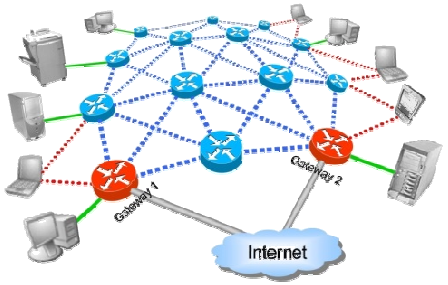
A Tutorial on Wireless Mesh Networks



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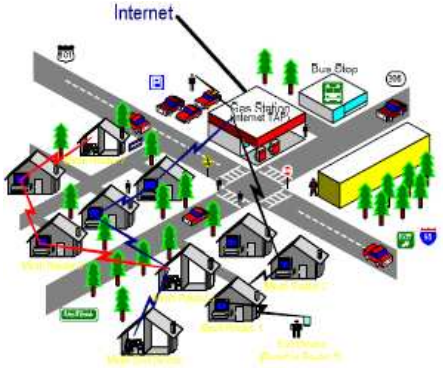
Mesh Networking



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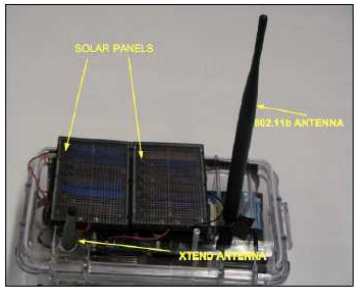

Tutorial Overview

- Overview of the technology
- Opportunities and Applications
- Research Challenges
- Current Testbeds
- Conclusions

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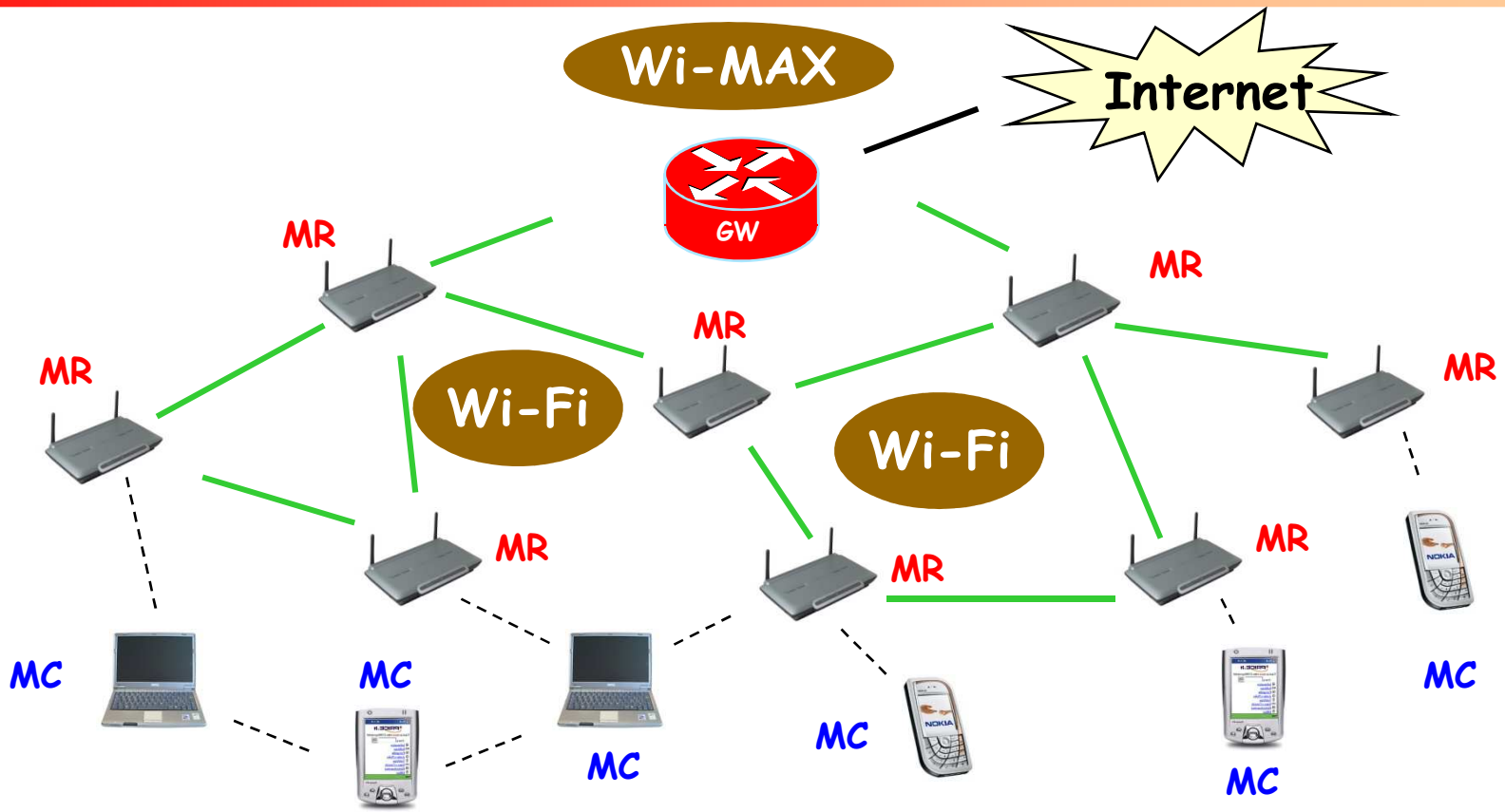
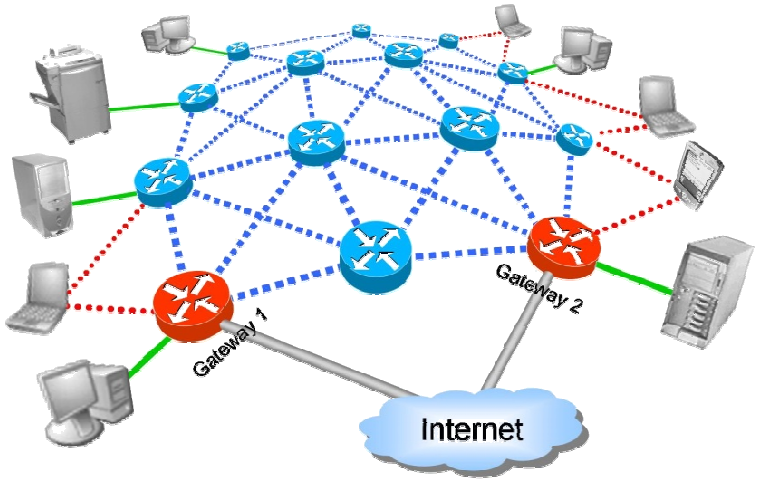
WMN: Network Architecture

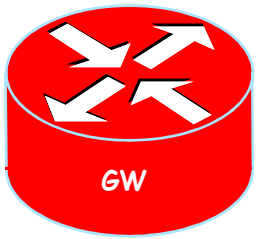


- Nodes Hetereogeneity: mesh clients (MC) vs mesh routers (MR)
- Wireless Backbone Infrastructure
- Multiple types of technologies for network access

Network Components: Gateways

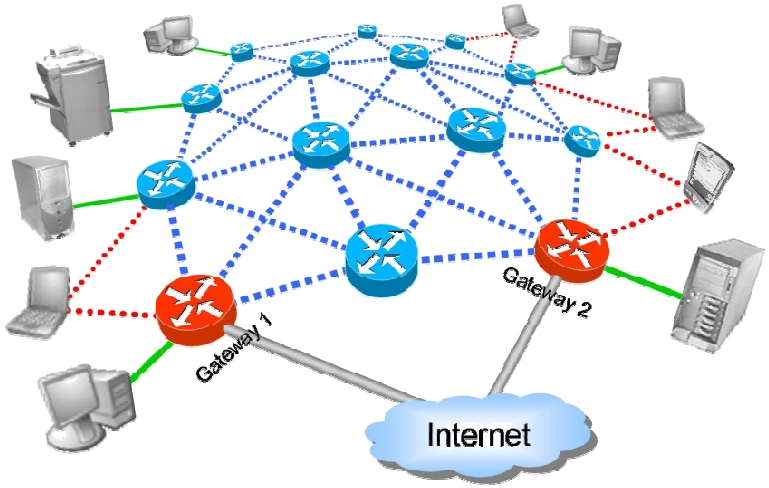
- Multiple interfaces (wired & wireless)
- Mobility
  - Stationary (e.g. rooftop) – most common case
  - Mobile (e.g., airplane, busses/subway)
- Serve as (multi-hop) "access points" to user nodes
- Relatively few are needed, (can be expensive)

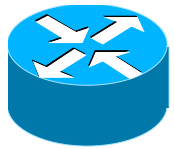




Network Components: Mesh Routers (MRs)

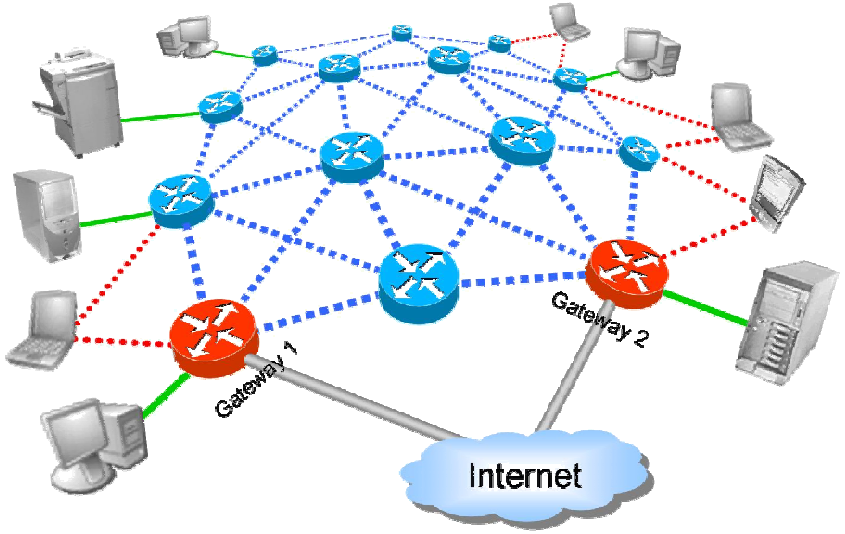
- At least one wireless interface.
- Form a static wireless backbone (WB)
- Mobility
  - Stationary (e.g. rooftop)
- Provide coverage (acts as a mini-cell-tower).
- Do not originate/terminate data flows
- Many needed for wide areas, hence, cost can be an issue.

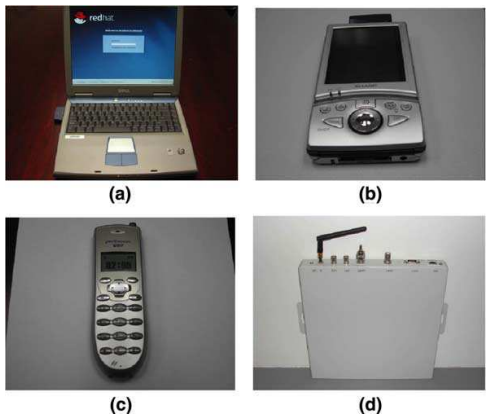




Network Components: Mesh Clients (MCs)

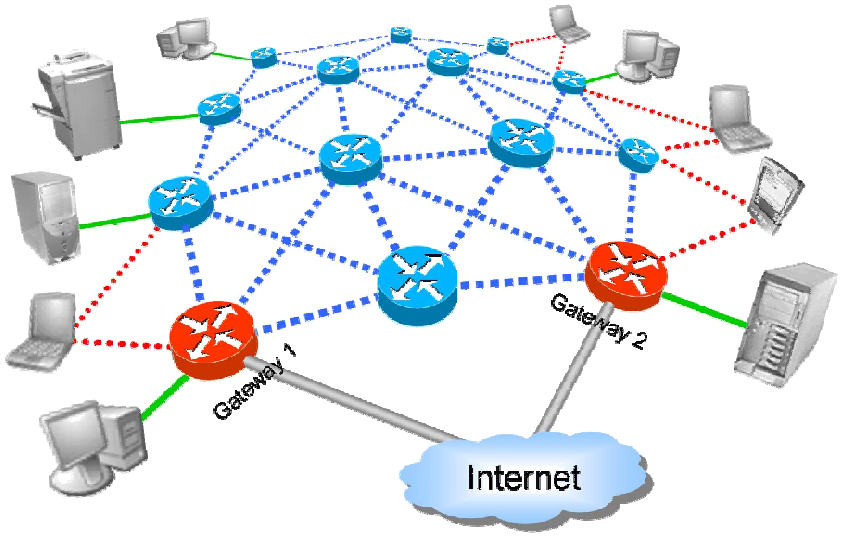
- Typically one interface.
- Mobility
  - Stationary
  - Mobile
- Connected to the mesh network through wireless routers (or directly to gateways)
- The only sources/destinations for data traffic flows in the network.





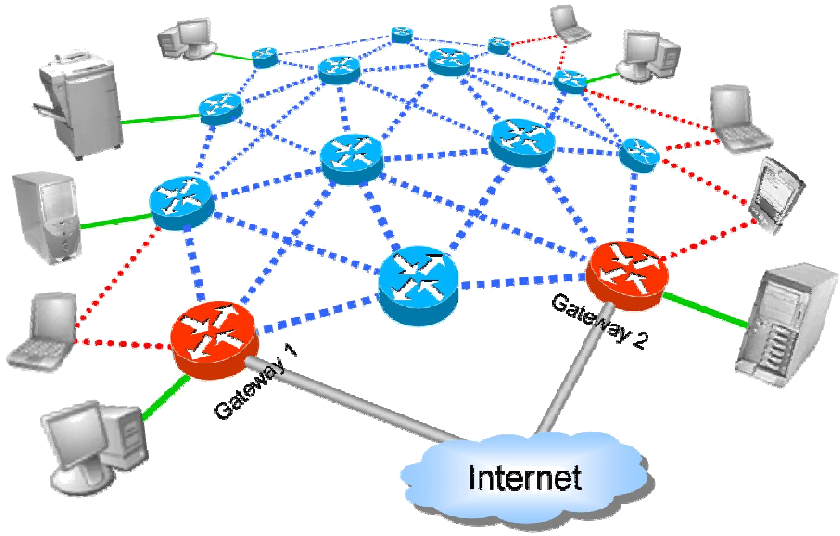
Network Components: MRs-MRs links

- **Wireless**
  - 802.11x
  - Proprietary
- **Usually multipoint to multipoint**
  - Sometimes a collection of point to point
- **Often the bottleneck**



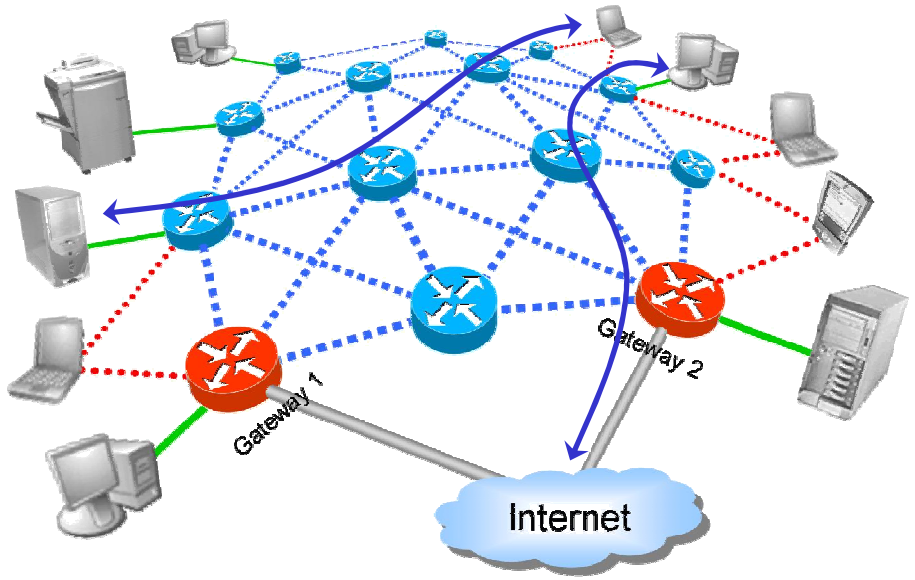
Network Components: IGs-Internet links

- 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



WMNs: Data Flows

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



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

Wireless Mesh Networks: Characteristics

- Multi-Hop Wireless Networks
- Capability of self-forming, self-healing and self-organization
- Multiple types of network access
- Dependence of power-consumption and mobility constraints on the type of mesh nodes
- Compatibility with existing wireless networks

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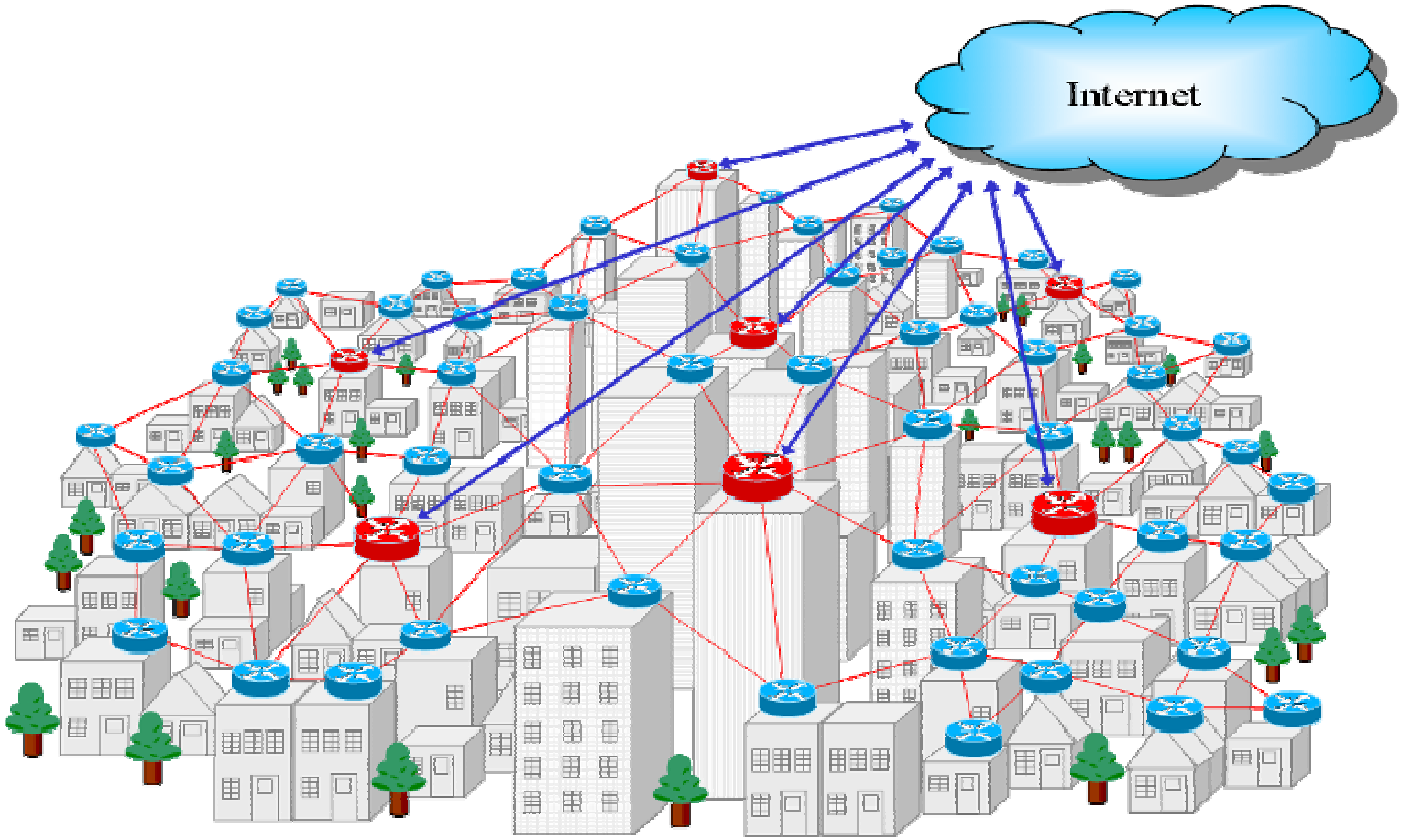
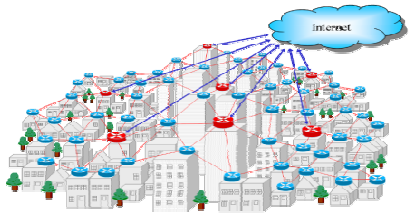
Broadband Internet Access

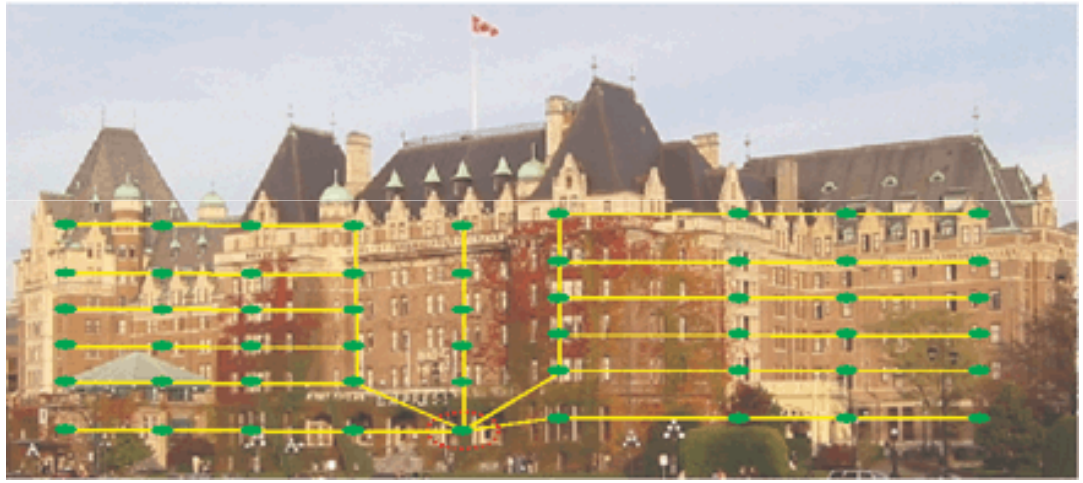


Compared to Other Technologies …

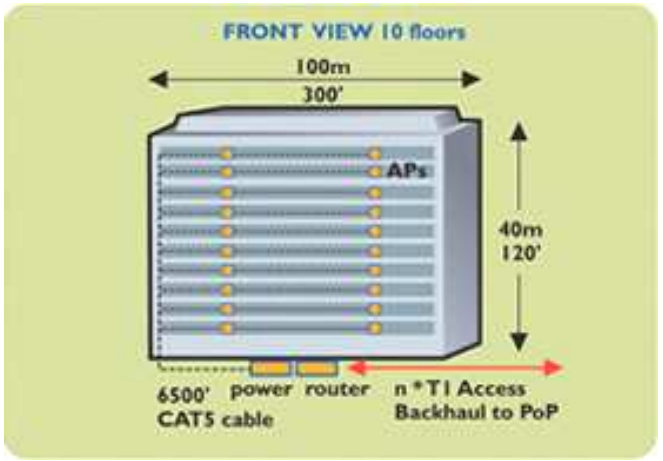
	Cable DSL	WMAN (802.16)	Cellular (2.5-3G)	WMN
Bandwidth	Very Good	Very Good	Limited	Good
Upfront Investments	Very High	High	High	Low
Total Investments	Very High	High	High	Moderate
Market Coverage	Good	Modest	Good	Good

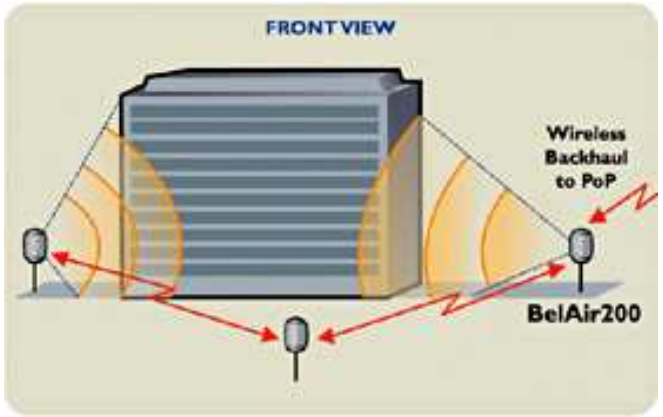
Extend WLAN Coverage

Hotel HotZone with MeshDynamics All Wireless Switch Stacks



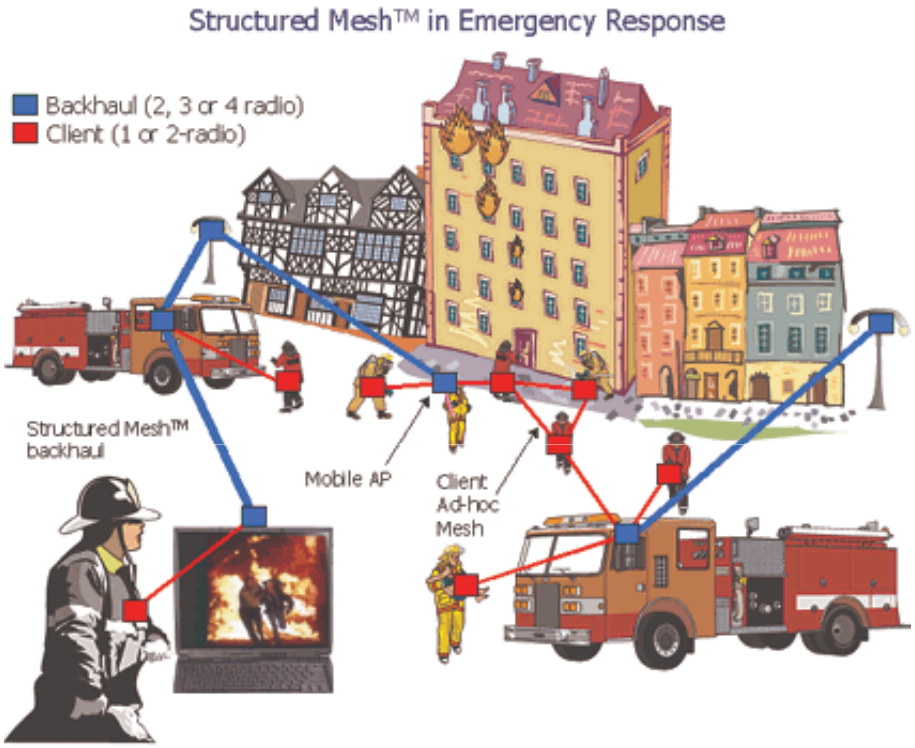
Source: www.meshdynamics.com

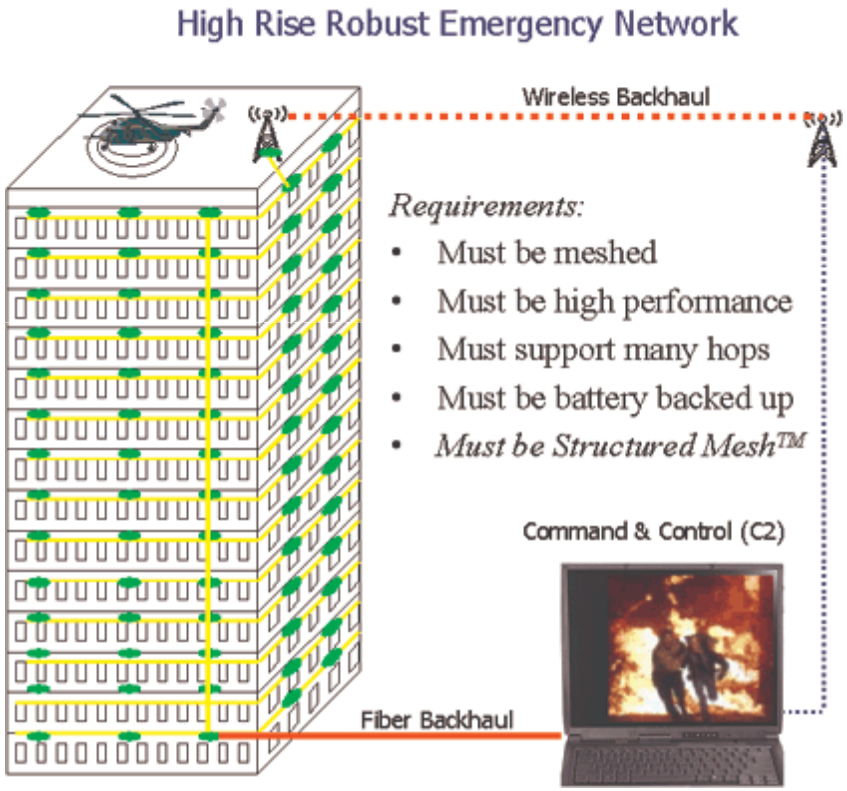




Source: www.belair.com

Emergency Response





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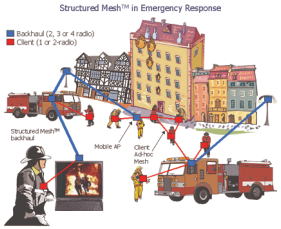
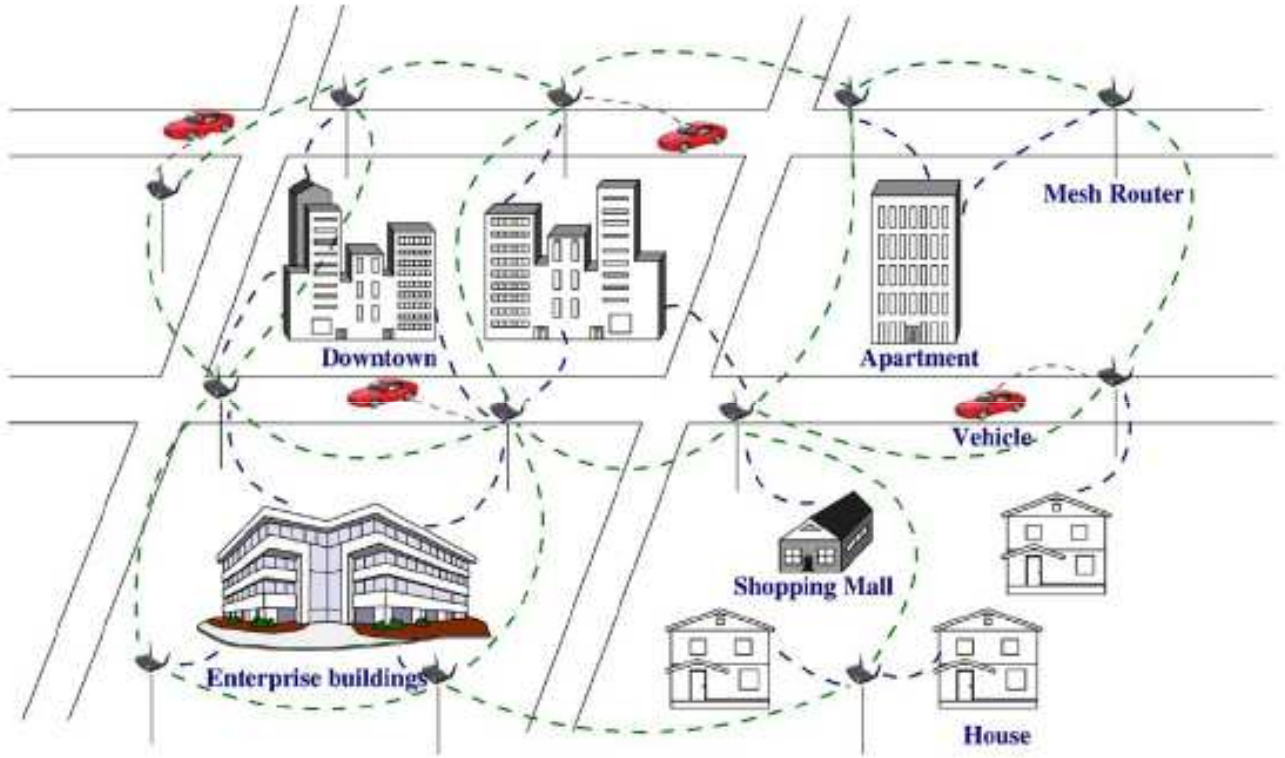
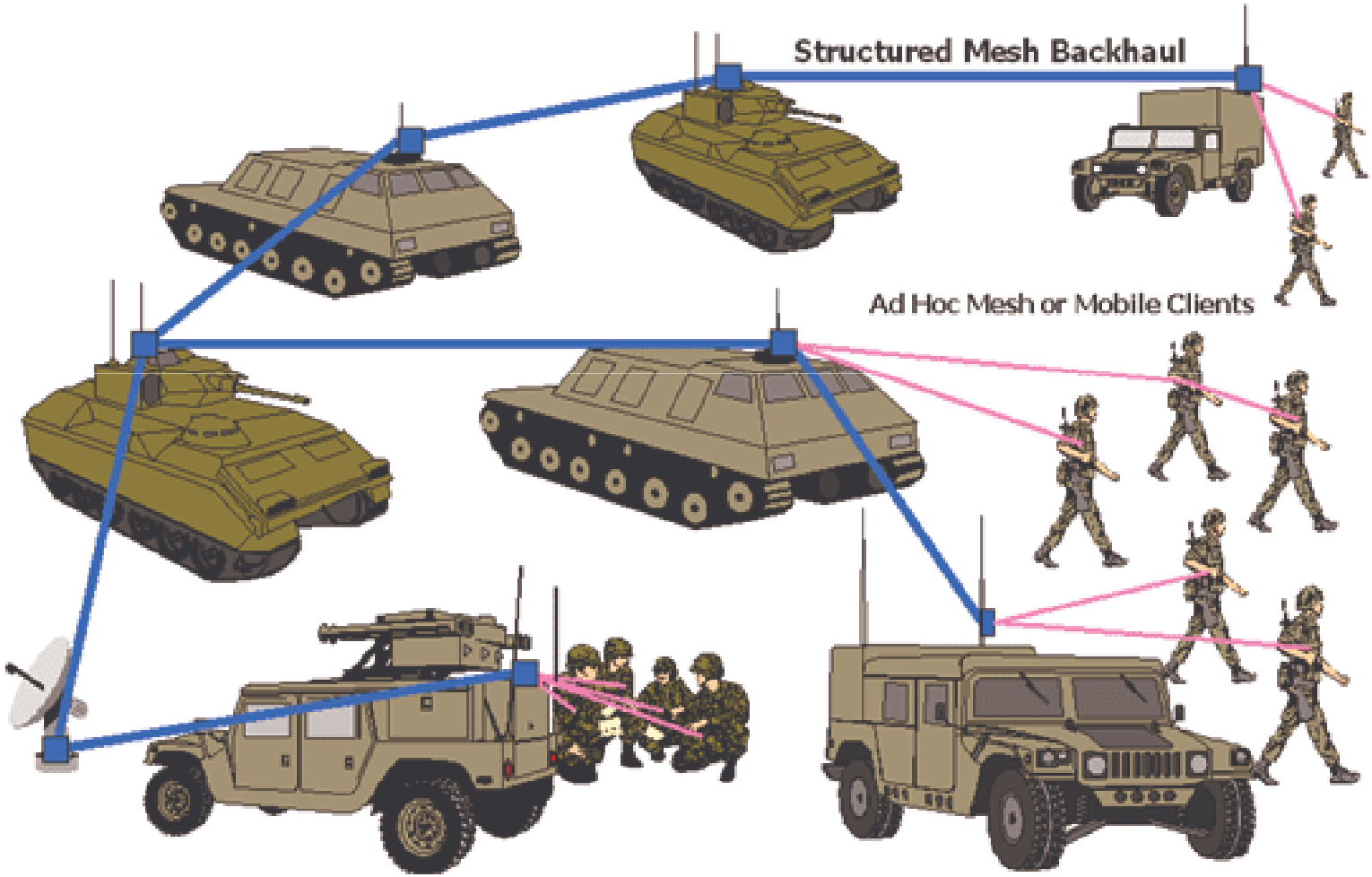
 Source: www.meshdynamics.com	Cellular 2.5 - 3G	Walkie Talkie	WMN
Availability	Reasonable	Good	Good
Bandwidth	Limited	Poor	Good
Geolocation	Poor	Poor	Limited

Integration with Transportation Systems



- Passenger information services
- Direct competition with G2.5 and G3 cellular systems.

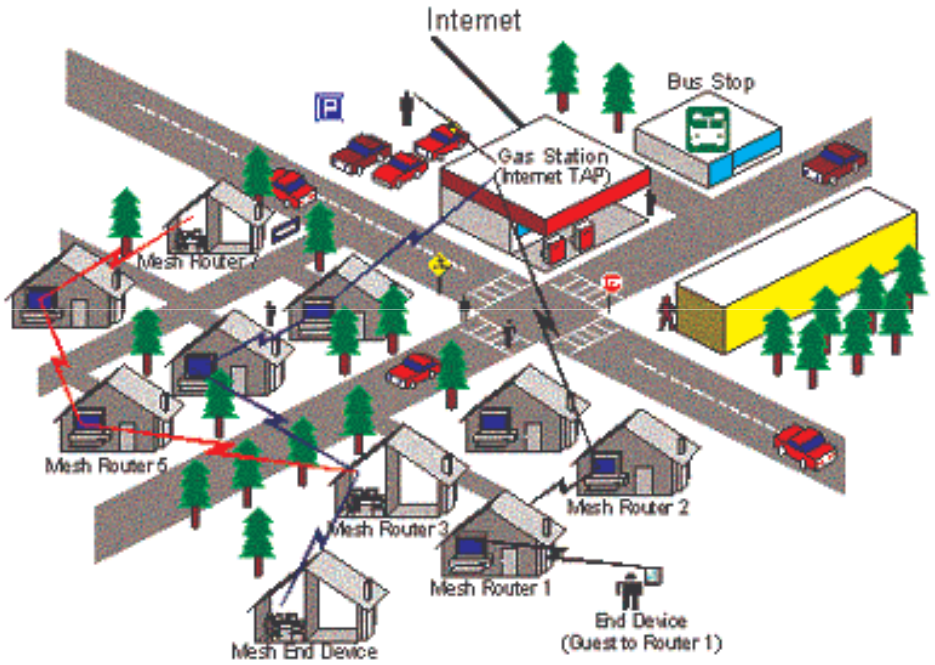
Military Communications



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



Many Other Applications

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

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

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Research Topics for WMNs

- **Physical Layer**
  - Smart Antennas
  - MIMO techniques
- **MAC Layer**
  - Multiple Channels
- **Network Layer**
  - Routing
  - Fairness and QoS
- **Transport Layer**
- Provisioning
- Security
- Network Management
- Geo-location

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PHY – WhishList

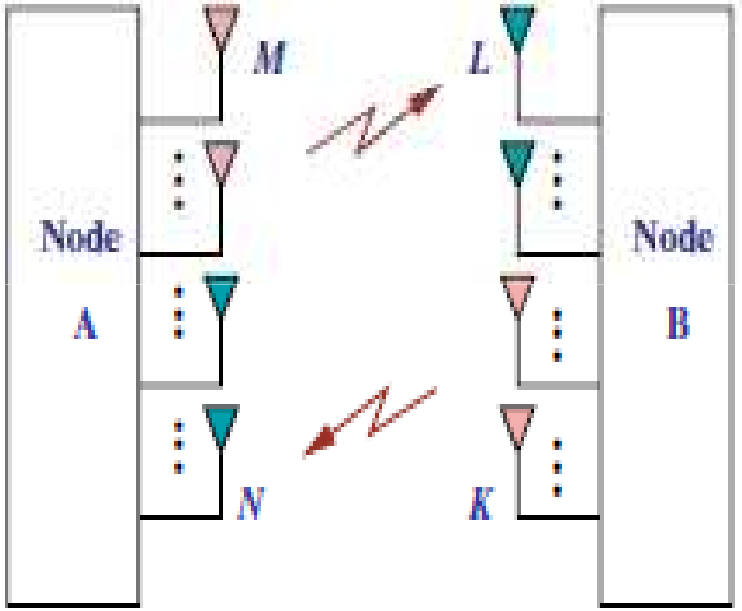
- **Performance**
  - Bandwidth
  - Robust modulation
  - Sensitivity
  - Short preamble
  - Fast switch between channels
  - Fast switch from Tx/Rx and back
- **Extras**
  - Mobility (potentially high-speed)
  - Link adaptation
  - Variable transmission power (details shortly)
  - Multiple channels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

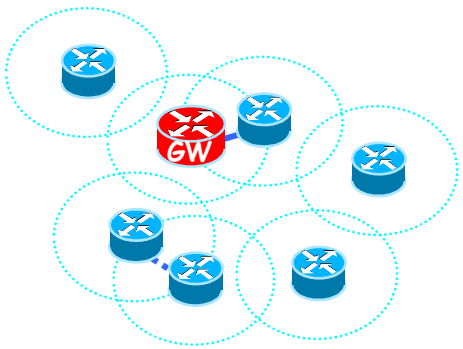
PHY: MIMO techniques

- MIMO: Multiple Input Multiple Output
- MIMO can improve the system capacity of three times or even more
- Functions of MIMO: precoding vs spatial multiplexing
- 802.11n standard



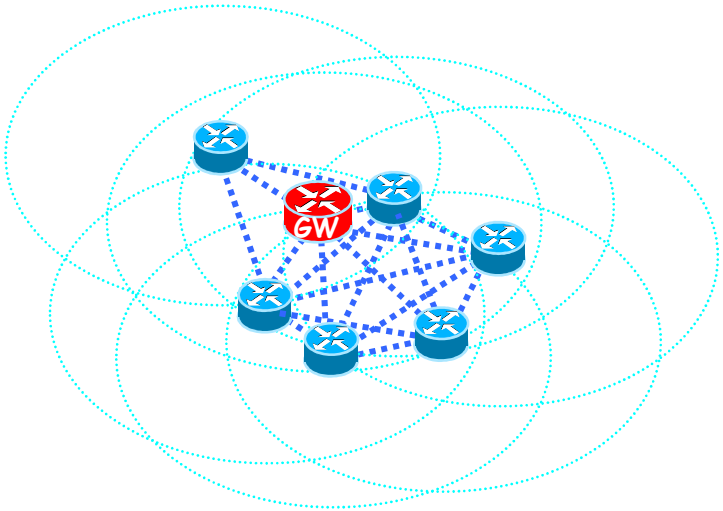
PHY: Trasmitting Power Control

Too low !!!



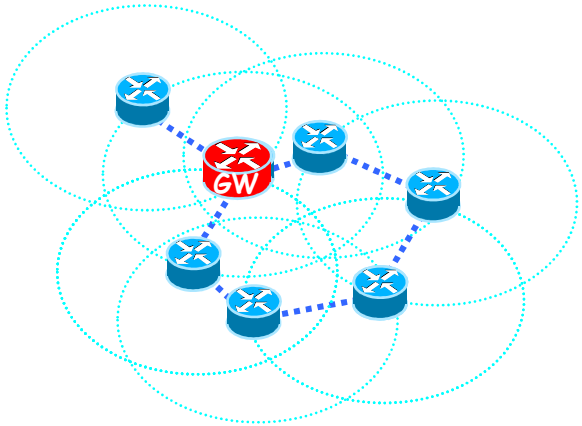
Network Disconnected !!!

Too high



High interference!!!

Just right



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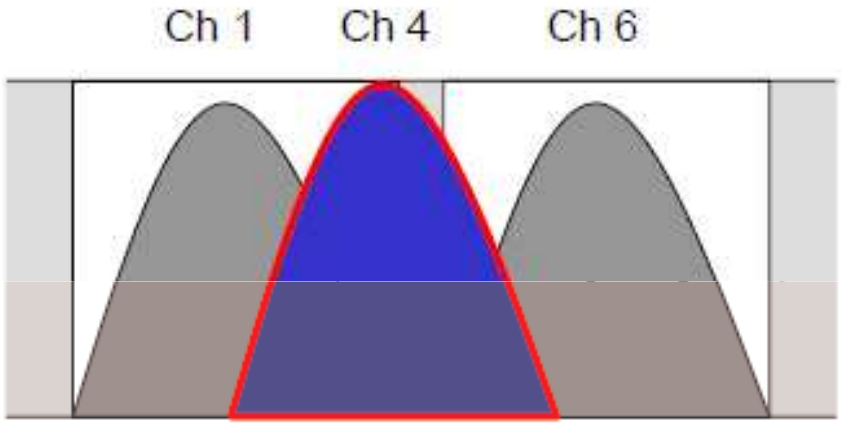
Channelization in 802.11a

- The overall bandwidth is divided into 11 channels

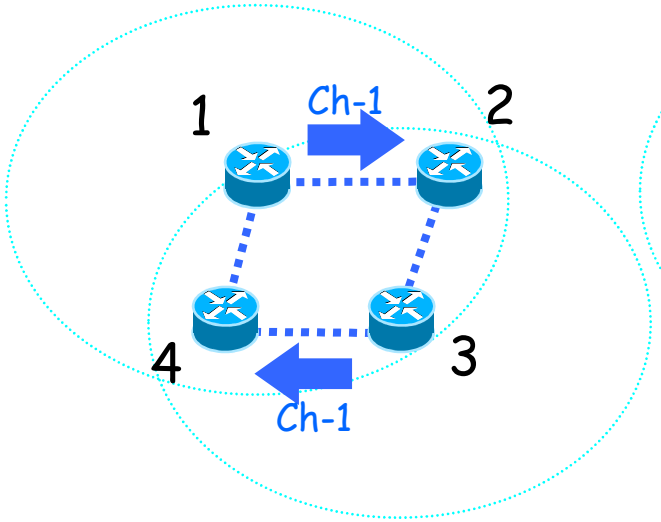


	P Li				Modula tion	Sensitivity (dBm)
U-NII Lower Band (5150 – 5350 MHz)	4((2.5 r				BPSK	-82
					BPSK	-81
U-NII Mid Band (5250 – 5350 MHz)	20 (12.5				QPSK	-79
					QPSK	-77
		64	5320	24	16-QAM	-74
U-NII Upper Band (5725 – 5825 MHz)	800 mW (50	149 153	5745 5765	36	16-QAM	-70
					AM	-66
					AM	-65

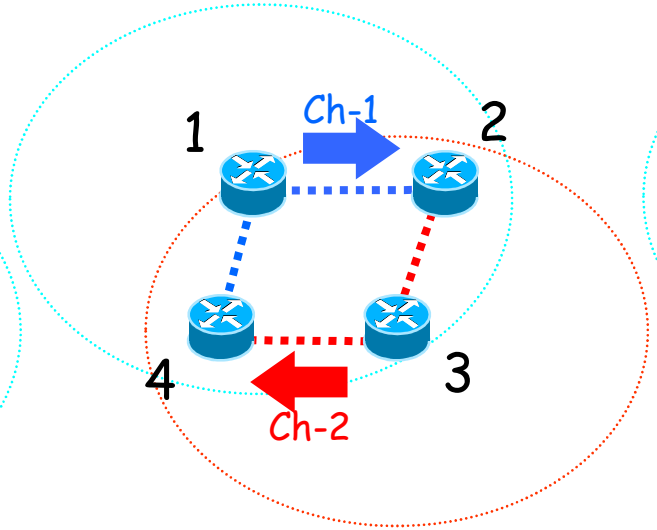
11 orthogonal channels in 802.11a
… just **3** in 802.11 b/g!!

MAC Multichannels: Why?

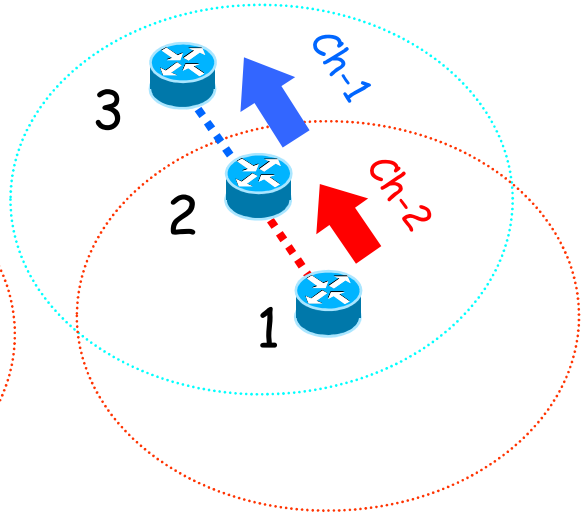
- Increases network capacity



User bandwidth = B/2



User bandwidth = B

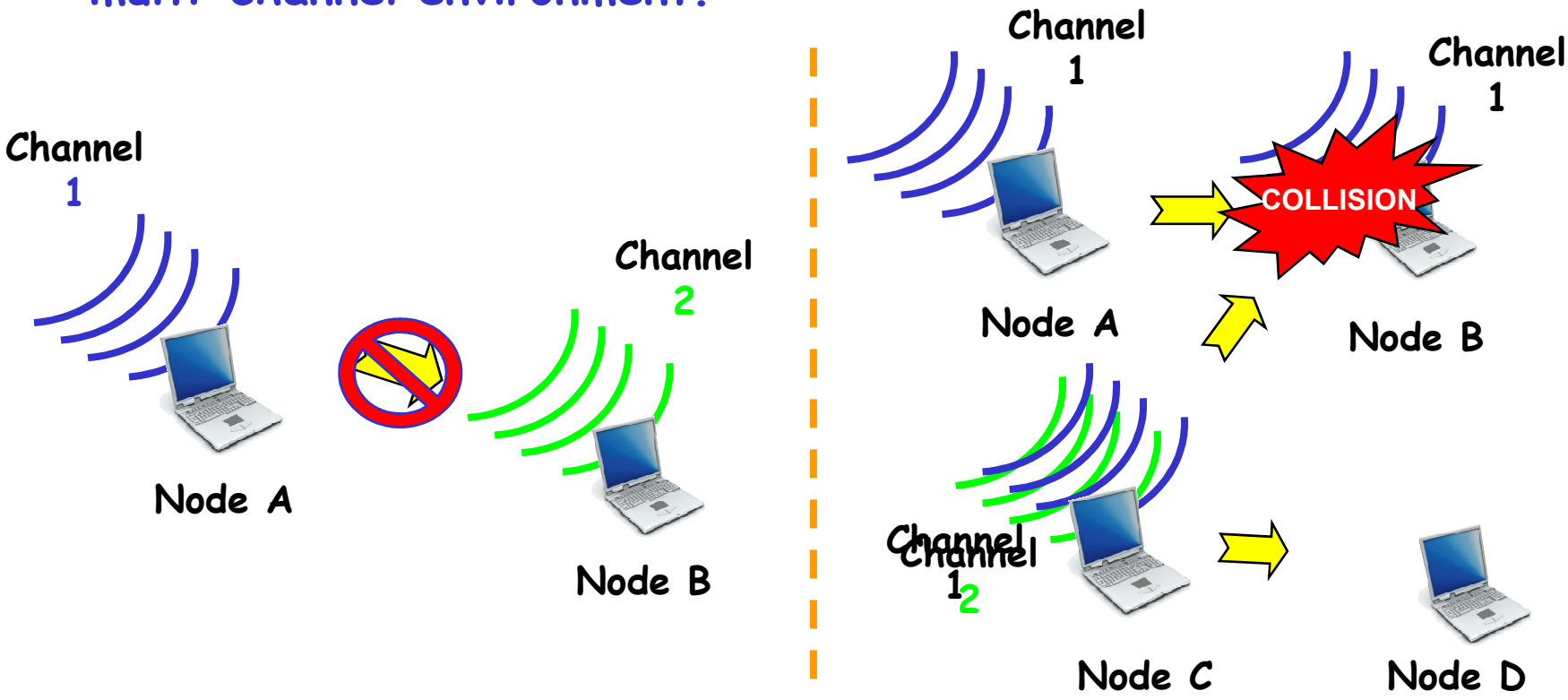


Chain bandwidth = B

B = bandwidth of a channel

MAC Problems and Design Issues

MAC Protocols for WMNs face new challenges caused by the multi-channel environment.



Deafness Problem

Multi-Channel Hidden Terminal Problem

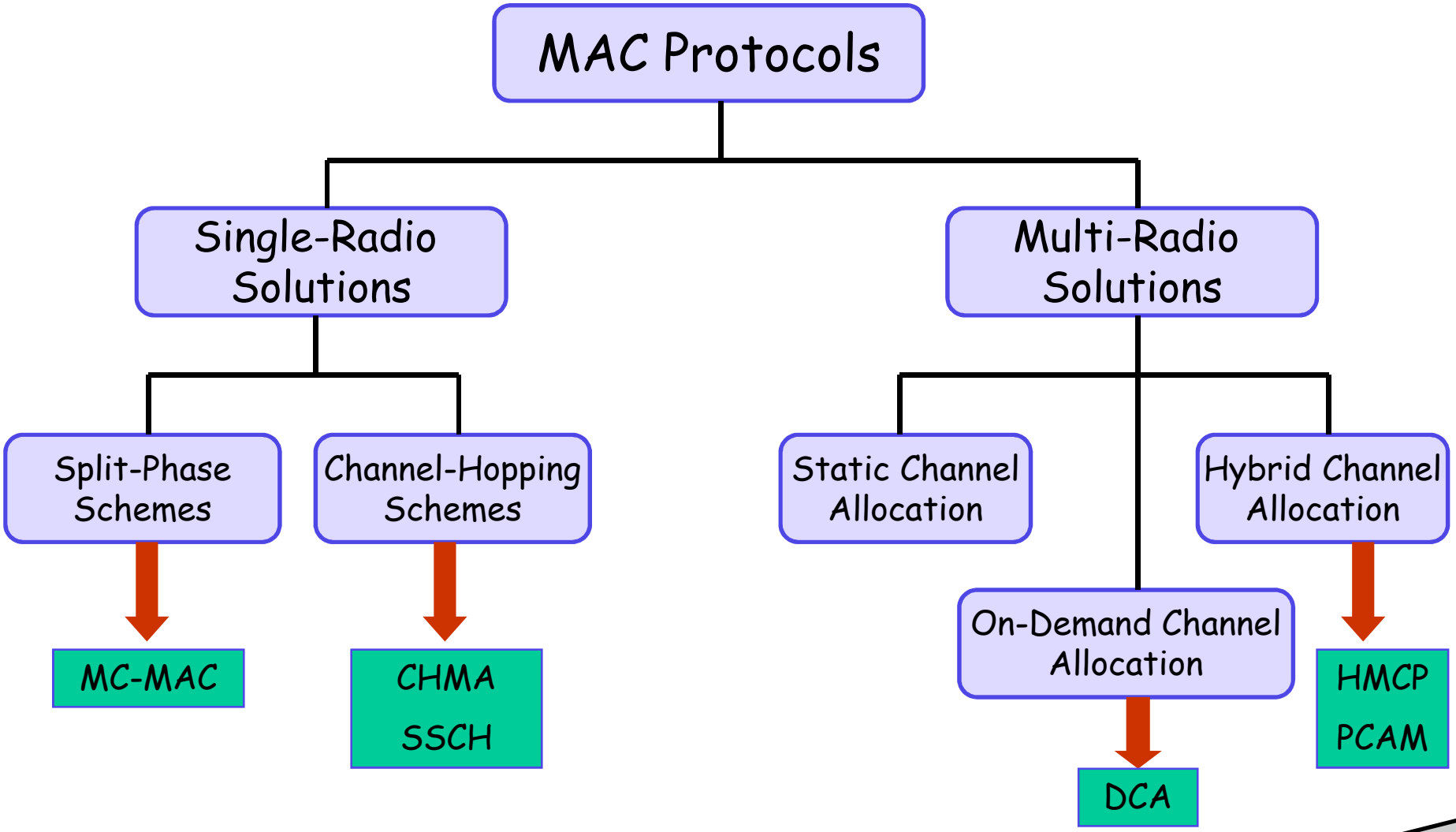
MAC Multi-Radio Multi-Channel Technology

- **GOAL:**

  Assign n non-interfering channels to n pair of nodes such that n packet transmissions can occur simultaneously.

	Single Channel	Multiple Channels
Single Radio	Today	☺
Multiple Radio	X	☺

MAC Solutions for WMNs



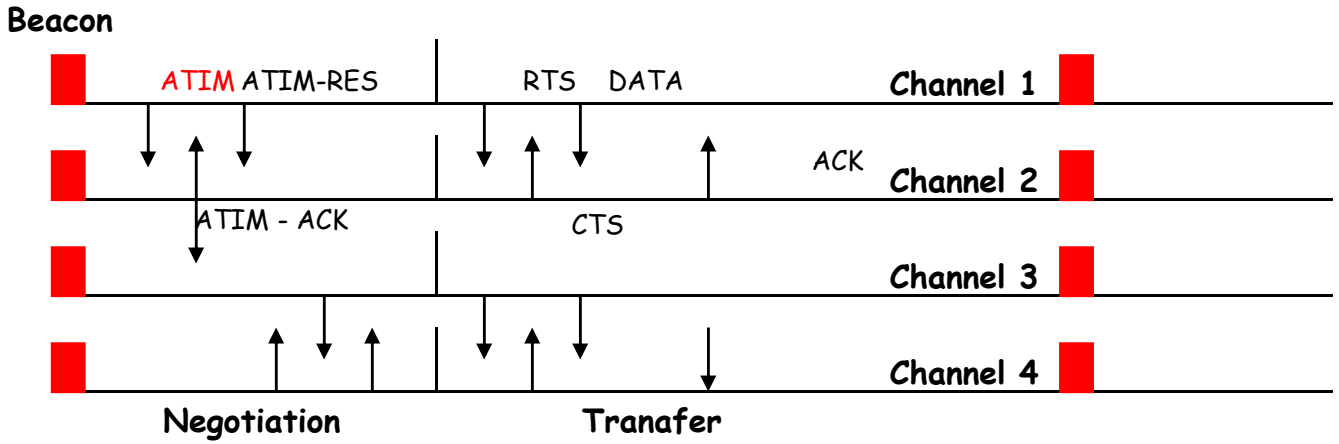
Multi-Channel Single-Radio MAC Solutions (1)

A) Multiple rendezvous on a control channel

Two-phases protocols:

- ***Negotiation Phase***: All nodes switch to a pre-defined *common channel* and negotiate the channel to use
- ***Transfer Phase***: Once a channel is selected, the source & receiver switch to this channel and data transfer occurs

. **MMAC Protocol**

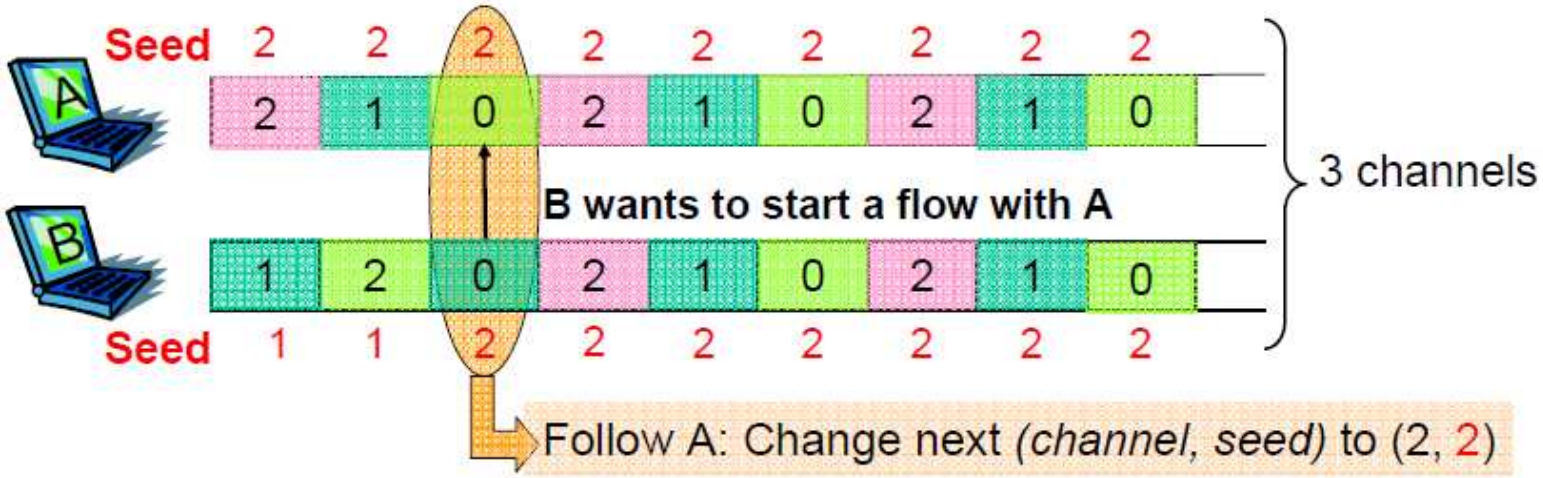


Multi-Channel Single-Radio MAC Solutions (2)

B) Multiple rendezvous at fixed time steps

Time-slotted protocols:
- At each slot hop to a different channel
- Senders and receivers probabilistically meet and exchange schedules

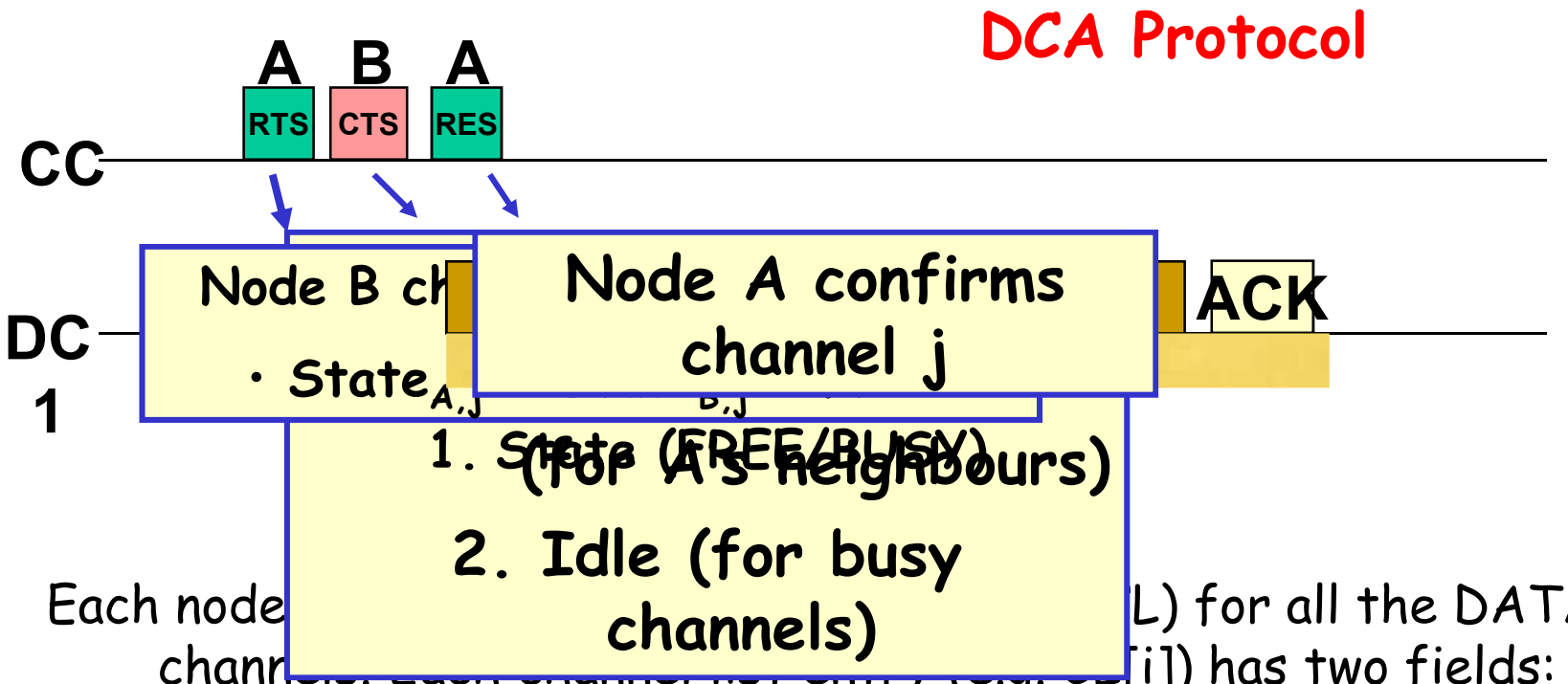
SSCH Protocol



Multi-Channel Multi-Radio MAC Solutions

- **Static Assignment**
  - One channel to one radio for all time
  - Suboptimal spectrum use
- **Dynamic Assignment**
  - Channels assigned to match traffic patterns and/or to reduce interference
- **Hybrid Assignment**
  - One channel to one interface for all time, for all other interfaces, channels are assigned dynamically to match traffic patterns and/or reduce interference

Multi-Channel Multi-Radio MAC Solutions



Each node [illegible] for all the DATA channels. Each channel [illegible] has two fields:

1. $State_{i,x}$ -> channel i is available for X or not ({Free,Busy })

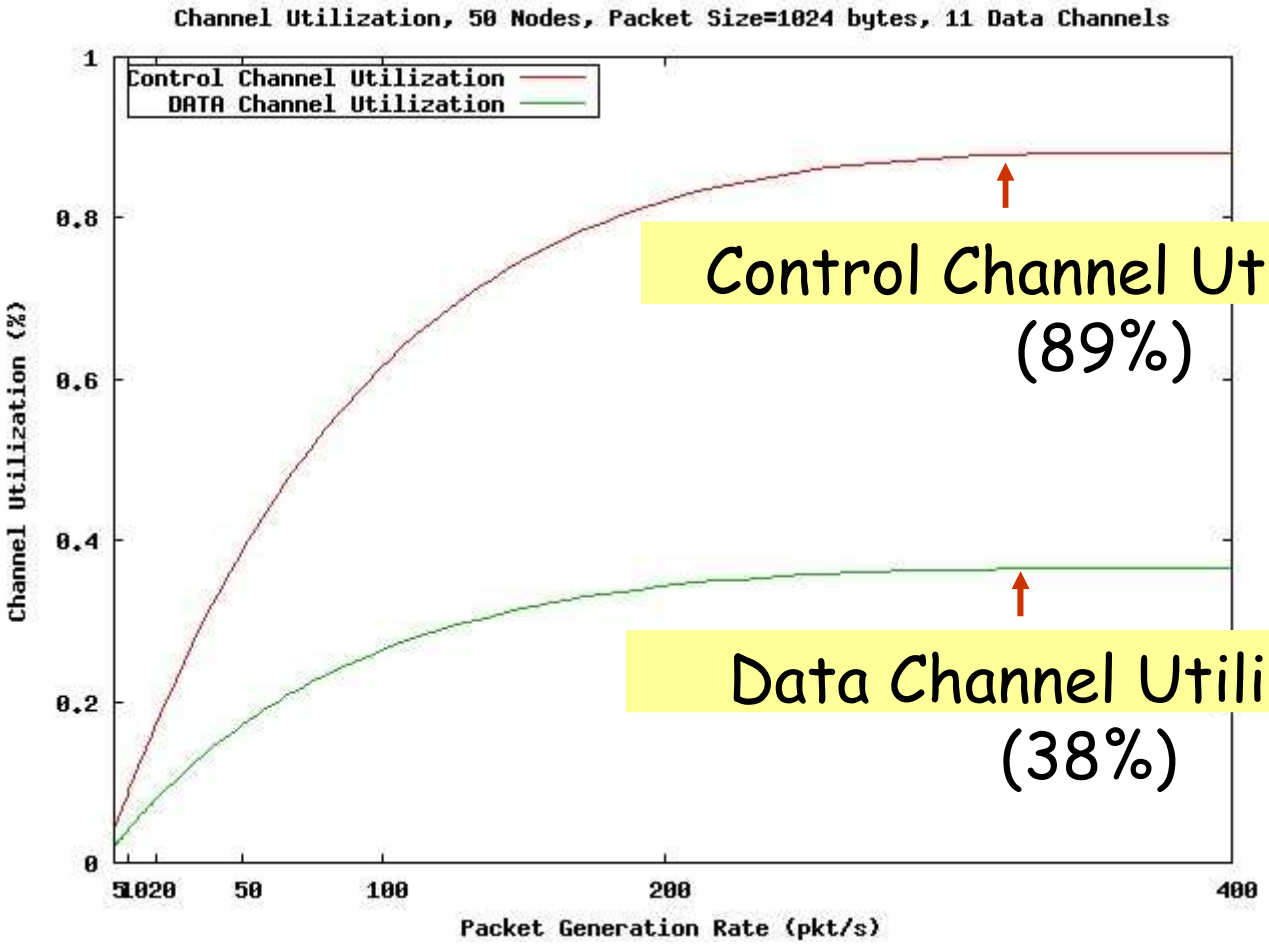
2. $Idle_{i,x}$ -> Time when channel i will be released by node X or by X's neighbours.

ON-DEMAND CHANNEL ALLOCATION

DCA MAC Scheme: Performance Analysis

When the #Channel is HIGH (11) -> CC saturated

DCs under-utilized



Control Channel Utilization (89%)

Data Channel Utilization (38%)

Research Topics for WMNs

- **Physical Layer**
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  - MIMO techniques
- **MAC Layer**
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- **Network Layer**
  - Routing
  - Fairness and QoS
- **Transport Layer**
- Provisioning
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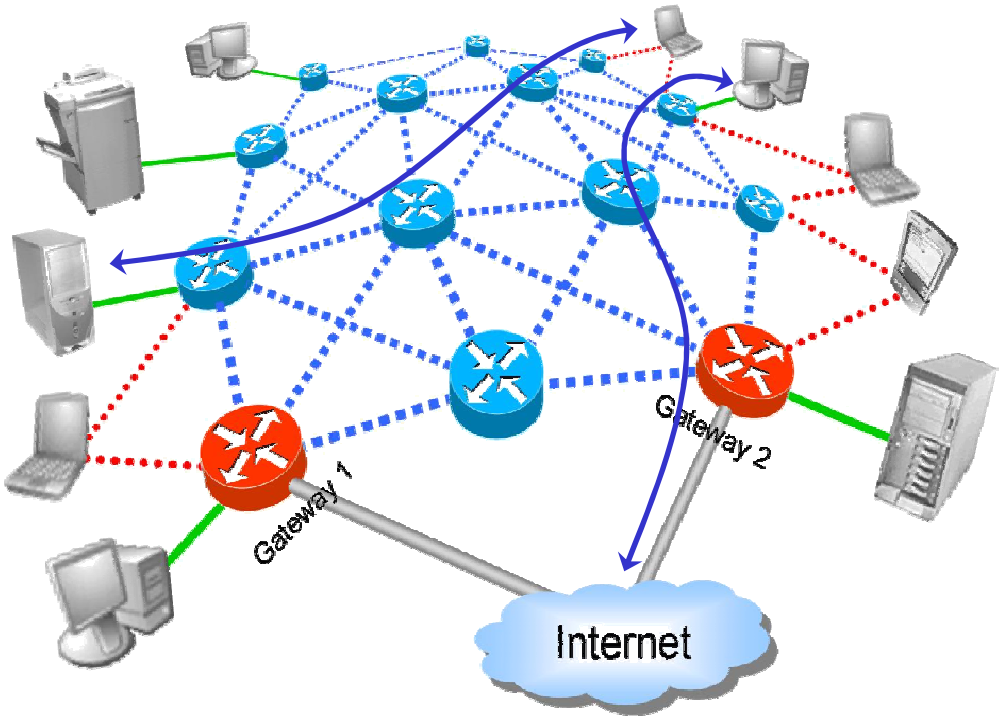
Routing for WMNs

- 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



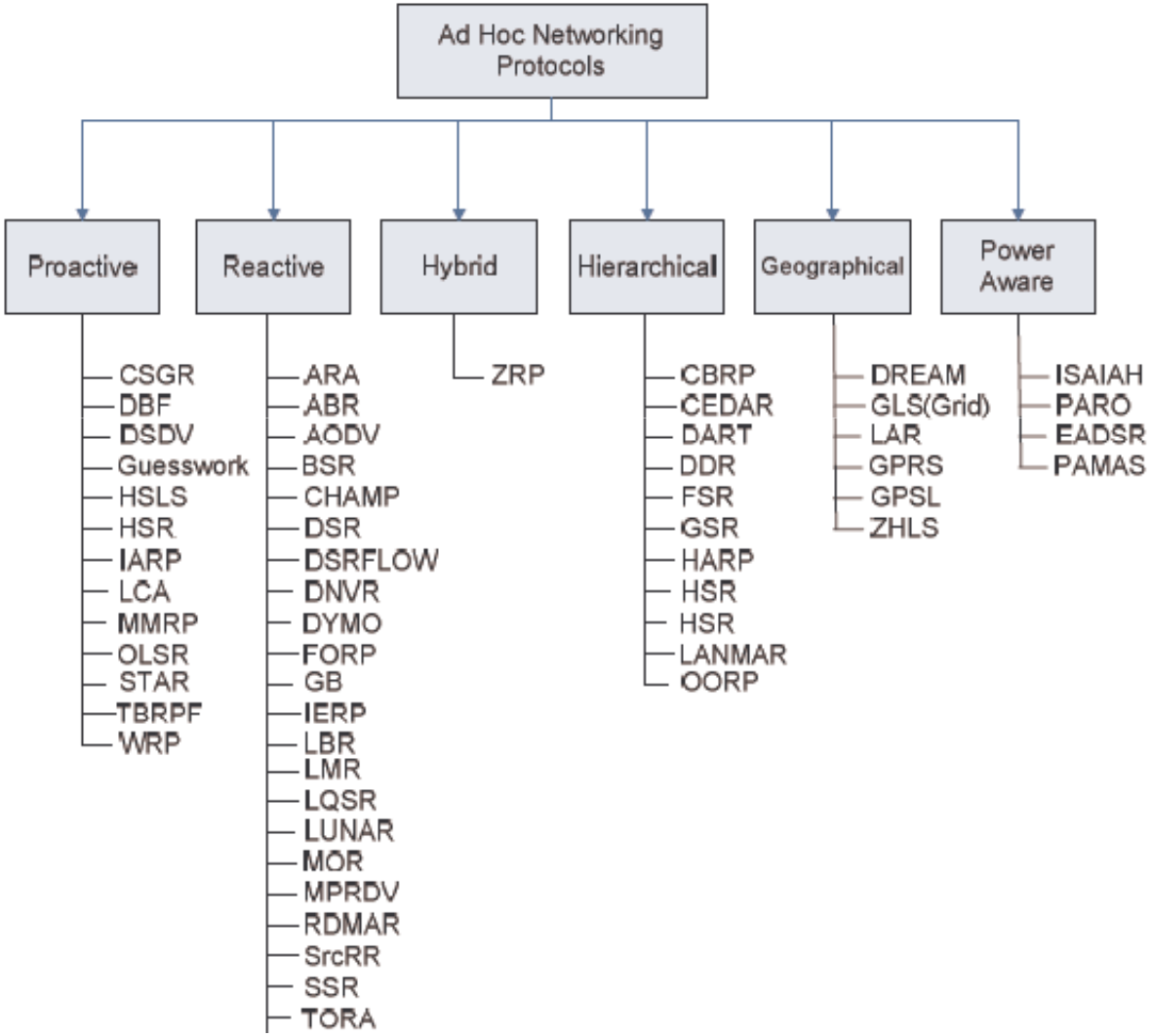
Routing – Wish List

- **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)

Routing Protocols for WMNs

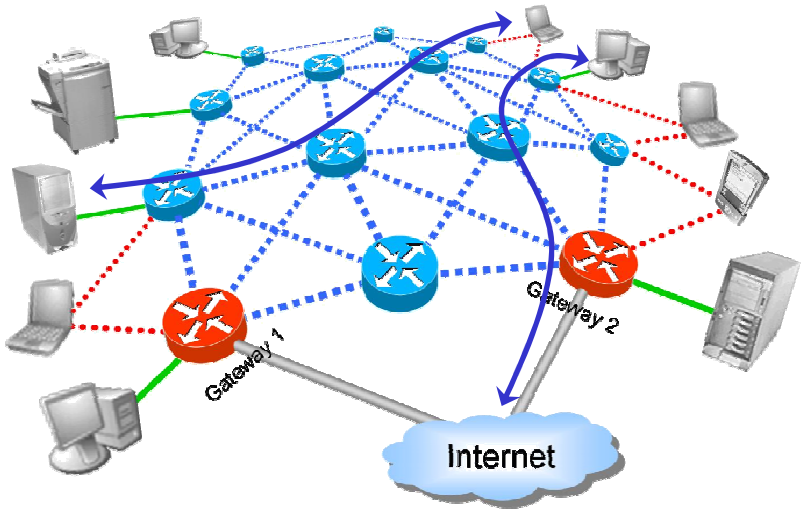
- ABR (Associativity-Based Routing Protocol)
- AODV (Ad Hoc On Demand Distance Vector)
- ARA (Ant-based Routing Algorithm)
- BSR (Backup Source Routing)
- CBRP (Cluster Based Routing Protocol)
- CEDAR (Core Extraction Distributed Ad hoc Routing)
- CHAMP (CacHing And MultiPath routing Protocol)
- CSGR (Cluster Gateway Switch Routing)
- DART (Dynamic Address Routing)
- DBF (Distributed Bellman-Ford)
- DDR (Distributed Dynamic Routing)
- DNVR (Dynamic Nix-Vector Routing)
- DSDV (Dynamic Destination-Seq. Dist. Vector)
- DSR (Dynamic Source Routing)
- DSRFLOW (Flow State in the DSR)
- DYMO (Dynamic Manet On-Demand)
- FORP (Flow Oriented Routing Protocol)
- FSR (Fisheye State Routing)
- GB (Gafni-Bertsekas)
- GLS(Grid) (Geographic Location Service)
- GPSAL (GPS Ant-Like)
- GSR (Global State Routing)
- Guesswork
- HARP (Hybrid Ad hoc Routing Protocol)
- HSLS (Hazy Sighted Link State)
- HSR (Hierarchical State Routing)
- HSR (Host Specific Routing)
- IARP (Intrazone Routing Protocol)
- IERP (Interzone Routing Protocol)
- LANMAR (LANdMARk Routing Protocol)
- LAR (Location-Aided Routing)
- LBR (Link life Based Routing)
- LCA (Linked Cluster Architecture)
- LMR (Lightweight Mobile Routing)
- LQSR (Link Quality Source Routing)
- LUNAR (Lightweight Underlay Network Ad hoc Routing)
- MMRP (Mobile Mesh Routing Protocol)
- MOR (Multipoint On-demand Routing)
- MPRDV (Multi Point Relay Distance Vector)
- OLSR (Optimized Link State Routing)
- OORP (OrderOne Routing Protocol)
- DREAM (Distance Routing Effect Algorithm for Mobility)
- PLBR (Preferred Link Based Routing)
- RDMAR (Relative-Distance Micro-discover Ad hoc Routing)
- Scar (DSR and ETX based)
- SSR (Signal Stability Routing)
- STAR (Source Tree Adaptive Routing)
- TBRPF (Topology dissemination Based on Reverse-Path Forwarding)
- TORA (Temporally-Ordered Routing Algorithm)
- WRP (Wireless Routing Protocol)
- ZHLS (Zone-Based Hierarchical Link State)
- ZRP (Zone Routing Protocol)
- ....

Routing Protocols for WMNs



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 Protocols for WMNs: ETX Metrics

- Each node periodically broadcasts a probe
- The probe carries information about probes received from neighbors
- Each node can calculate loss rate on forward (P_f) and reverse (P_r) link to each neighbor
- Selects the path with least total ETX

$$ETX = \frac{1}{(1-P_f)*(1-P_r)}$$

Advantages

- Explicitly takes loss rate into account
- Implicitly takes interference between successive hops into account
- Low overhead

Disadvantages

- PHY-layer loss rate of broadcast probe packets is not the same as PHY-layer loss rate of data packets
  - Broadcast probe packets are smaller
  - Broadcast packets are sent at lower data rate
- Does not take data rate or link load into account

Routing Protocols for WMNs: WCETT Metrics

Given a *n* hop path, where each hop can be on any one of *k* channels, and two tuning parameters, *a* and *b*:

Sum of ETTs of all links on the path
- Favors short paths

Path throughput is dominated by the max of the sum of ETTs of path links on the same channel

$$WCETT = \frac{\left(a * \sum_{i=1}^{n} ETT_i\right) + \left(b * \max_{1 \le j \le k} X_j\right)}{a + b}$$

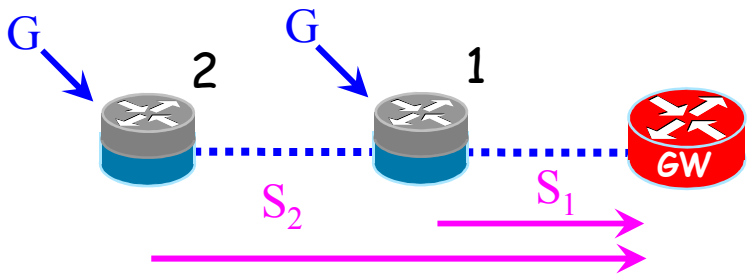
where

$$X_j = \sum_{\text{hop } i \text{ is on channel } j} ETT_i$$

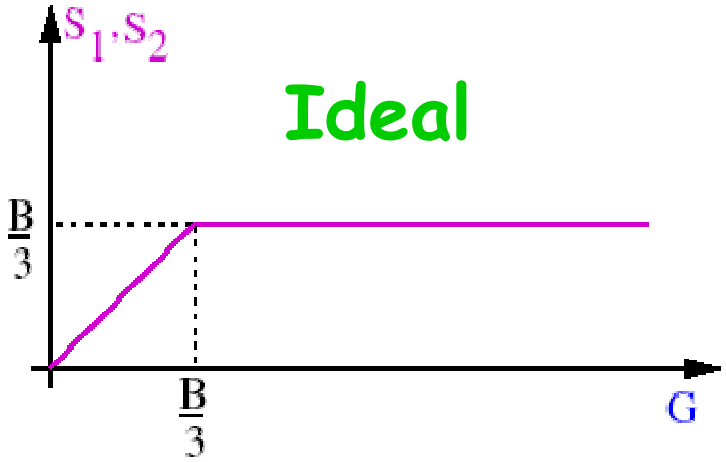
Sum of ETTs of all links on the path that are on the same channel

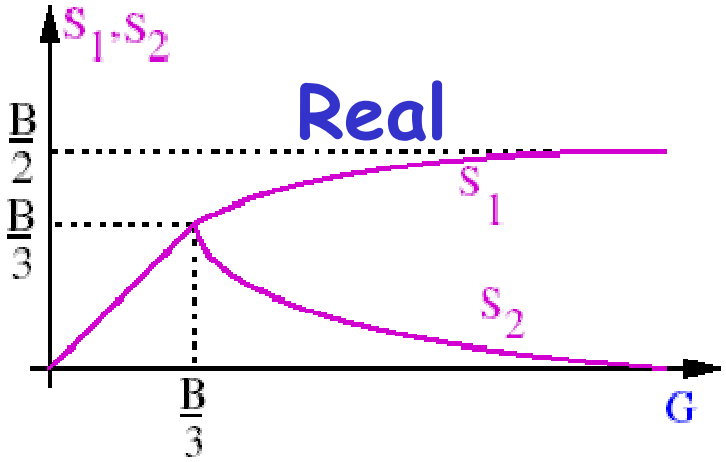
Select the path with min WCETT

Fairness Problem



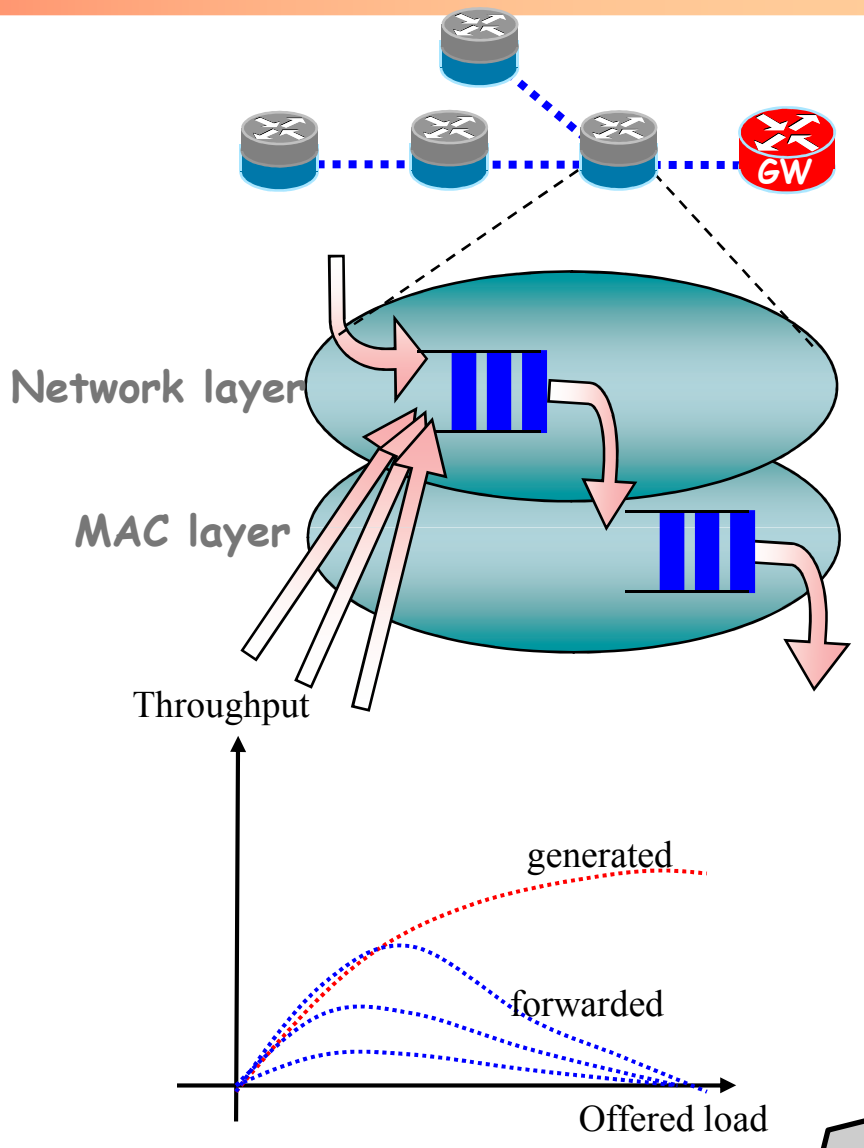
- Unfair
- Inefficient





Network Fairness

- 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



Research Topics for WMNs

- **Physical Layer**
  - Smart Antennas
  - MIMO techniques
- **MAC Layer**
  - Multiple Channels
- **Network Layer**
  - Routing
  - Fairness and QoS
- **Transport Layer**
- Provisioning
- Security
- Network Management
- Geo-location

TCP Problems in WMNs

- **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 Solutions for WMNs

- **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

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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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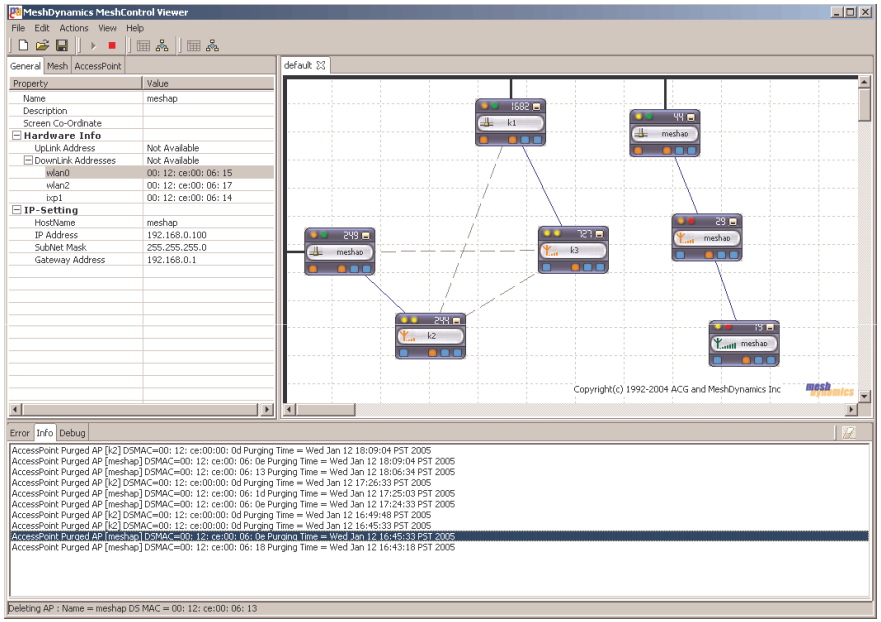
Network Monitoring

- 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



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- Security
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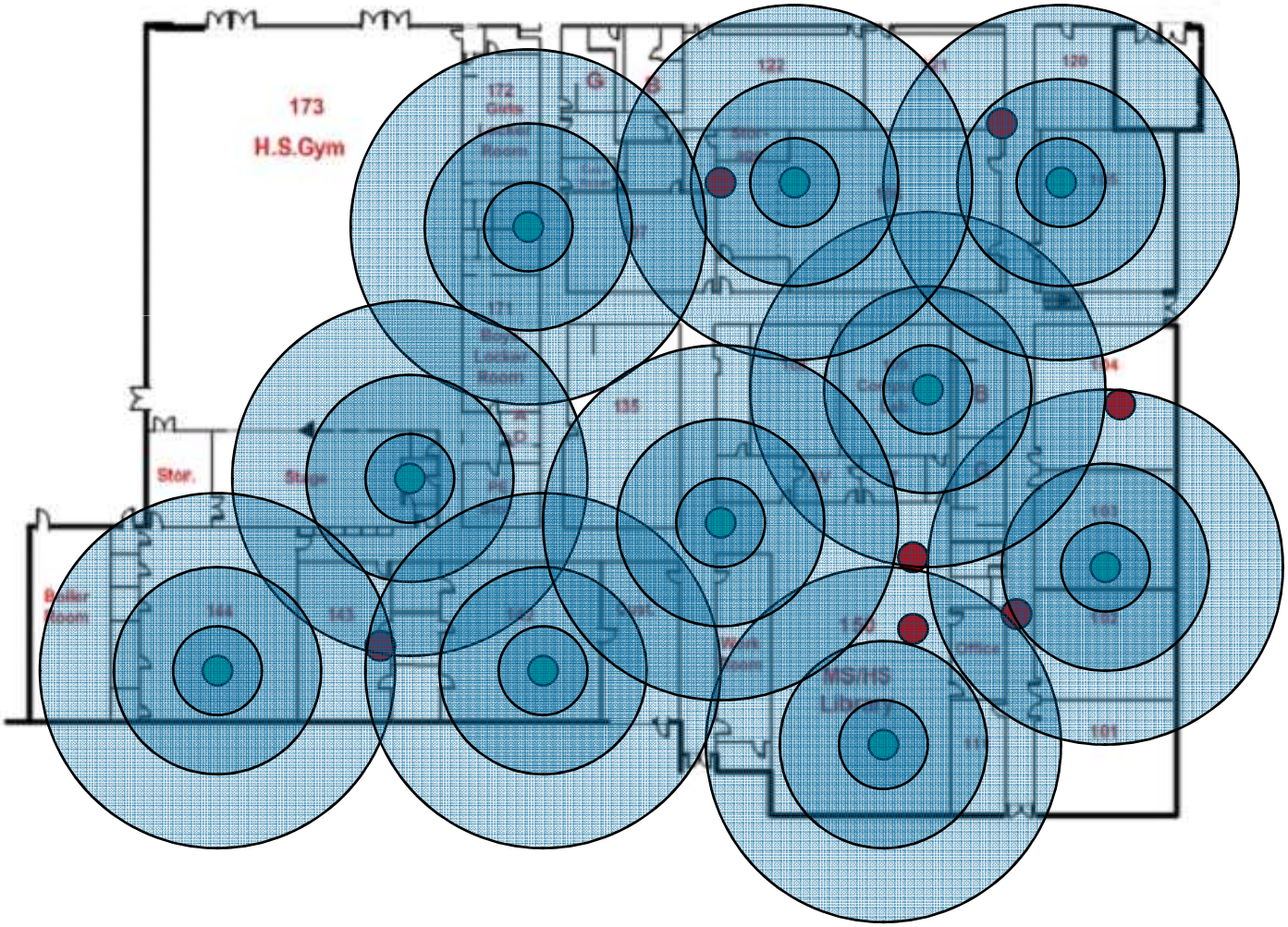
- **Geo-location**

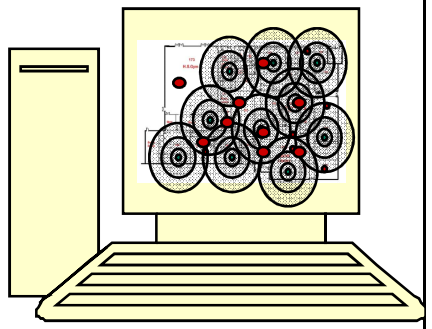
Geolocation: What?



Wireless Routers

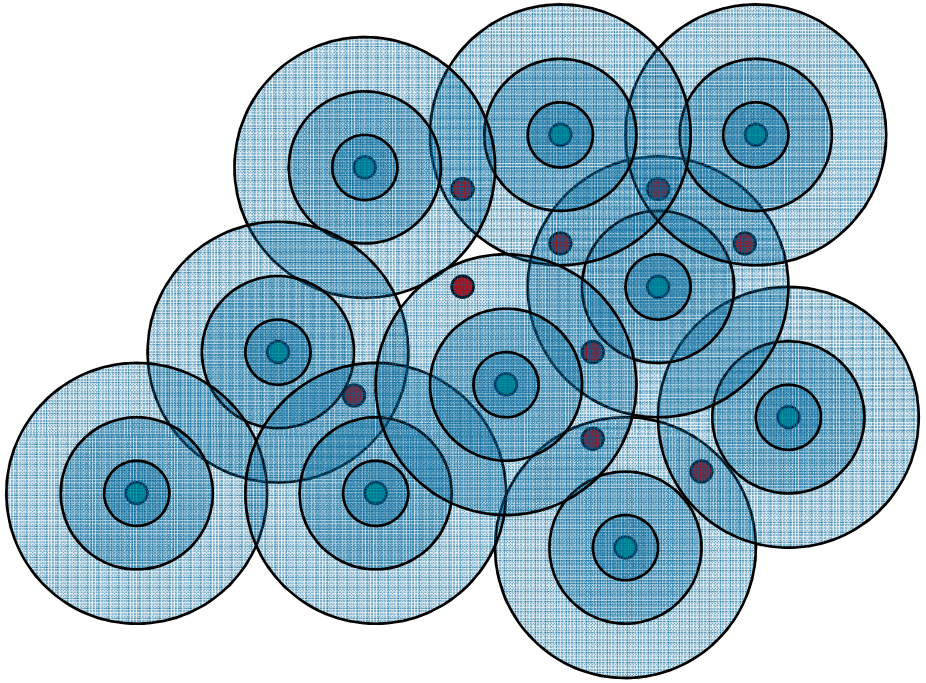
Users

Monitoring Station



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.

Tutorial Overview

- Overview of the technology
- Opportunities and Applications
- Research Challenges
- Current Testbeds
- Conclusions

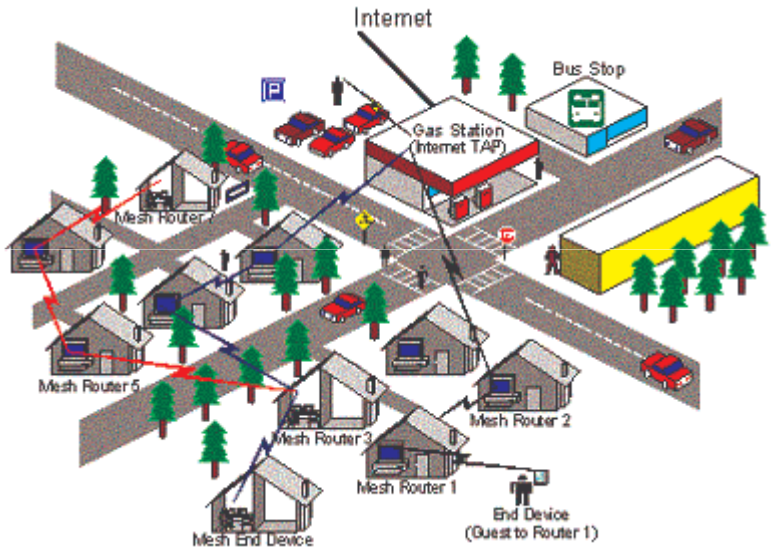
Companies

- 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

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/

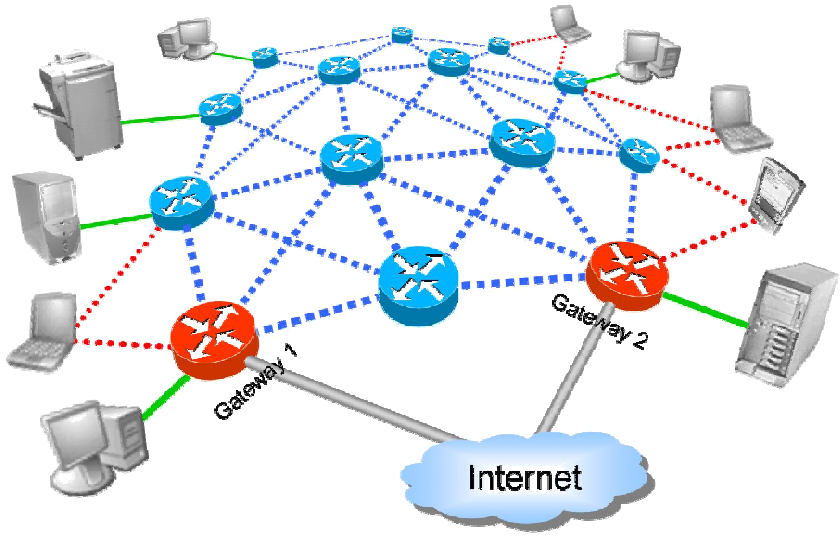


Locust World

- 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

Intel

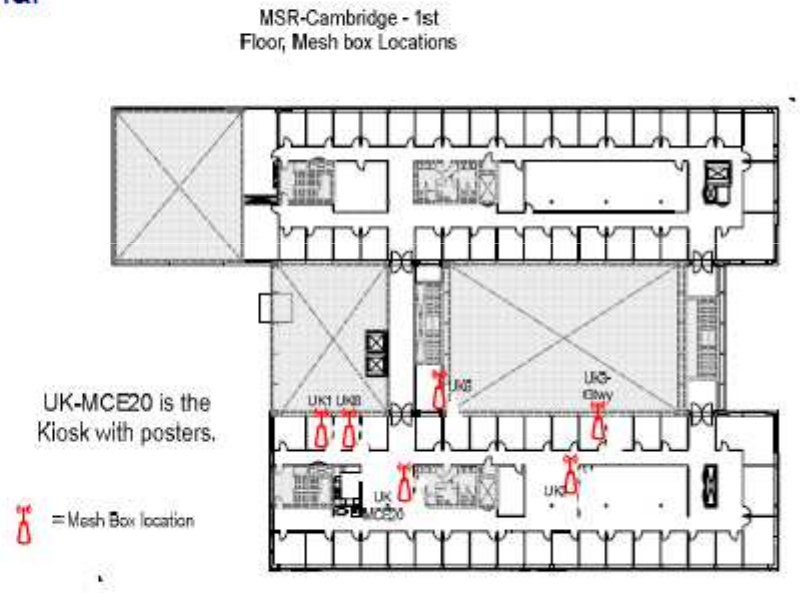
- Expressed interest in WMNs (since 2002).
- Research in:
  - Low power – related with their wireless sensor networks activities at Intel Research Berkeley Lab.
  - Traffic balancing
- Together with Cisco active in 802.11s standardization process



MSR's Cambridge UK Trial

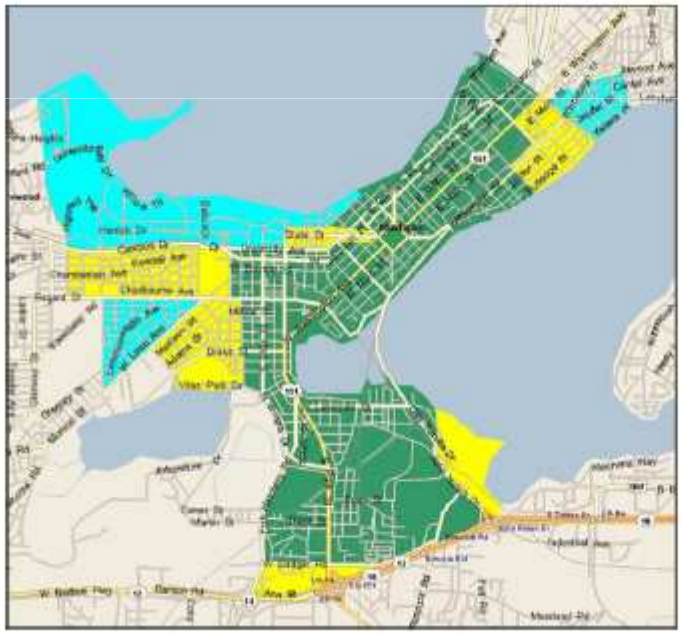
Worked with *ehome team* to create a media sharing demo in collaboration with ZCast DVB trial

10 node 802.11a mesh



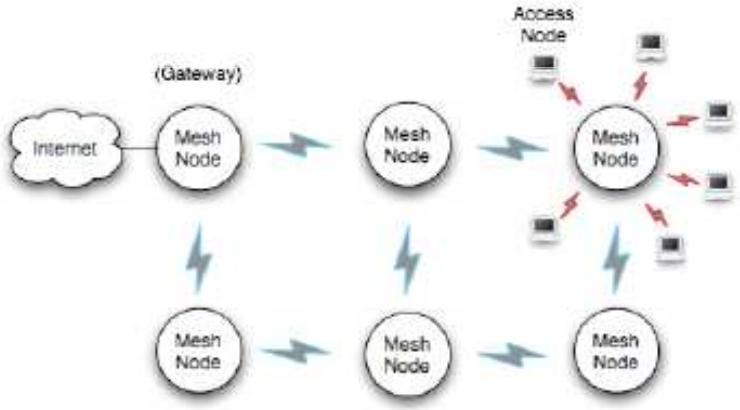
Madcity's Madison Broadband Downtown WMN

- Motivation: Commercial endeavor, local ISP, $20/month to cover the entire city
- Location: Madison, Wisconsin, USA
- Scale: 200+ mesh nodes (not all completely functional), coverage 9 miles^2
- Access Speed: 802.11a speed in the backbone, 802.11b access link
- Applications: Broadband Internet Access



Rice's Technology for TFA Project

- Motivation: "Empower low income communities through technology"
- Location: Houston's East End
- Scale: 15 nodes deployed, 2 Km^2 coverage, 700+ users
- Access Speed: > 1 Mbps, Backhaul links > 3 Mbps
- Application: Education and work-at-home



Two-Tier Architecture

- Limited gateways wired to Internet
- Backhaul tier - Mesh
- Access tier – Client to mesh node

Coverage map with location of mesh nodes

Standards related to WMNs

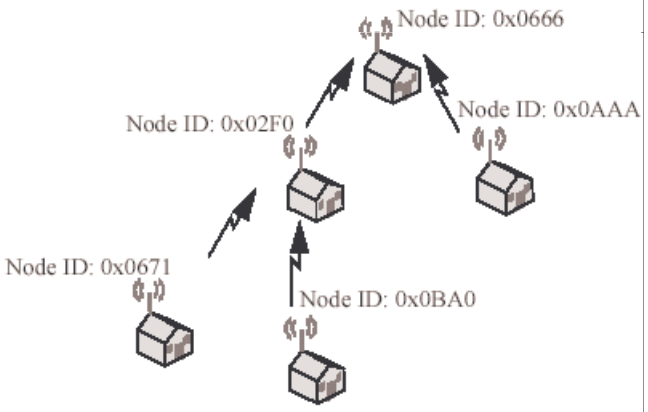
- IEEE 802.11s
- IEEE 802.15.1 (Bluetooth)
- IEEE 802.15.4 (Zigbee)
- IEEE 802.15.5 (WPAN)
- IEEE 802.16a

802.11s 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 802.16a 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.



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