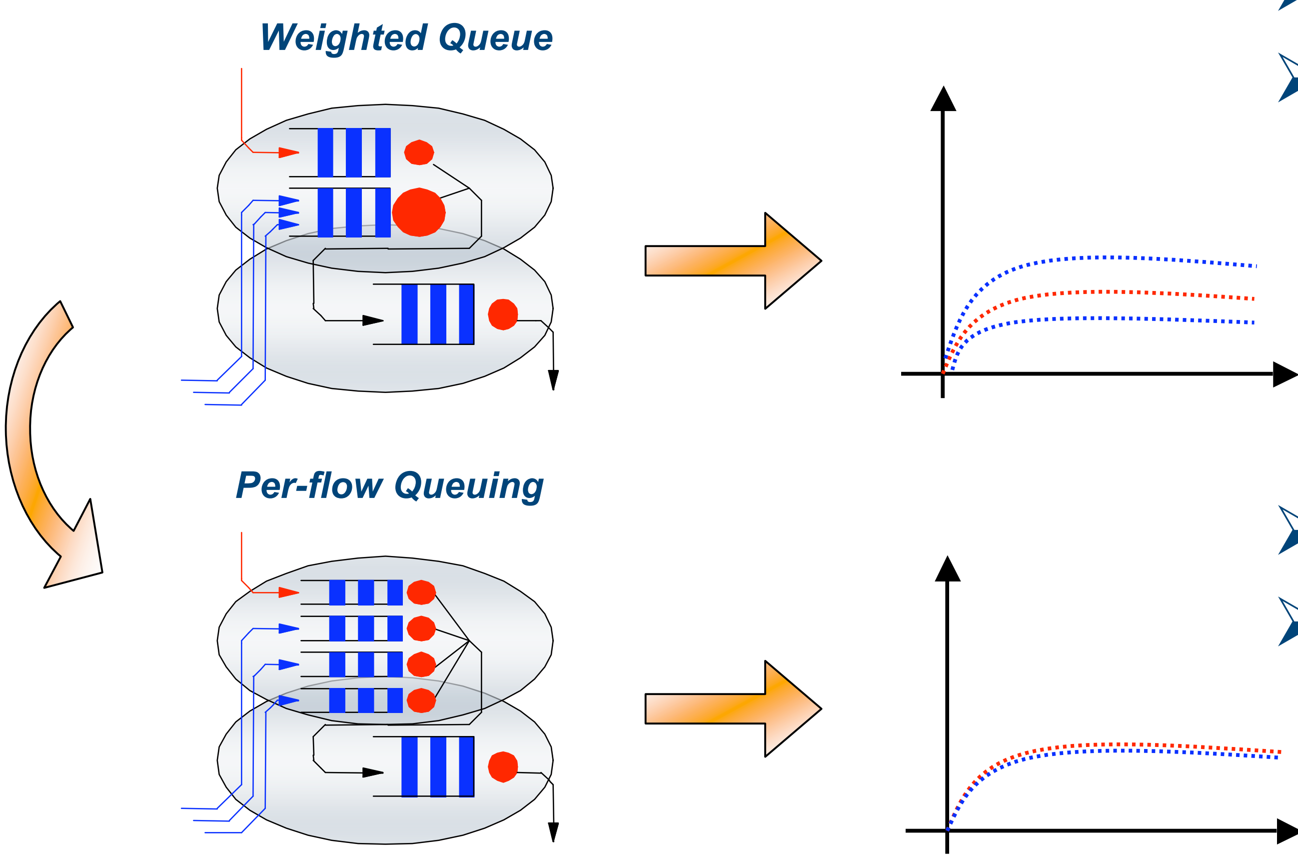




- Unfair
- Inefficient

$f_1:f_2:f_3:f_4 = 4:6:3:3$

Fairness
Per-flow Queueing



- Unfair
- Inefficient

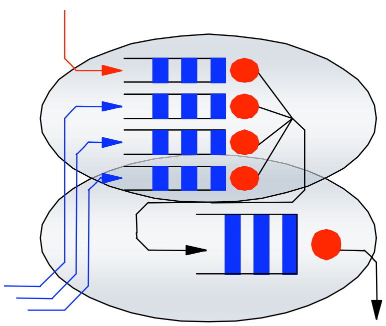
$f_1:f_2:f_3:f_4 = 4:6:3:3$

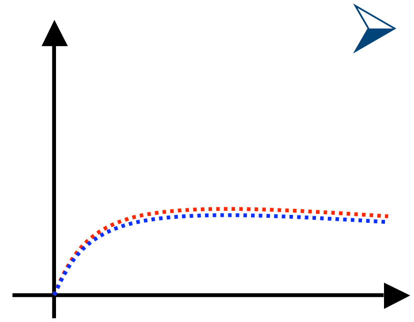
- Fair
- Inefficient

$f_1:f_2:f_3:f_4 = 1:1:1:1$

Fairness
Per-flow Queues + MAC Layer QoS

Per-flow Queuing

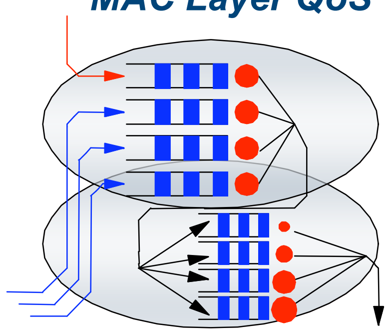


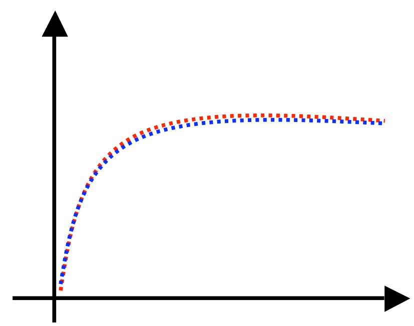


- Fair
- Inefficient

$f_1:f_2:f_3:f_4 = 1:1:1:1$

Per-flow Queues+ MAC Layer QoS





- Fair
- Efficient

$f_1:f_2:f_3:f_4 = 1:1:1:1$

$n_1:n_2:n_3:n_4 = 4:2:1:1$

QoS
Support required at every layer

- Physical Layer
  - Robust modulation
  - Link adaptation
- MAC Layer
  - Offer priorities
  - Offer guarantees (bandwidth, delay)
- Network Layer
  - Select “good” routes
  - Offer priorities
  - Reserve resources (for guarantees)
- Transport
  - Attempt end-to-end recovery when possible
- Application
  - Negotiate end-to-end and with lower layers
  - Adapt to changes in QoS

QoS Flavors

Guarantees

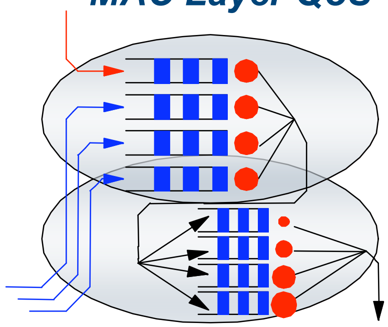
- Similar to RSVP in the Internet
- Has to implement connection admission control
- Difficult in WMNs due to:
  - Shared medium (see provisioning section)
  - Fading and noise

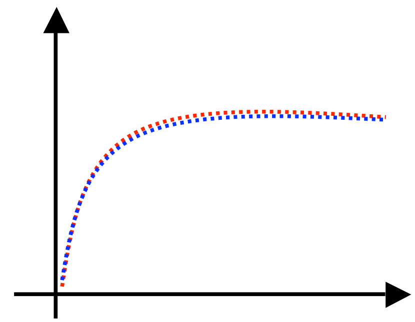
Priorities

- Similar to diffserv in the Internet
- Offers classes of services
- Generalization of fairness
- A possible implementation on next slide

Network Layer QoS (Priorities)

Per-flow Queues+ MAC Layer QoS

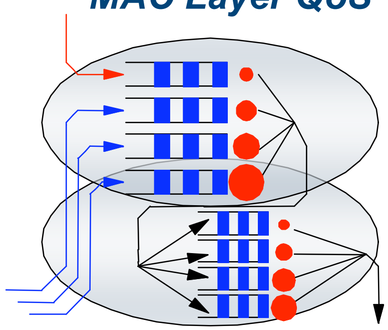


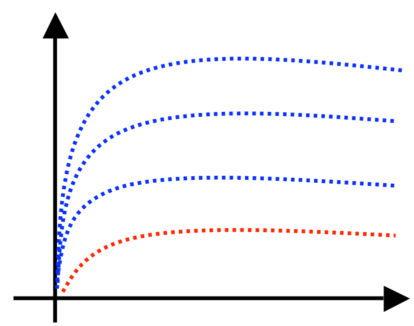


$f_1:f_2:f_3:f_4 = 1:1:1:1$

$n_1:n_2:n_3:n_4 = 4:2:1:1$

Per-flow Weighted Queues+ MAC Layer QoS





$f_1:f_2:f_3:f_4 = 1:2:3:4$

$n_1:n_2:n_3:n_4 = 4:2:1:1$

Overview of Research Topics

- Physical Layer
  - Smart Antennas
  - Transmission Power Control
- MAC Layer
  - Multiple Channels
- Network Layer
  - Routing
  - Fairness and QoS
- Transport Layer
- Provisioning
- Security
- Network Management
- Geo-location

TCP Problems

- Efficiency – TCP assumes that a missing (or late) ACK is due to network congestion and slows down:
  - to half if the missing ACK shows up fast enough
  - to zero if it times out
- Causes for missing ACKs in WMNs:
  - Wireless transmission error
  - Broken routes due to mobility (both users and wireless routers)
  - Delays due to MAC contention
  - Interplay between MAC and TCP back-off mechanisms

TCP
Efficiency Solutions

- Focus on eliminating the confusion between congestion loss and all other reasons
- Many approaches developed for single-hop wireless systems
  - Snoop
  - I-TCP
  - M-TCP
- End to end
  - SACK
  - Explicit error notification
  - Explicit congestion notification (e.g. RED)
- Several solutions for multi-hop
  - A-TCP
  - Freeze-TCP

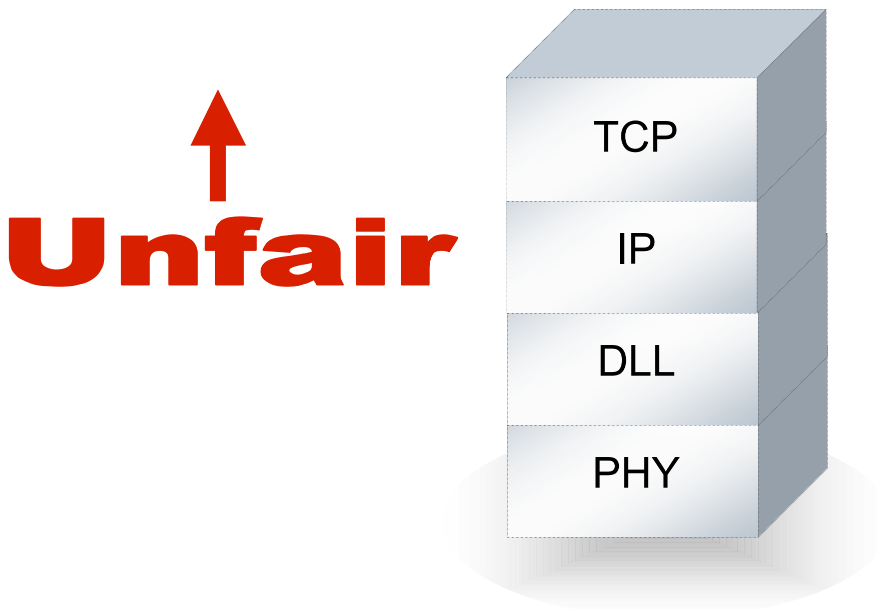
Applicability
Clean Layering

Trade-off

Improvement in
Efficiency
Layer Violations

TCP
Problems (cont)

- Unfairness
  - Due to network layer unfairness
  - Due to variation in round trip delays
  - Likely both will be fixed if network layer fairness is ensured



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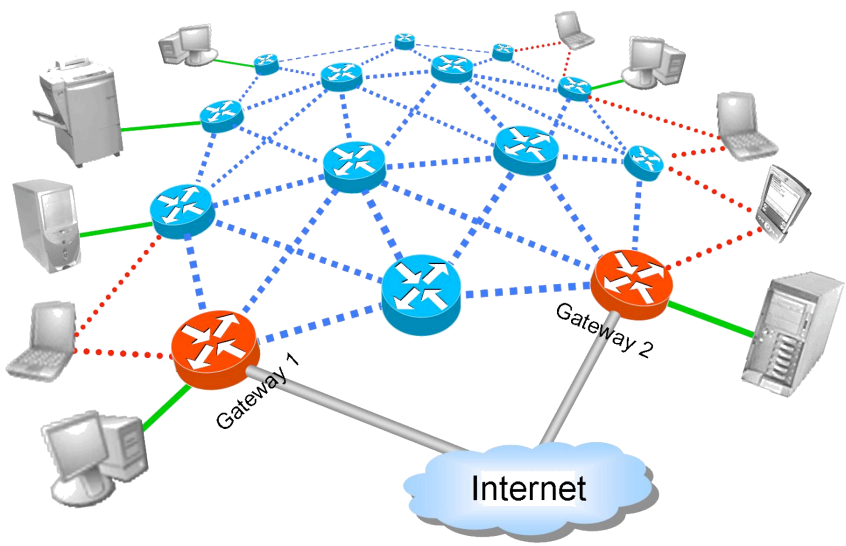
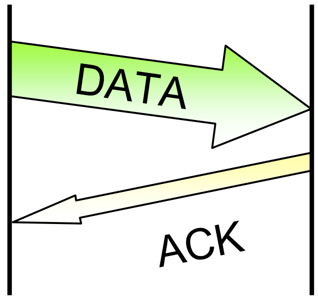
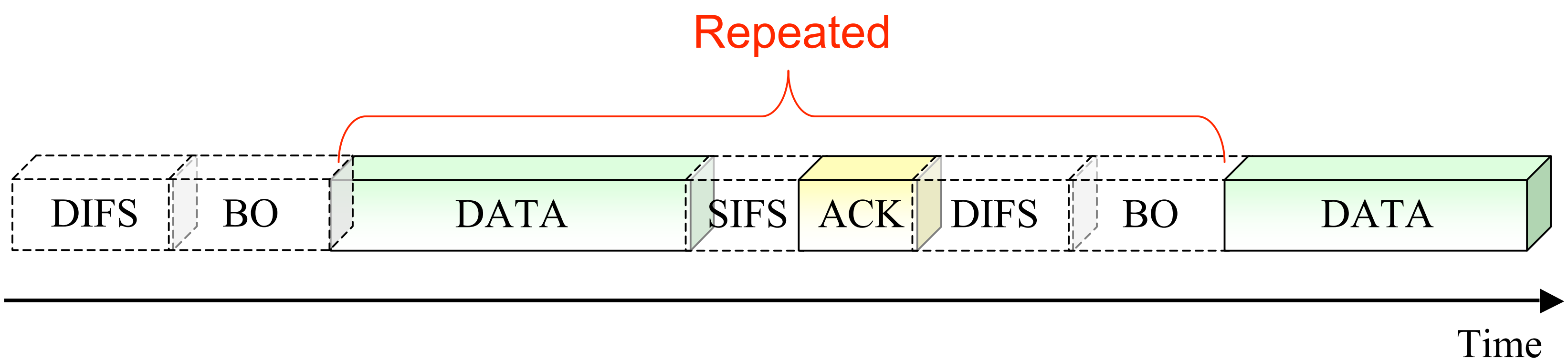
Provisioning

- Two related questions:
  - How much bandwidth for each user?
  - Where to place the next gateway?
- Essential for QoS guarantees
- Complicated by the shared medium and multi-hop routing

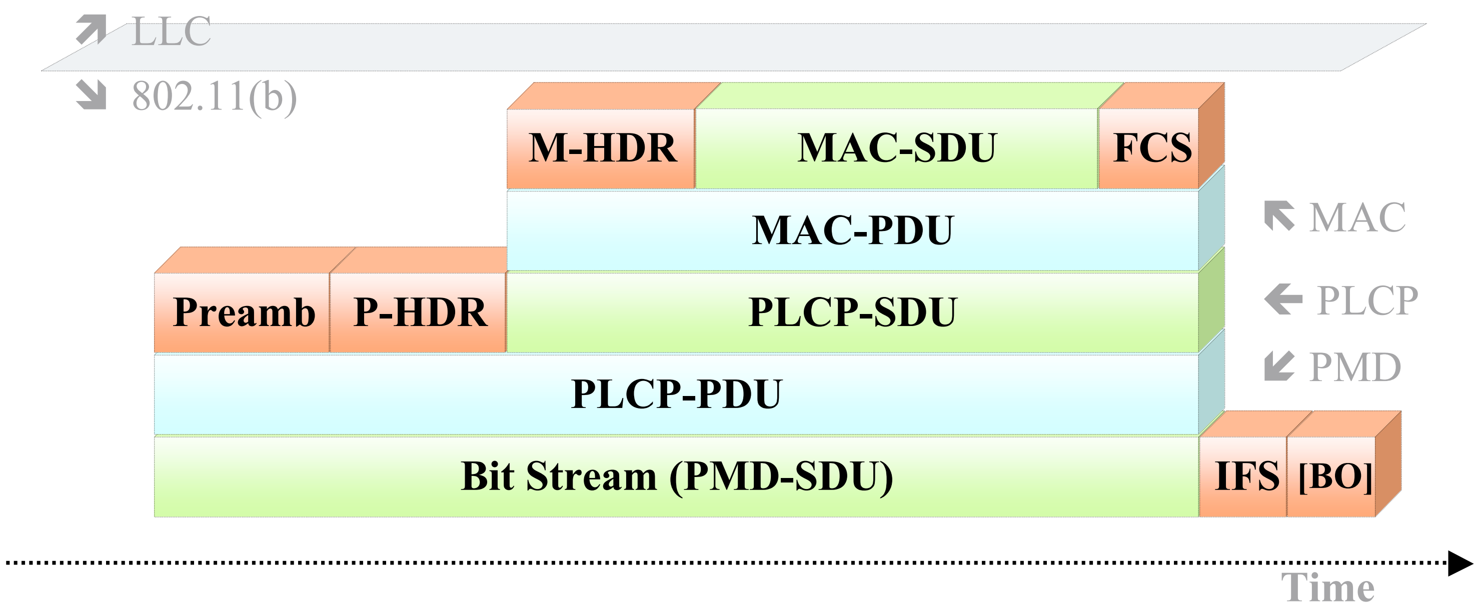


Provisioning
802.11 Timing diagram for CSMA/CA

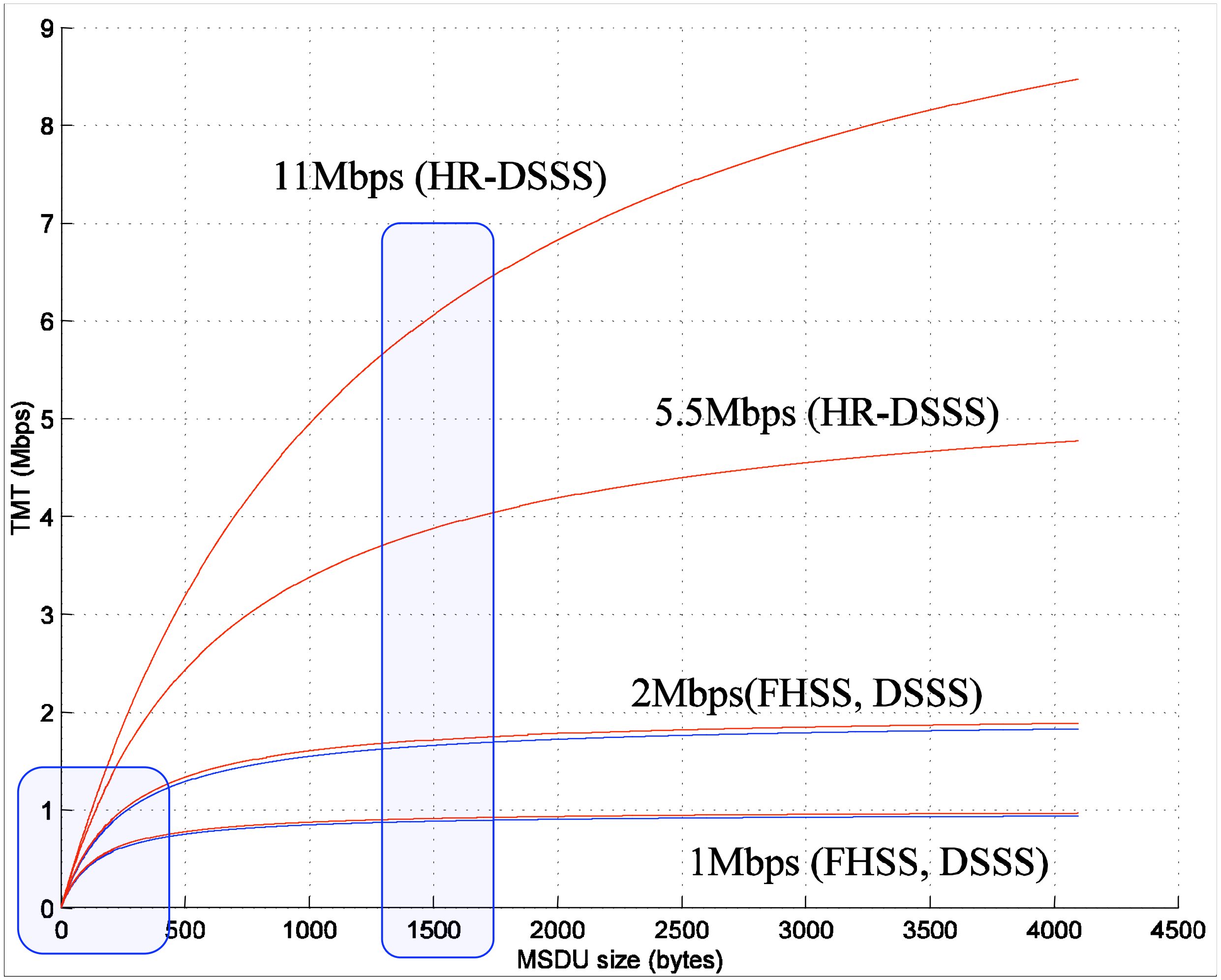




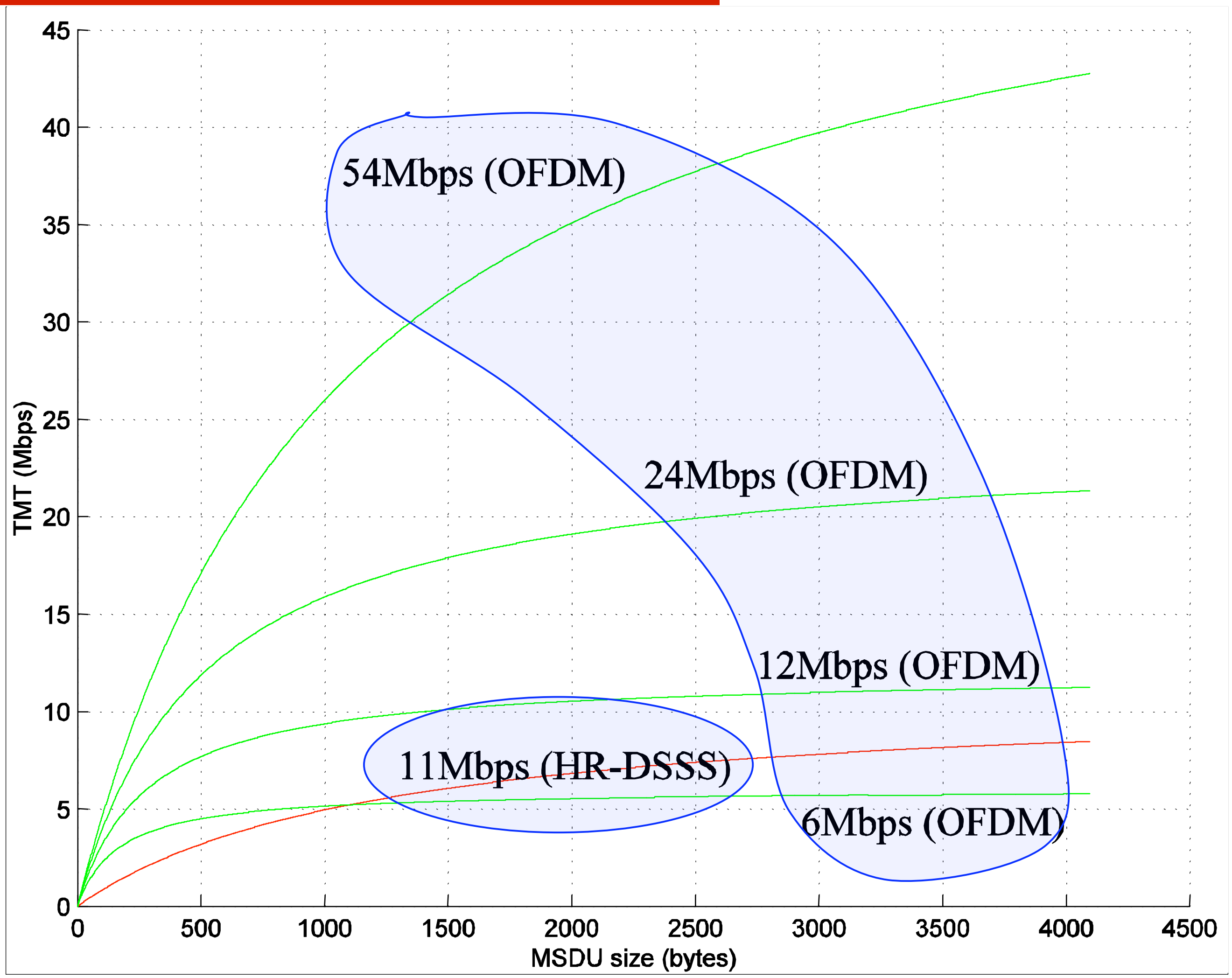
Provisioning
802.11 Overhead



Provisioning
TMT of 802.11 and 802.11b (CSMA/CA)

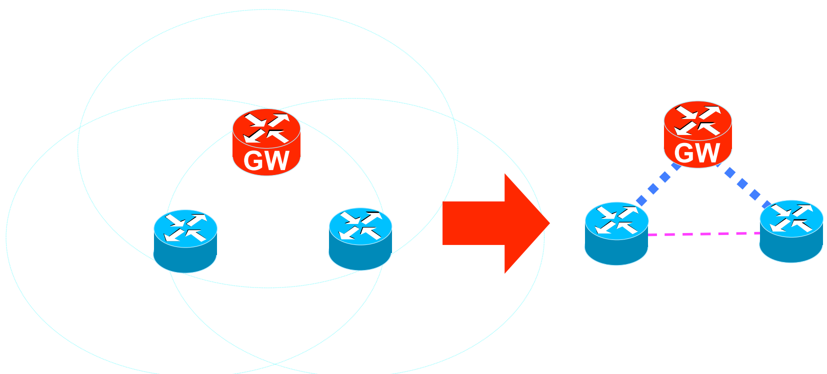


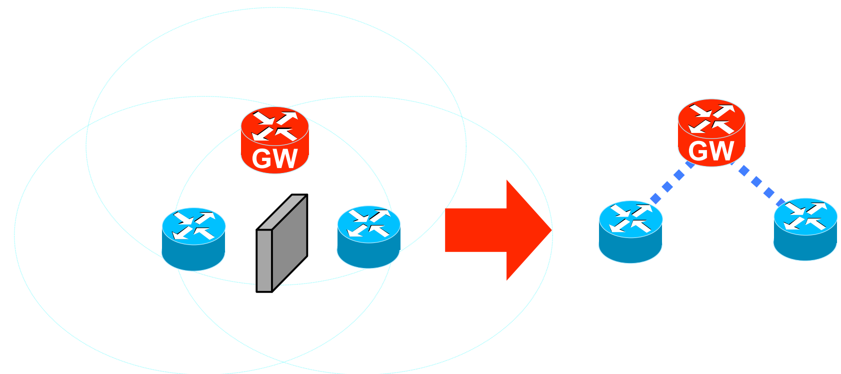
Provisioning
TMT of 802.11b and 802.11a (CSMA/CA)

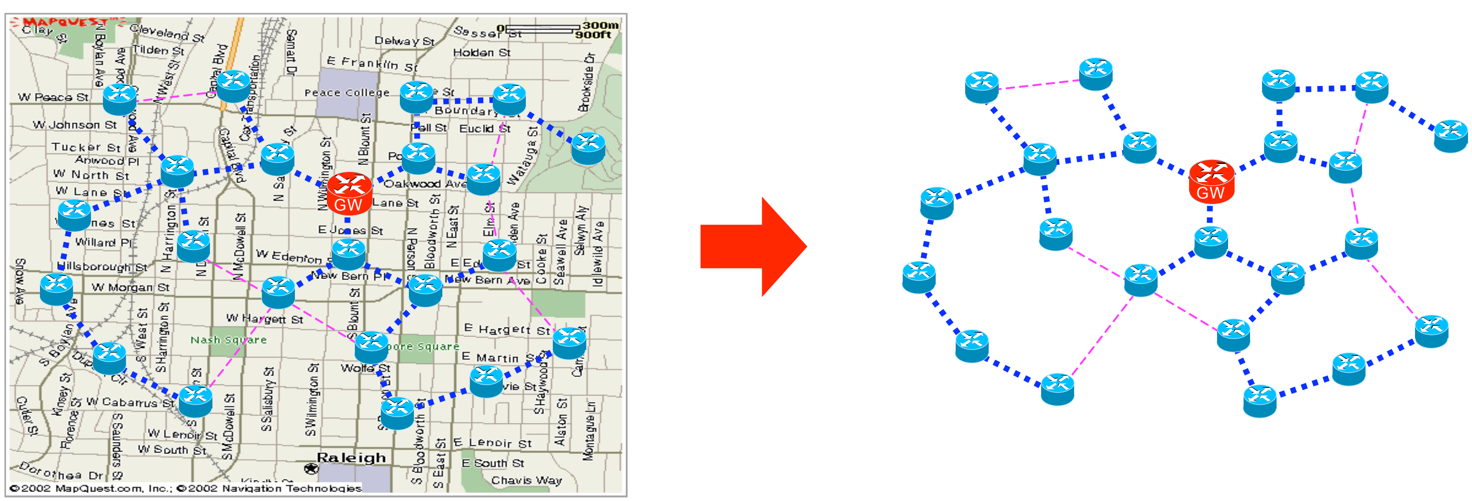


Provisioning
Topology Modeling

WALAN

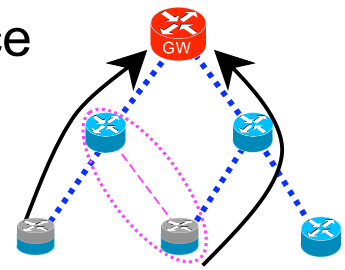


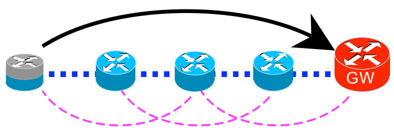




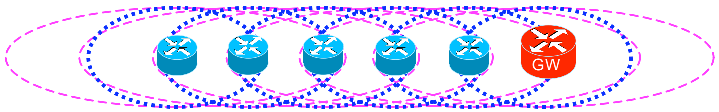
Provisioning
Intra-flow Interference & Chain Utilization

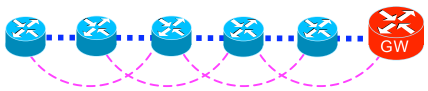
- Inter- and intra-flow interference



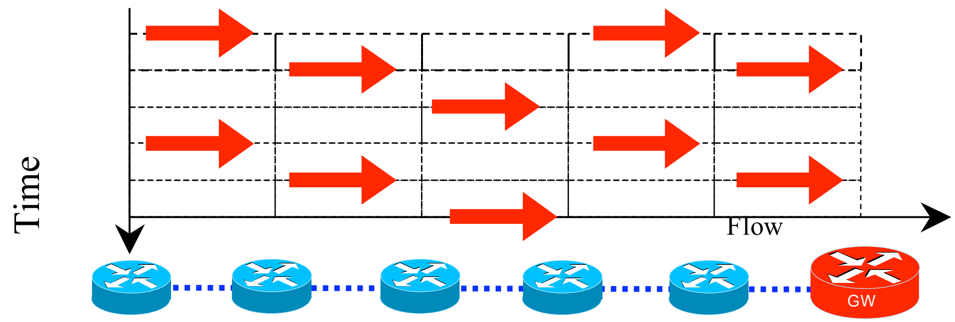


- Interference and topological models

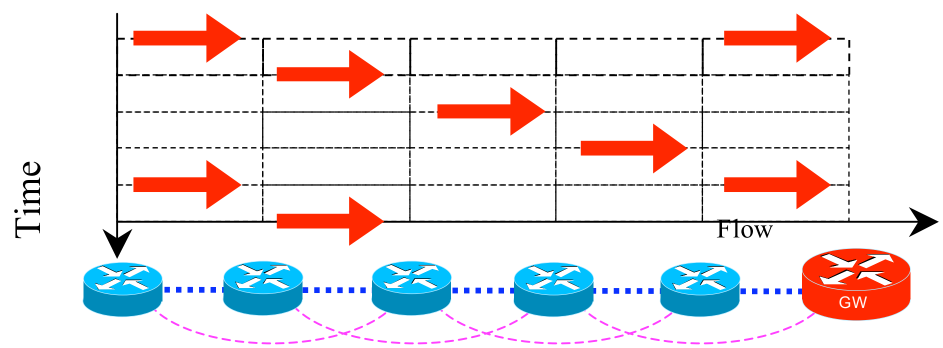




Provisioning
Chain Utilization

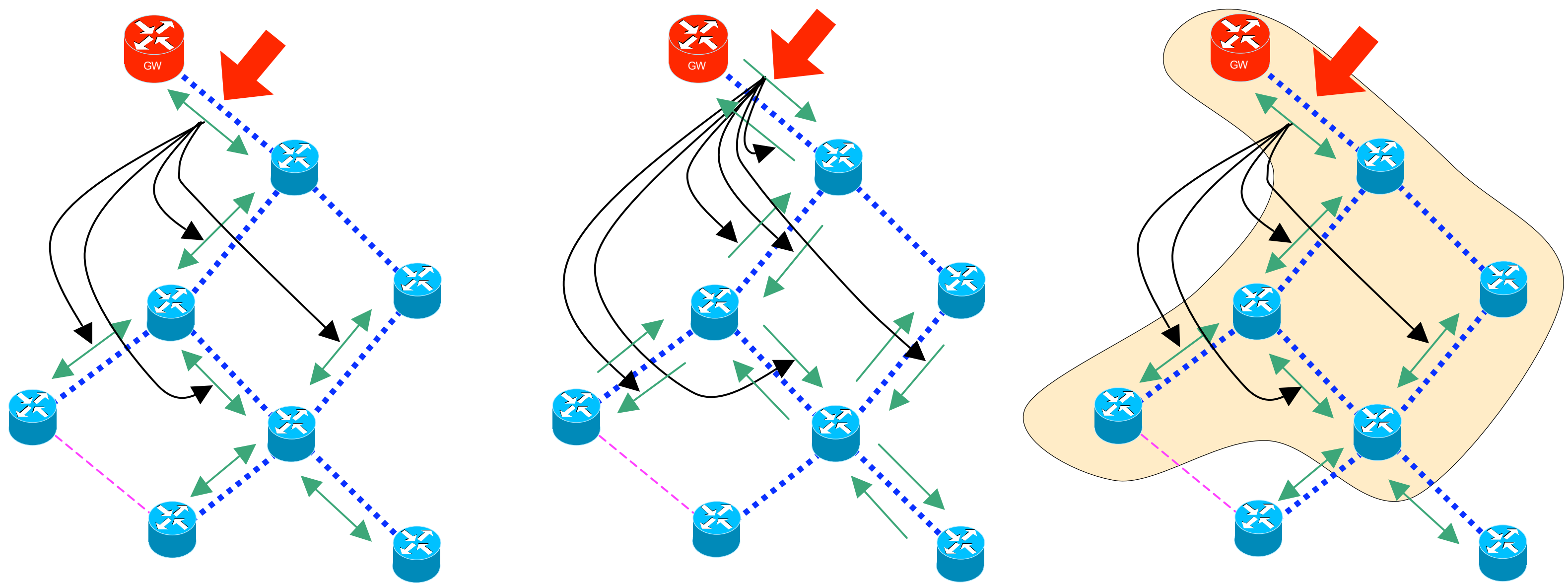


$\mu = 1/3$



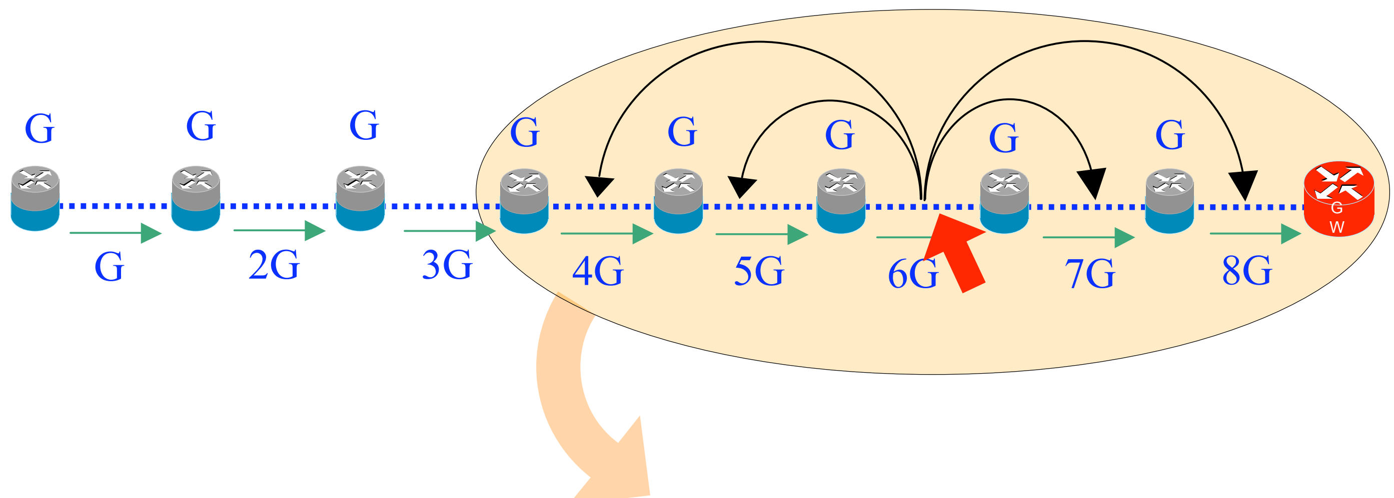
$\mu = 1/4$

Provisioning Collision Domains



Symmetric MAC   Asymmetric MAC   Collision Domain (Symmetric MAC)

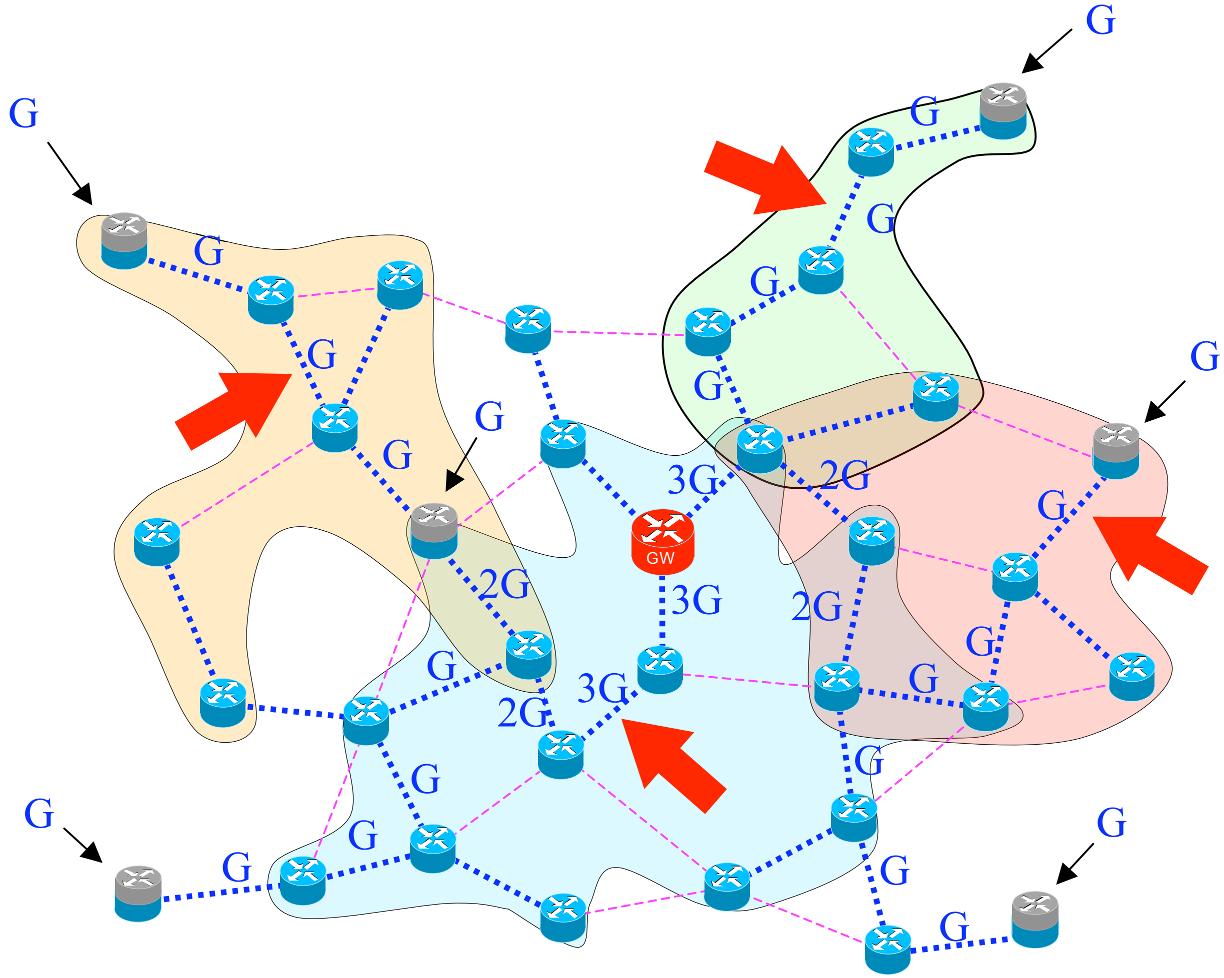
Provisioning
Chain Topology



4G + 5G + 6G + 7G + 8G = 30 G

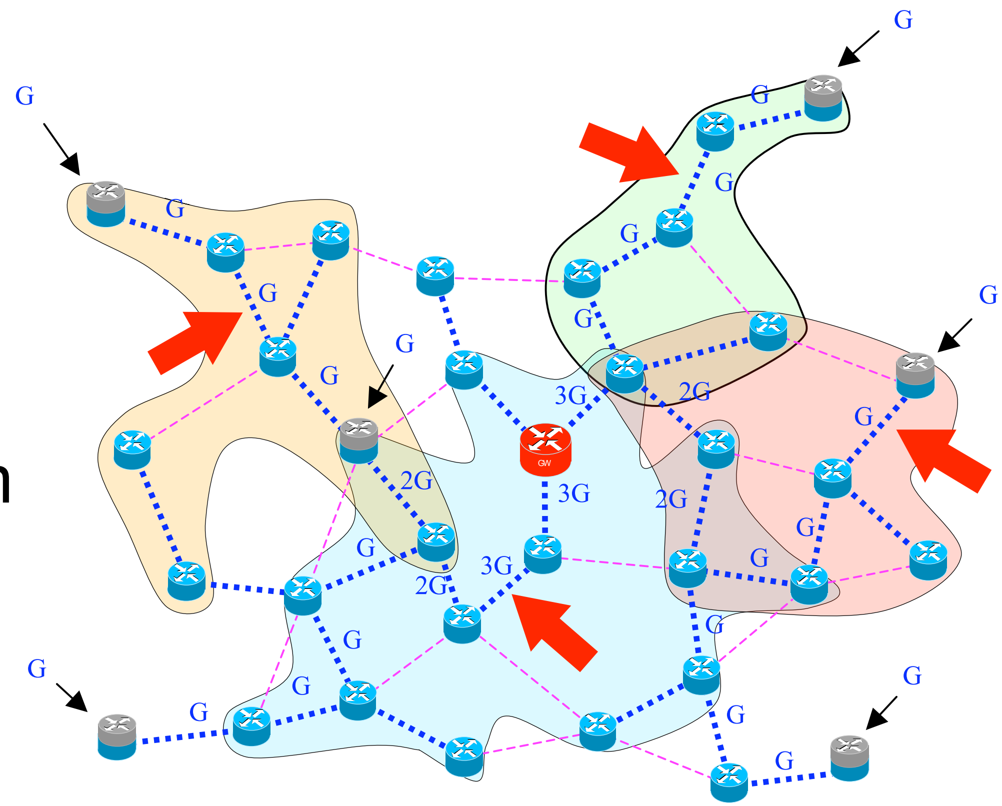
Therefore, G ≤ B/30

Provisioning Arbitrary Topology



Provisioning Conclusion

- Non-trivial procedure
- Capacity depends on:
  - Network topology
  - Traffic load
- Any practical algorithm will trade-off:
  - Responsiveness
  - Efficiency



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Security

- Authentication
  - Prevent theft of service
  - Prevent intrusion by malicious users
- Privacy - user data is at risk while on transit in the WMN due to:
  - Wireless medium
  - Multi-hop
- Reliability – protect:
  - Routing data
  - Management data
  - Monitoring data
  - Prevent denials of service (very difficult at the physical layer)

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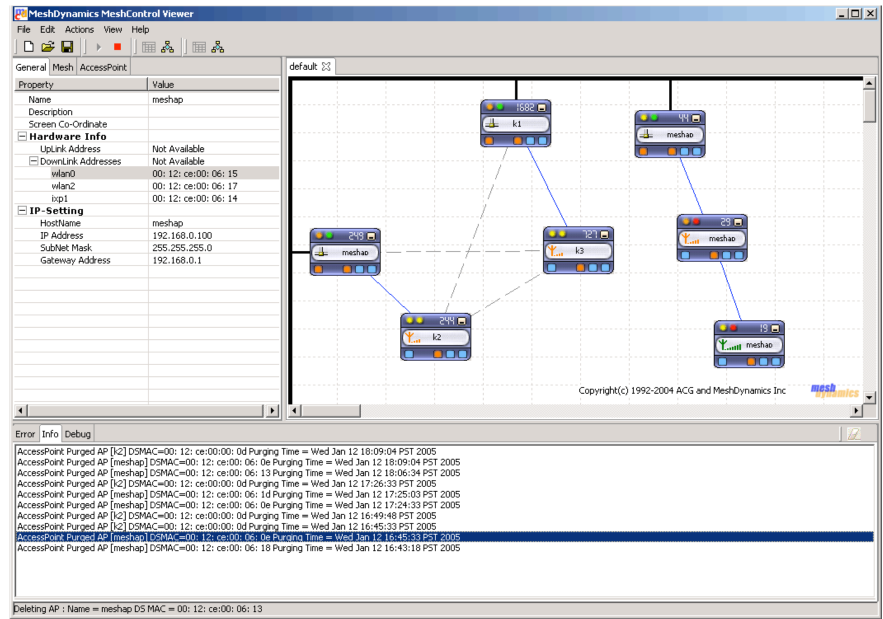
Network Management

- Monitor the "health" of the network
- Determine when is time to upgrade
  - Either hardware
  - New gateway
- Detect problems
  - Equipment failures (often hidden by the self-repair feature of the network)
  - Intruders
- Manage the system



Source: www.meshdynamics.com

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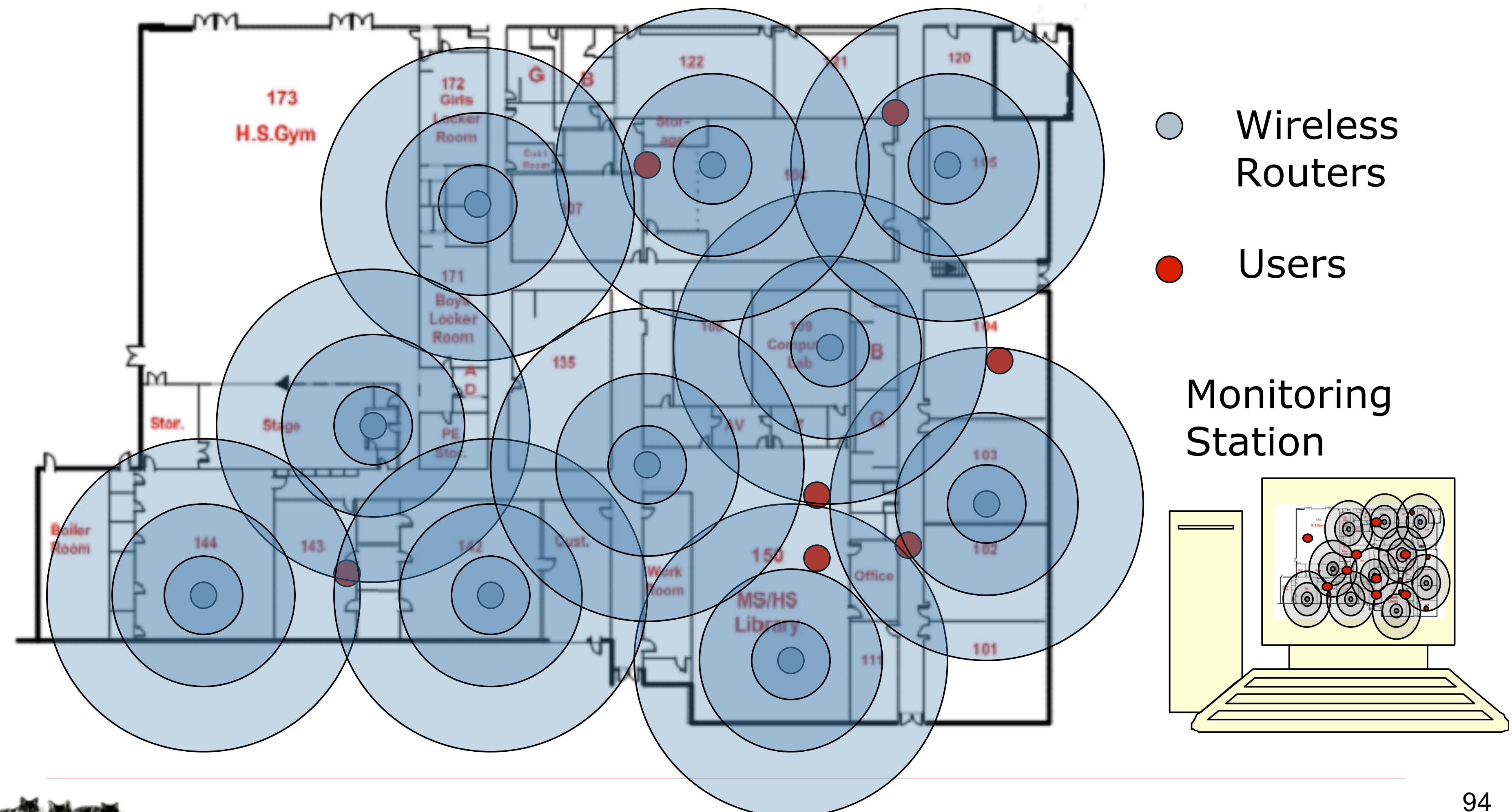
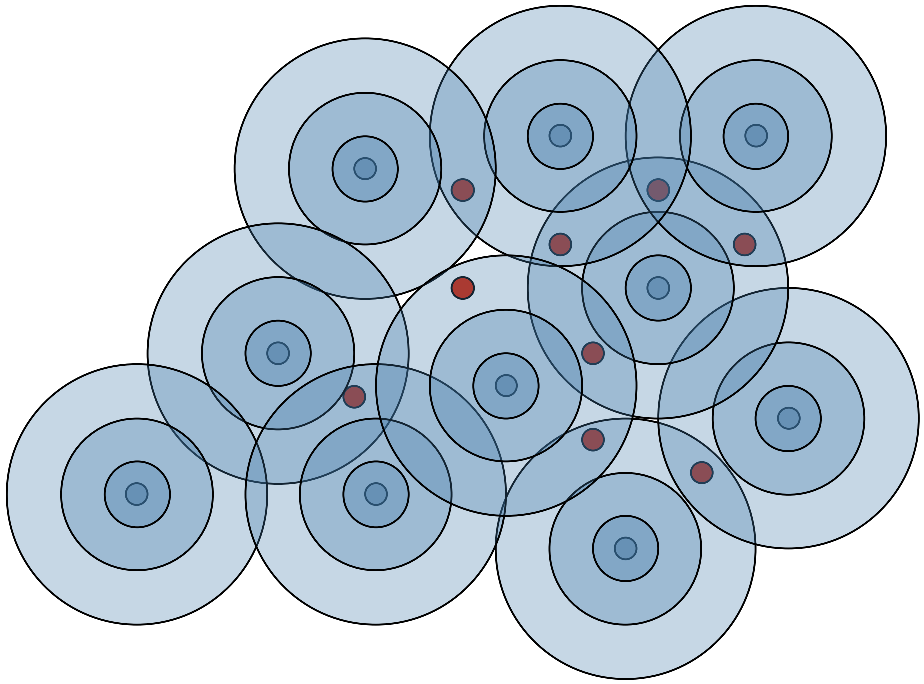
Geolocation
What?



Geolocation
How?

- Measure ranges between mobile users and some known fixed points (wireless routers).
- Triangulate (same as cellular systems).
- Since the "cells" are much smaller, much better precisions is possible.



- Many improvements possible as users can talk to each other.

Outline

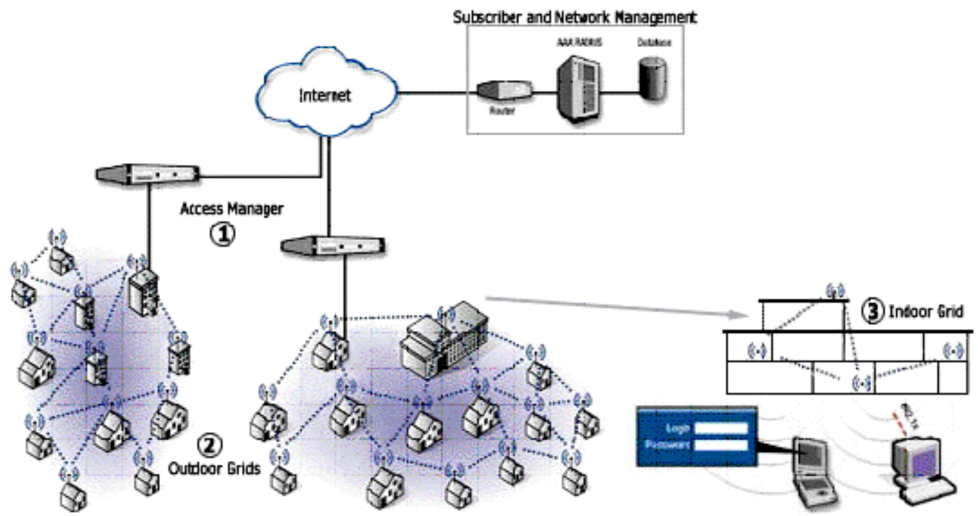
- Overview of the technology
- Opportunities
- (Research) Challenges
- Current state of the art
  - Companies
  - Universities
  - Standards
- Conclusion

Companies

- Aerial Broadband
- BelAir Networks
- Firetide
- Intel
- Kiyon
- LamTech (ex. Radiant)
- Locust World
- Mesh Dynamics
- Microsoft
- Motorola (ex. Mesh Networks)
- Nokia Rooftop
- Nortel Networks
- Packet Hop
- Ricochet Networks
- SkyPilot Networks
- Strix Systems
- Telabria
- Tropos Networks

Aerial Broadband

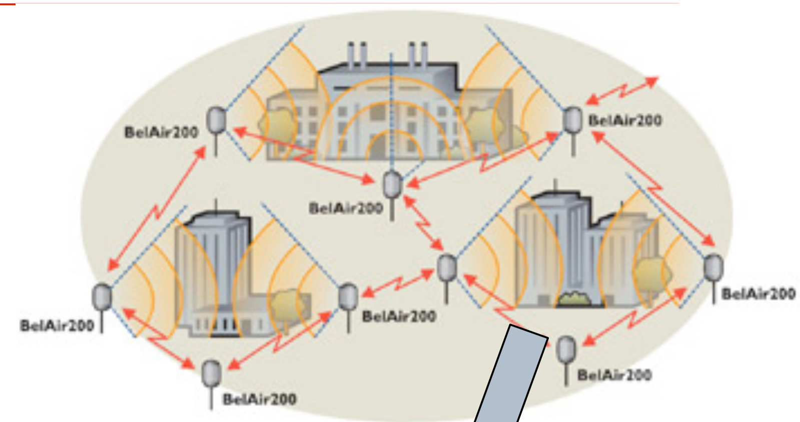
- Tiny start-up in RTP, NC, USA in 2002
- Closed its doors shortly after its start
- Application: broadband Internet access to apartment complexes
- Features
  - 802.11b-compatible product
  - Zero configuration
  - Layer 2 “routing”

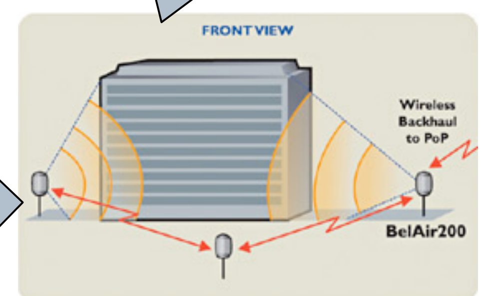


Source: www.aerialbroadband.com

BelAir Networks

- Based in Ontario, Canada
- Application: 802.11b coverage of large zones
- Features:
  - Three radios on each wireless router; dynamically mapped on:
  - 8 fixed directional antennas
  - Dynamic Tx power and data rate control
  - Routing based on PHY feedback, congestion, latency
  - Load balancing features

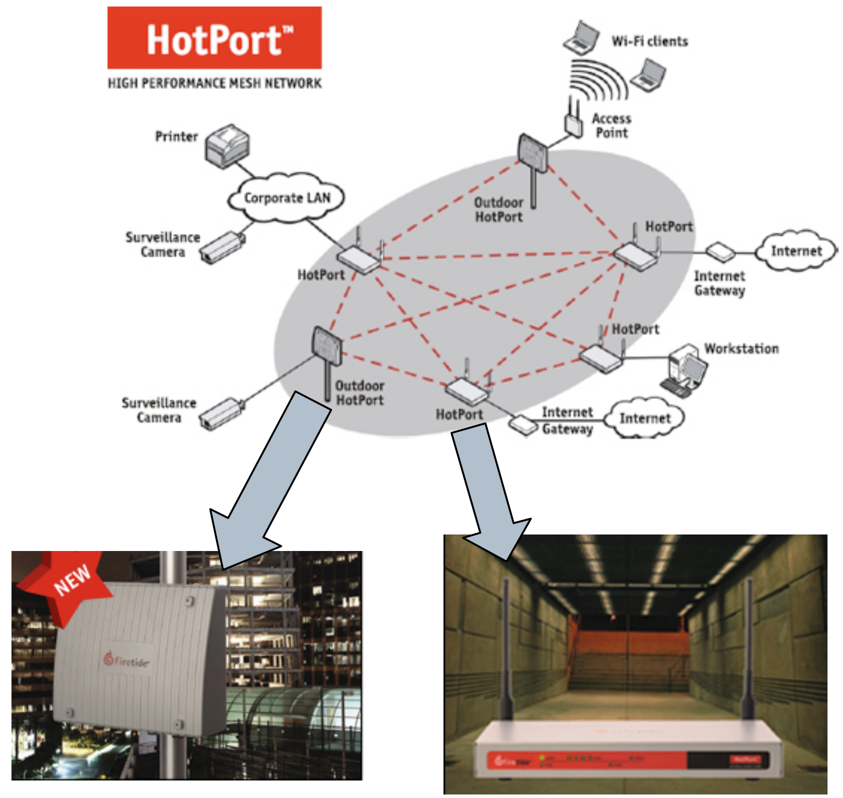




Source: www.belairnetworks.com

Firetide

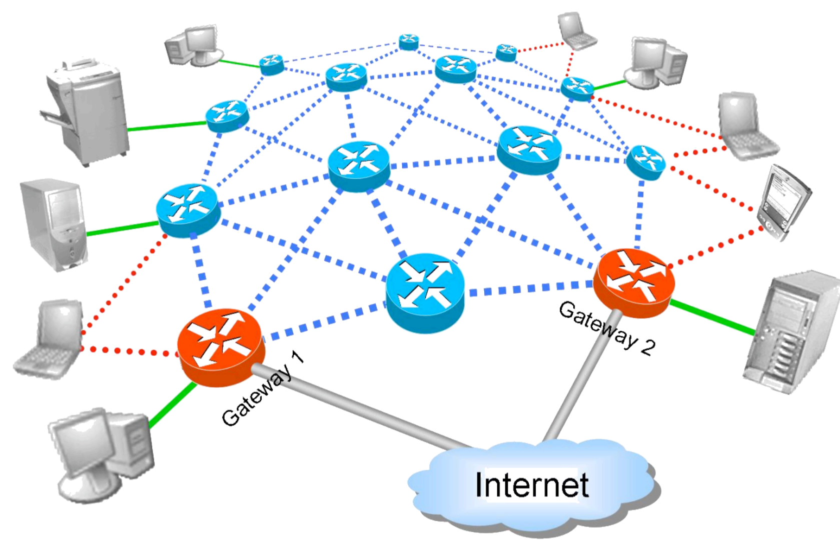
- Based in Hawaii and Silicon Valley, USA
- Application: Layer 2 connectivity (indoor and outdoor)
- Features:
  - Proprietary routing protocol
  - 2.4GHz and 5GHz products
  - AES, WEP security
  - Variable Tx Power
  - Management software



Source: www.firetide.com

Intel

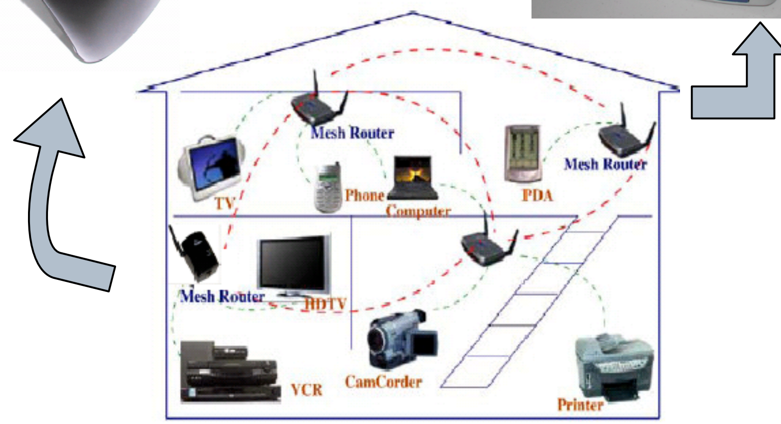
- Expressed interest in WMNs (since 2002).
- Research in:
  - Low power – related with their wireless sensor networks activities at Intel Research Berkeley Lab.
  - Traffic balancing
- Together with Cisco active in 802.11s standardization process

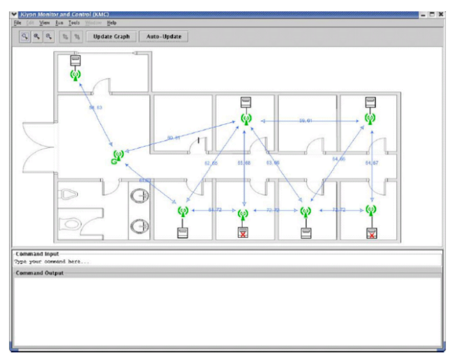


Source: www.intel.com

Kiyon

- Based in La Jolla, CA, USA
- Applications: extended 802.11 indoor coverage
- Features:
  - Products based on 802.11a/b/g
  - Custom routing (WARP)
  - Management software

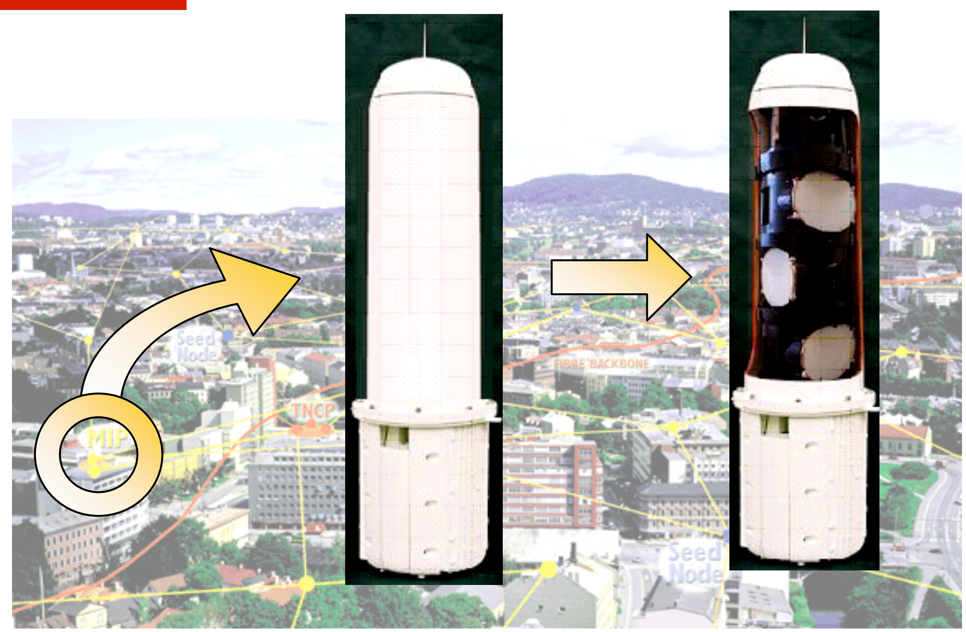


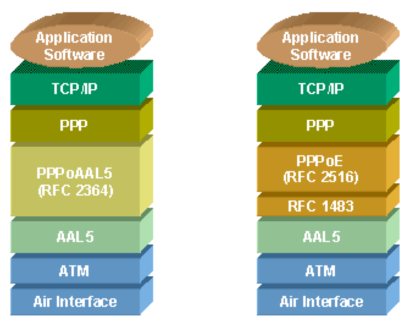


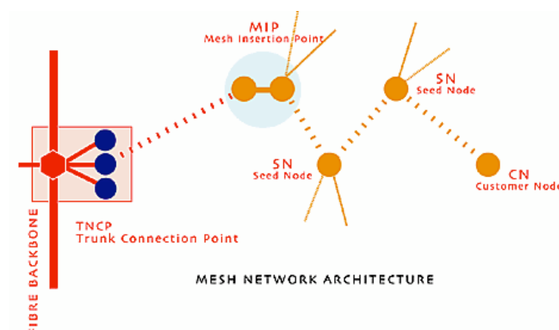
Source: www.kiyon.com

LamTech (ex. Radiant Networks)

- UK-based company
- Purchased by LamTech in 2004
- Applications: broadband Internet access
- *MESHWORK™*
  - ATM switch in wireless router
  - 90 Mbps
  - Directional links
  - 4 mobile directional antennas
  - QoS - CBR & VBR-NR







Source: www.radiantnetworks.com

Locust World

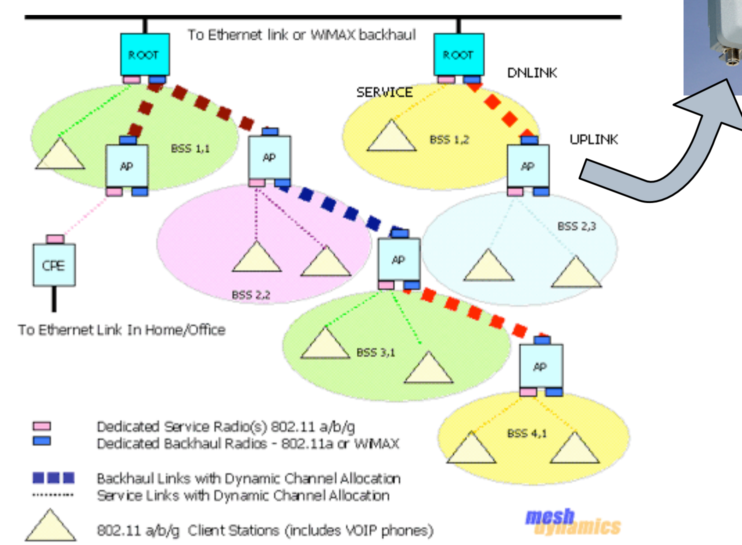
- Based in UK
- Application: community networks
- Features:
  - Free, open source software
  - Off-the-shelf hardware + open source software
  - Monitoring software
  - Several deployments around the world

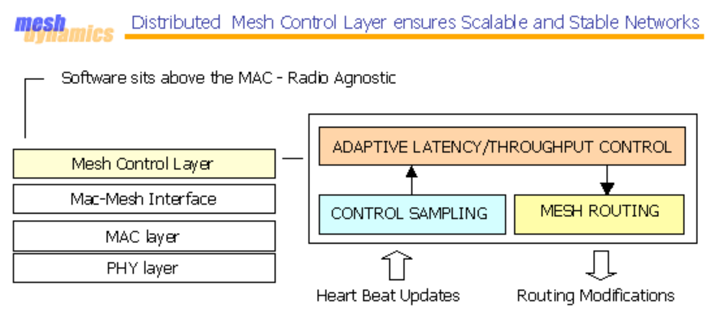
Source: www.locustworld.com

Mesh Dynamics

- Based on Santa Clara, CA, USA
- Application: 802.11 coverage (indoor, outdoor, citiwide), VoIP, video
- Features:
  - 802.11a/b/g compatible
  - Multiple radios options (1-4)
  - Dynamic channel selection
  - Dynamic tree topology
  - Management software
  - Radio agnostic control layer

Source: www.meshdynamics.com

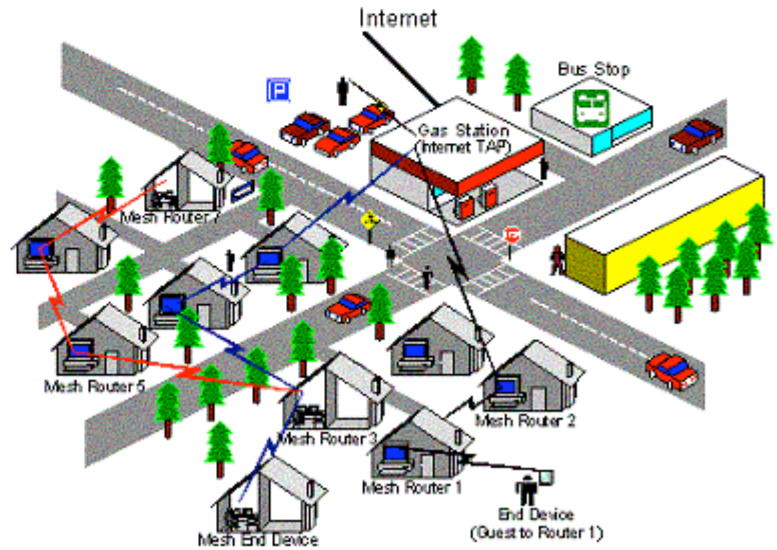




Microsoft

- Application: community networks
- Software
  - Routing
  - Link quality

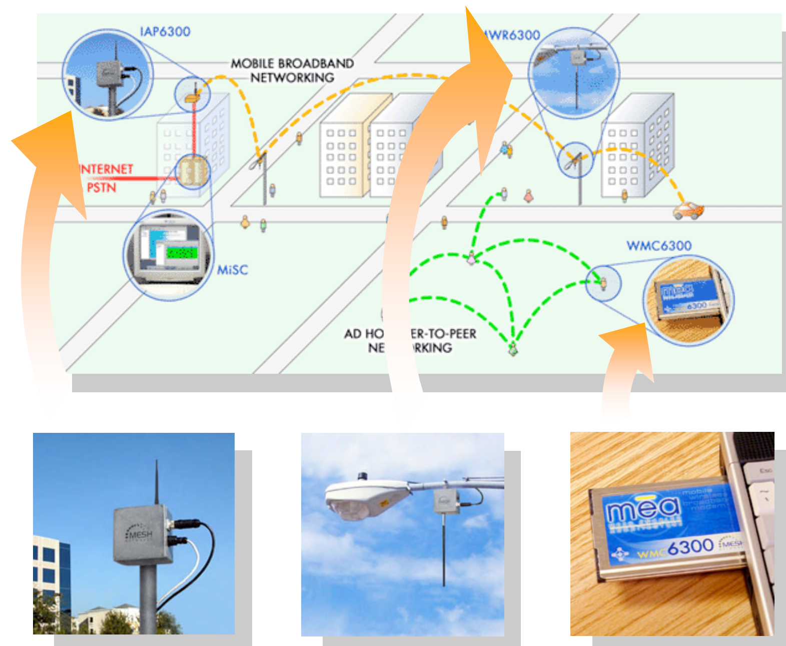
  } Mesh Connectivity Layer (MCL
- Routing based on DSR (named LQSR)
- Transparent to lower and higher layers
- Binaries for Windows XP available at research.microsoft.com/mesh/



Source: research.microsoft.com/mesh/

Motorola – ex. MeshNetworks

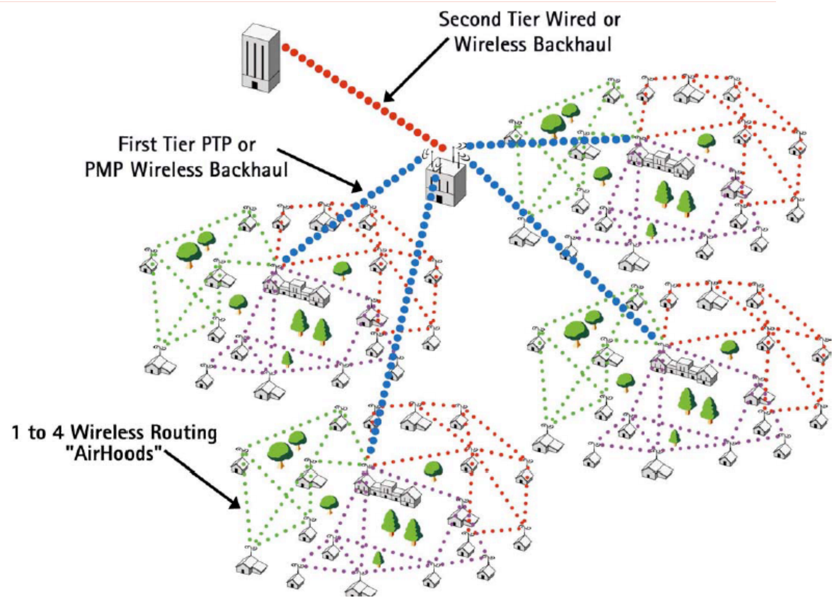
- Based in Orlando, FL, USA
- Acquired by Motorola in Nov. 2004
- Application: mobile broadband Internet access
- Features:
  - Support for high speed mobile users
  - Proprietary routing protocol
  - Adaptive transmission protocol
  - Proprietary QDMA radio
  - Proprietary multichannel MAC
  - Proprietary geolocation feature
  - Support for voice applications
  - Local testbeds

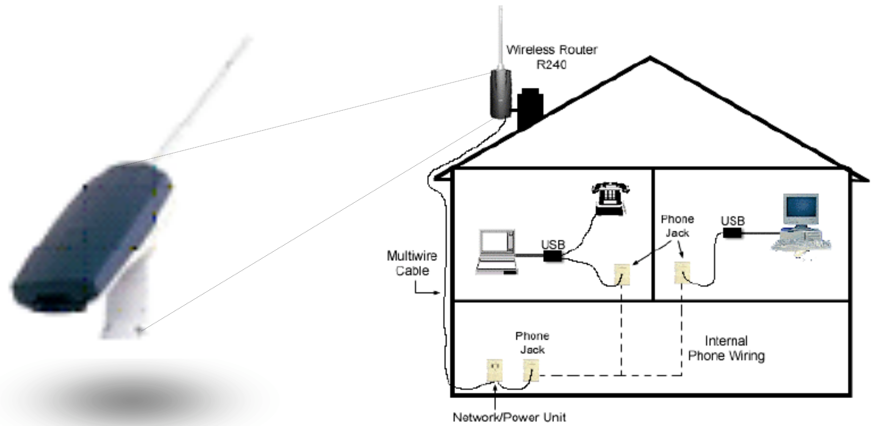


Source: www.meshnetworks.com
(now www.motorola.com)

Nokia Rooftop

- Acquisition of Rooftop Comm.
- Discontinued in 2003
- Application: broadband Internet access
- Features:
  - Proprietary radio
  - Proprietary multi-channel MAC
  - Variable TX Power
  - Management and monitoring tools

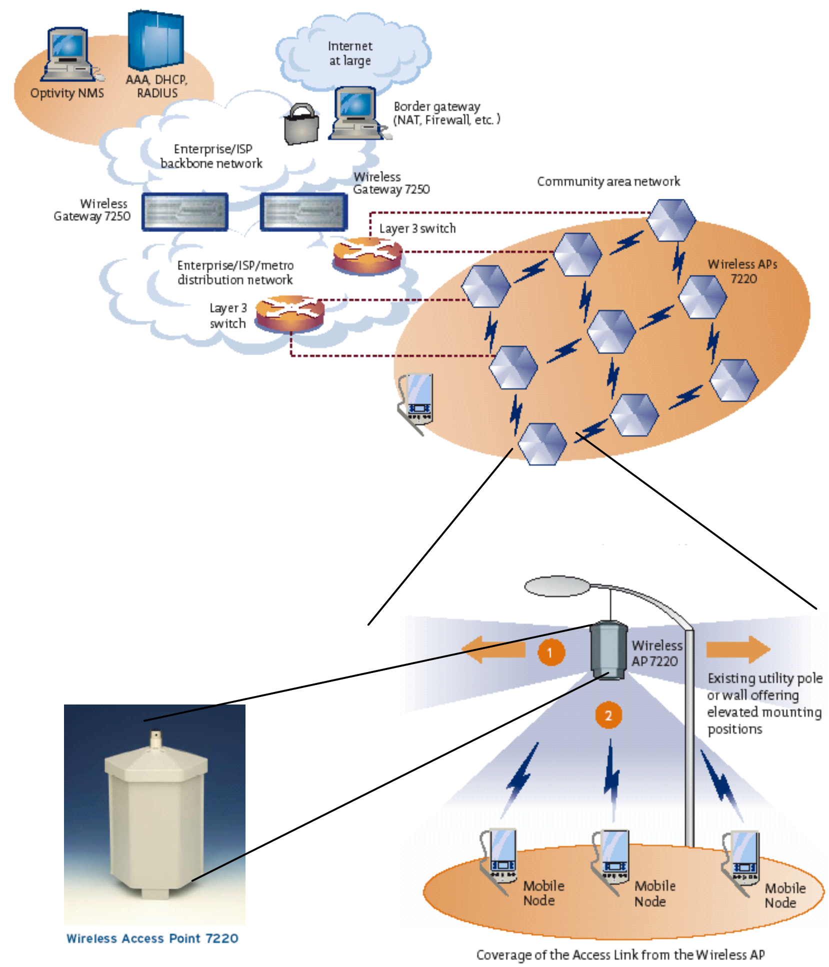




Source: www.rooftop.com

Nortel Networks

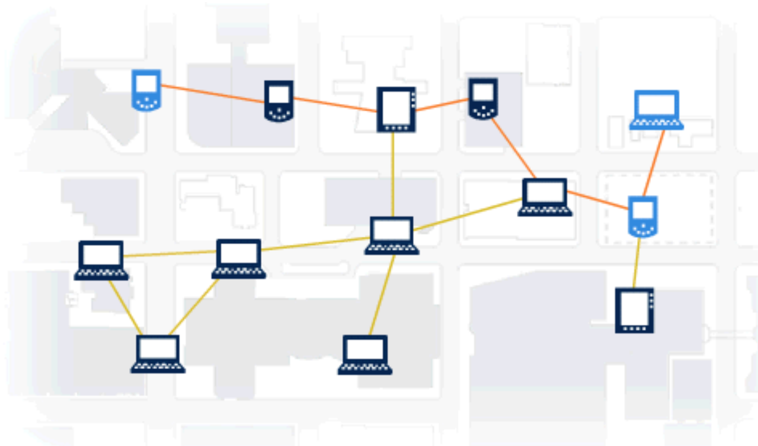
- Applications: extended WLAN coverage
- Features:
  - 802.11a backhaul
  - 802.11b for users
  - Management software



Source: www.nortelnetworks.com

Packet Hop

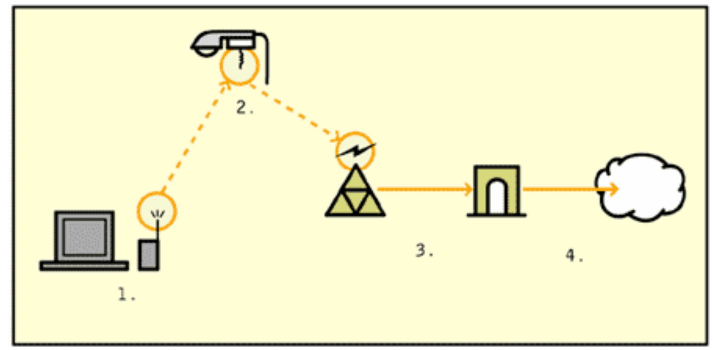
- Based in Belmont, CA, USA
- Application: emergency response
- Product: software for mesh networking
- Features:
  - Works on 802.11a/b/g based hardware platforms
  - Security
  - Management software
  - Deployed testbed near Golden Gate Bridge in Feb. 2004

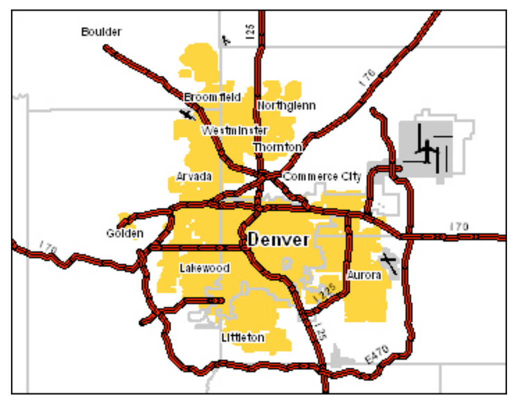


Source: www.packethop.com

Ricochet Networks

- Based in Denver, CO, USA
- Application: Internet access
- Features:
  - Mobile user support
  - 2 hop architecture
  - 900 MHz user – pole top
  - 2.4GHz pole top - WAP
  - Sell both hardware and service in Denver and San Diego
  - Speed: “up to 4 times the dial-up speed”

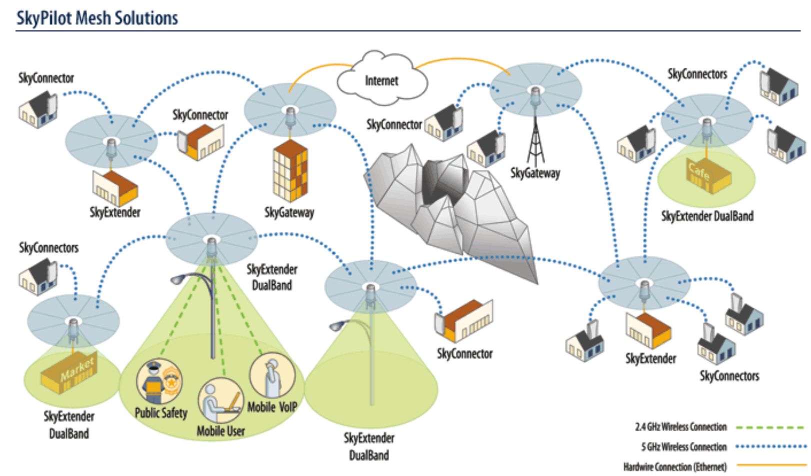




Source: www.ricochet.net

SkyPilot Networks

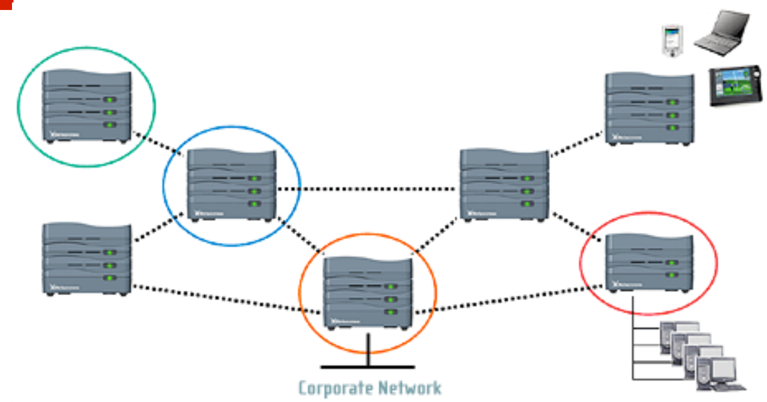
- Based in Santa Clara, CA, USA
- Application: broadband Internet access
- Features:
  - High power radio + 8 directional antennas
  - Proprietary routing (based on link quality and hop count)
  - Dynamic bandwidth scheduling (decides who transmits when)
  - Management software
  - Dual band (2.4GHz for users, 5GHz for backhaul)



Source: www.skypilot.com

Strix Systems

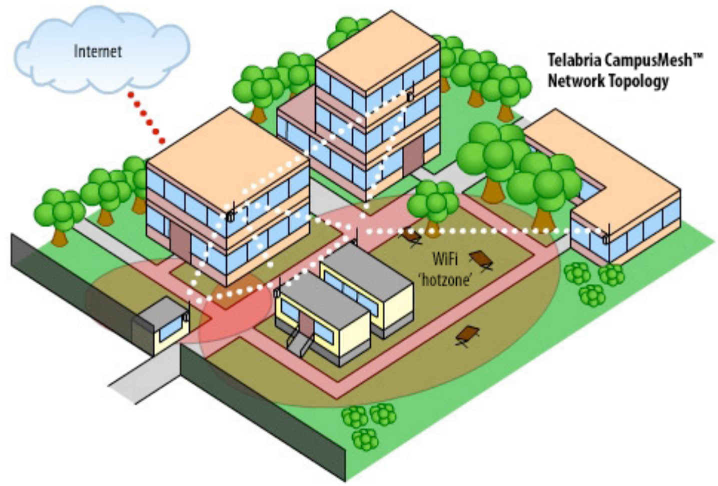
- Based in Calabasas, CA, USA
- Application: indoor and outdoor WLAN coverage, temporary networks
- Features:
  - Compatible with 802.11a/b/g
  - Supports multiple (up to 6) radios
  - Management software
  - Soon to come testbeds

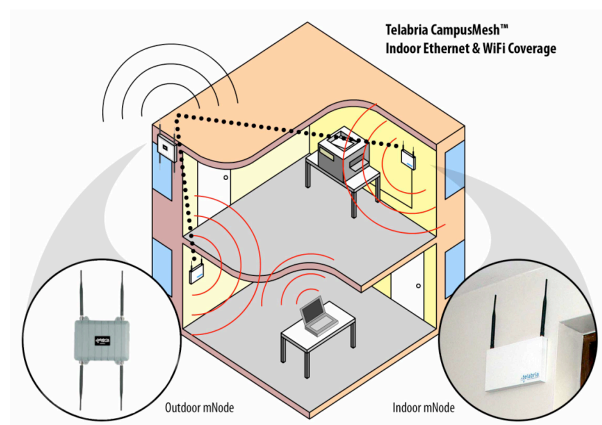


Source: www.strixsystems.com

Telabria

- Based in Kent, UK
- Application: WLAN coverage (campus/city);
- Features:
  - 802.11 compatibility
  - Compatible indoor/outdoor products
  - Dual radio 802.11a/(b,g) (one for router-router, one for router-user traffic).

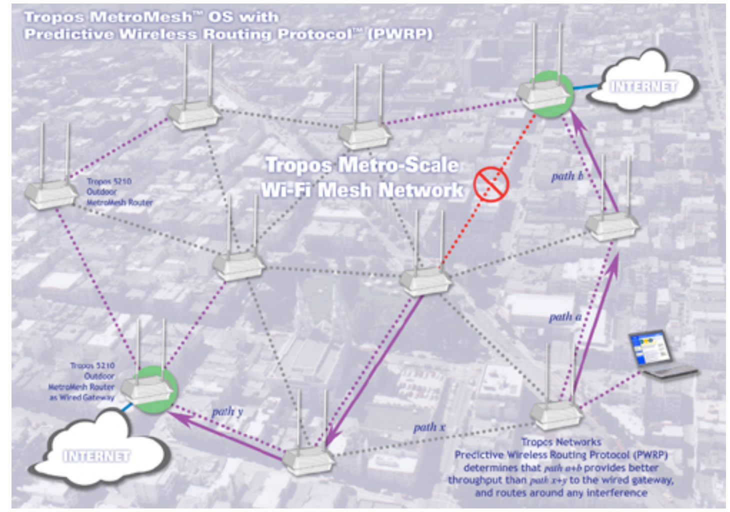


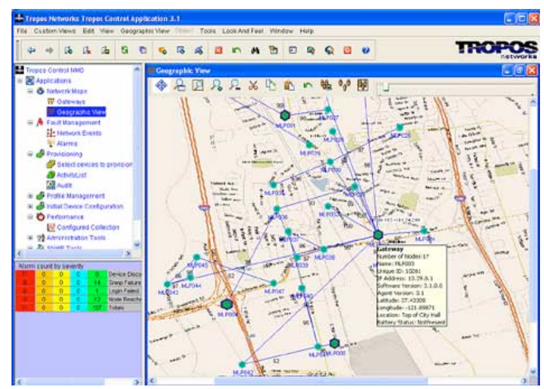


Source: www.telabria.com

Tropos Networks

- Based in Sunnyvale, CA, USA
- Ex – FHP wireless
- Applications: citywide 802.11b/g coverage
- Features:
  - Proprietary routing optimizing throughput
  - Support for client mobility
  - Security
  - Management software
  - Indoor/outdoor products
  - 150 customers installed their products





Source: www.tropos.com

Outline

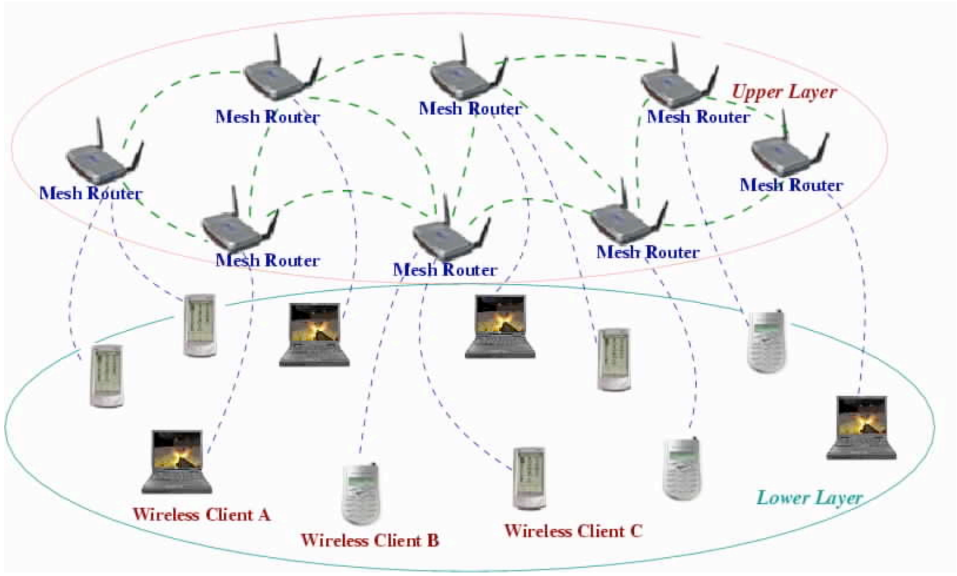
- Overview of the technology
- Opportunities
- (Research) Challenges
- Current state of the art
  - Companies
  - Universities
  - Standards
- Conclusion

University Testbeds

- Georgia Tech - BWN-Mesh
- MIT - Roofnet
- Rutgers WinLab – Orbit
- SUNY Stonybrook – Hyacinth
- University of Utah - Emulab

Georgia Institute of Technology BWN-Mesh

- 15 IEEE 802.11b/g nodes
- Flexible configuration and topology
- Can evaluate routing and transport protocols for WMNs.
- Integrated with the existing wireless sensor network testbed



Source: http://users.ece.gatech.edu/~ismailhk/mesh/work.html

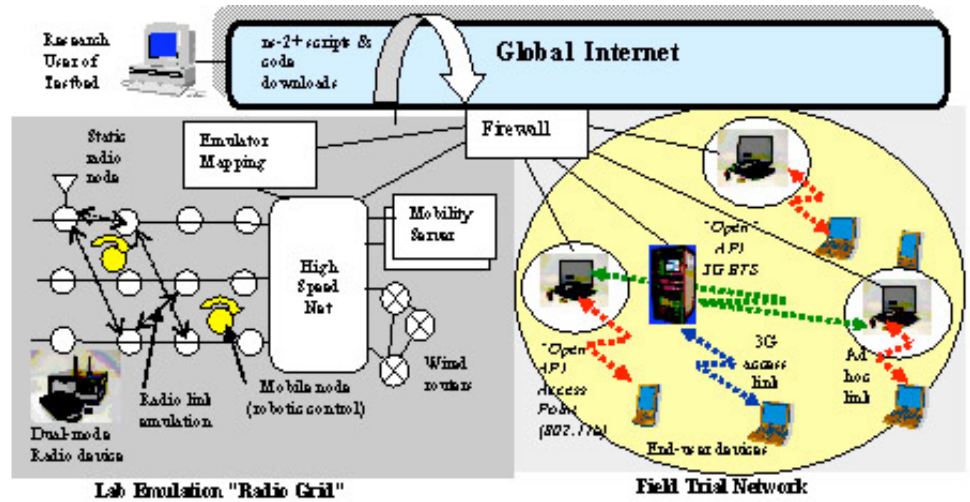
MIT Roofnet

- Experimental testbed
- 40 nodes at the present
- Real users (volunteers)
- Focus on link layer measurements and routing protocols
- Open source software runs on Intersil Prism 2.5 or Atheros AR521X based hardware

Source: http://pdos.csail.mit.edu/roofnet/doku.php

Rutgers Winlab ORBIT

- Collaborative NSF project (Rutgers, Columbia, Princeton, Lucent Bell Labs, Thomson and IBM Research)
- Start date: September 2003
- Emulator/field trial wireless system
- 400 nodes radio grid supporting 802.11x
- Software downloaded for MAC, routing, etc.
- Outdoor field trial

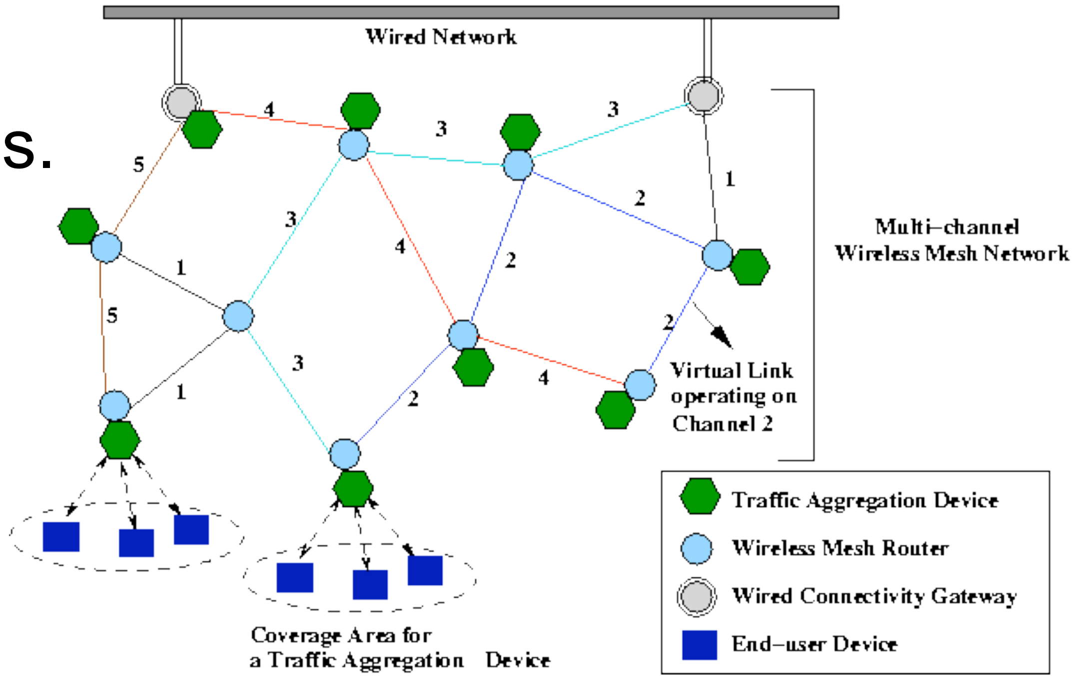


High-level Architecture of Proposed 2-Tier ORBIT Wireless Network Testbed

Source: www.winlab.rutgers.edu

SUNY Stonybrook Hyacinth

- Multichannel testbed based on stock PCs with two 802.11a NICs.
- Research focus on:
  - interface channel assignment
  - routing protocol



Source: http://www.ecsl.cs.sunysb.edu/multichannel/

University of Utah Emulab

- Three experimental environments
  - simulated,
  - emulated, and
    - hundreds of PCs (168 PCs in racks)
    - Several with wireless NICs (802.11 a/b/g)
  - wide-area network
    - 50-60 nodes geographically distributed across approximately 30 sites
- Smaller brothers at
  - U. of Kentucky
  - Georgia Tech

Source: www.emulab.net

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Standards related to WMNs

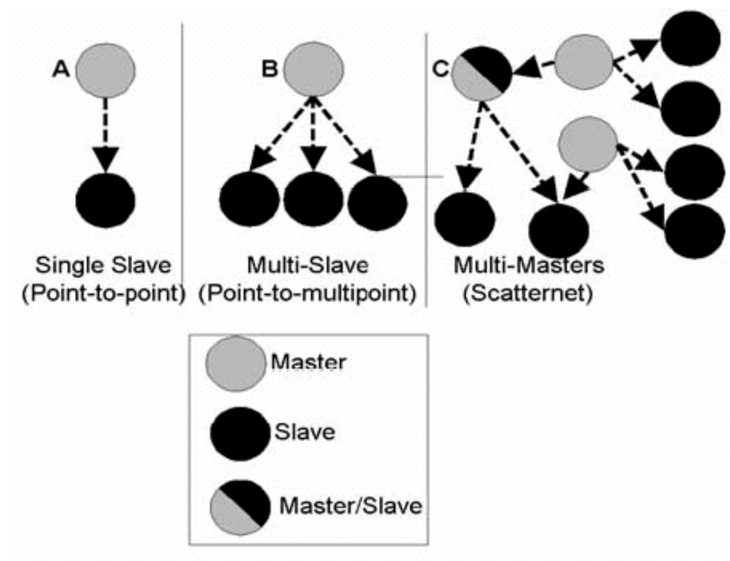
- IEEE 802.11s
- IEEE 802.15.1
- IEEE 802.15.4
- IEEE 802.15.5
- IEEE 802.16a

IEEE 802.11s
ESS Mesh Networking

- Started on May 13th, 2004
- 802.11a/b/g were never intended to work multi-hop
- Target application: extended 802.11 coverage
- Will define an Extended Service Set (ESS), and a Wireless Distribution System (WDS)
- Purpose: "To provide a protocol for auto-configuring paths between APs over self-configuring multi-hop topologies in a WDS to support both broadcast/multicast and unicast traffic in an ESS Mesh [...]".
- Status: 35 proposals will likely be submitted in July 2005.
- Intel and Cisco are active in this area

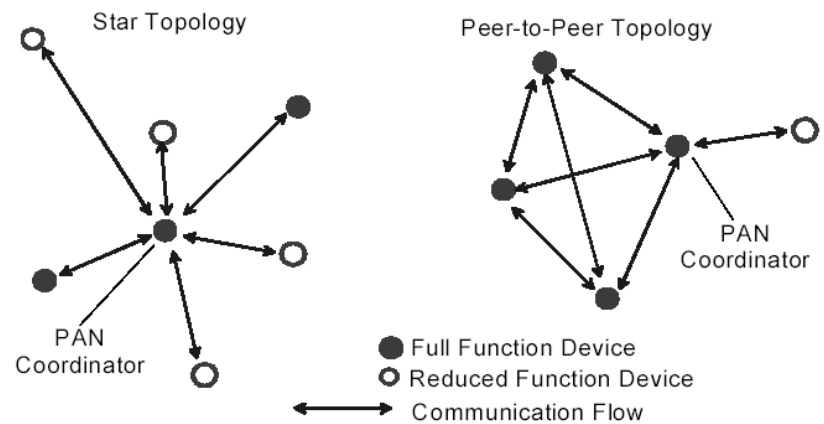
IEEE 802.15.1
Bluetooth

- Low data rate (1Mbps bit-rate) PAN technology
- Targets wire replacement
- Has provisions for multi-hop scatternets
- Not a popular wireless mesh network platform due to:
  - the low bandwidth and
  - limited hardware support for scatternets.



IEEE 802.15.4
Zigbee

- Lower data rate PAN (250,40,20kbps)
- Multi-months – years lifetime on small batteries
- Supports mesh topology – one coordinator is responsible for setting up the network
- Characteristics suitable for wireless sensor networks rather than wireless mesh networks.

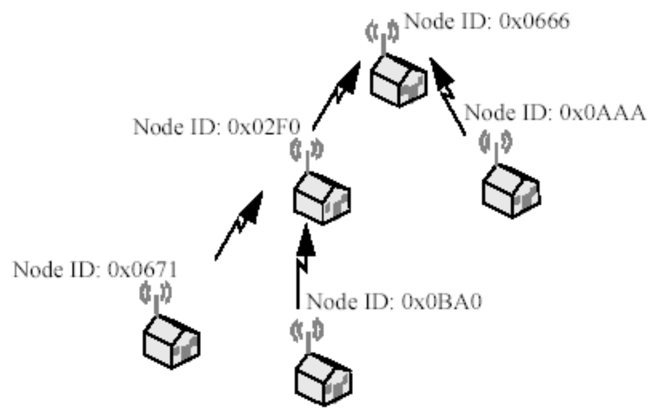


IEEE 802.15.5
Mesh Topology Capability in (WPANs).

- Standard applicable to all other WPANs
- Mesh networks have the capability to provide:
  - Extension of network coverage without increasing transmit power or receive sensitivity
  - Enhanced reliability via route redundancy
  - Easier network configuration
  - Better device battery life due to fewer retransmissions

IEEE 802.16a
WiMax

- Published April 1st 2003
- Enhances the original 802.16 standard
- Original IEEE 802.16 specifies only point to multipoint functionality – great for gateway to internet links
- The extensions specifies user-user links using:
  - either centralized schedules,
  - or distributed schedules.



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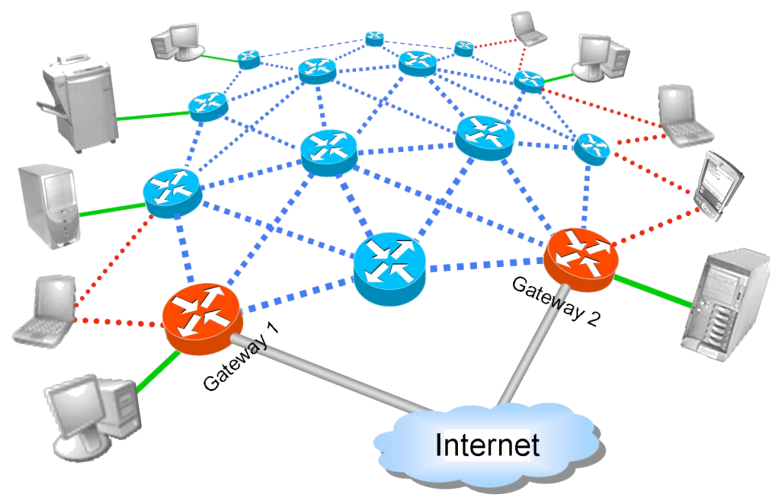
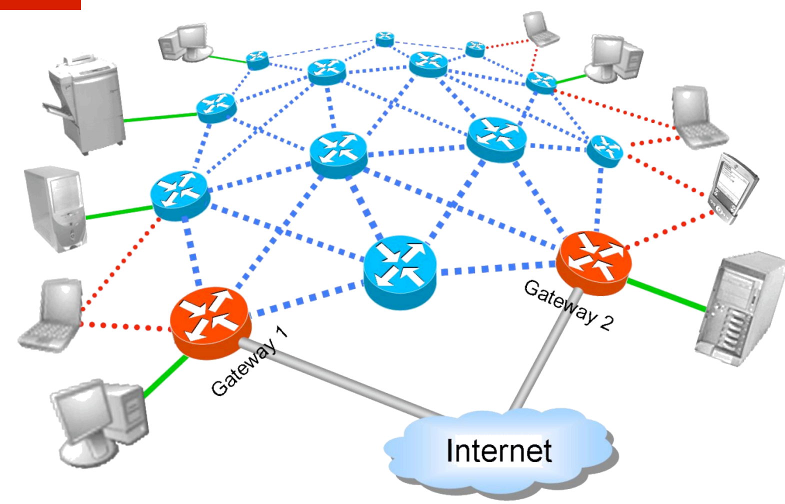
Conclusion

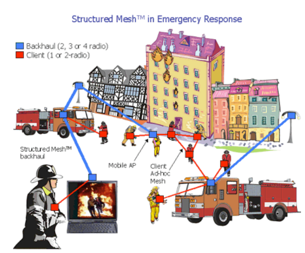
- Relatively new technology
- Significant advantages for many applications
- Significant amount of research exist and, yet,
- Significant improvements can be enabled by more research.
- Impressive products from several companies
- Multiple standardization activities are on the way

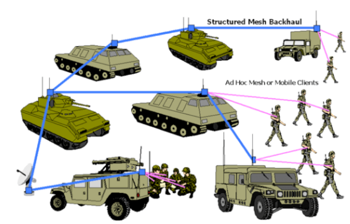


Acknowledgements and Disclaimer

- Special thanks to Jangeun Jun for practically all original artwork in this presentation
- Many thanks to all companies that graciously allowed the use of their artwork for this presentation







Source: www.meshdynamics.com

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