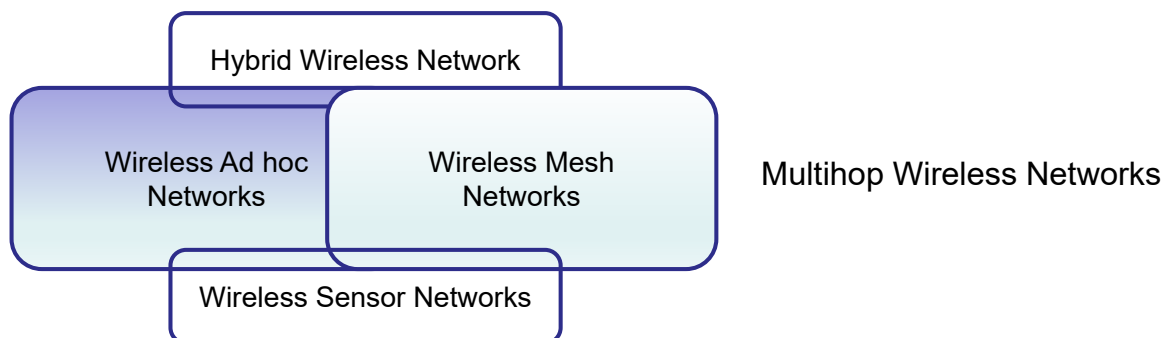


# Wireless Mesh Networks

## Chapter 5

## Introduction

- The term 'wireless mesh networks' describes wireless networks in which each node can communicate directly with one or more peer nodes.
- The term 'mesh' originally used to suggest that all nodes were connected to all other nodes, but most modern meshes connect only a sub-set of nodes.
- Complement and improve performance/costs of WPANs, MANETs, WLANs, WMANs
- Can be seen as an extension of multi-hop ad-hoc networks
- Each node also behaves as a router, forwarding packets on behalf of other nodes to the intended destinations.



## Ad Hoc Networks

- Multihop
- Nodes are wireless, possibly mobile
- Usually infrastructureless
- Traffic mainly node-to-node

## Wireless Mesh Networks

- Multihop
- Nodes are wireless, some mobile, some fixed
- Relies on backbone infrastructure
- Traffic mainly node-to-gateway

## Wireless Sensor Networks

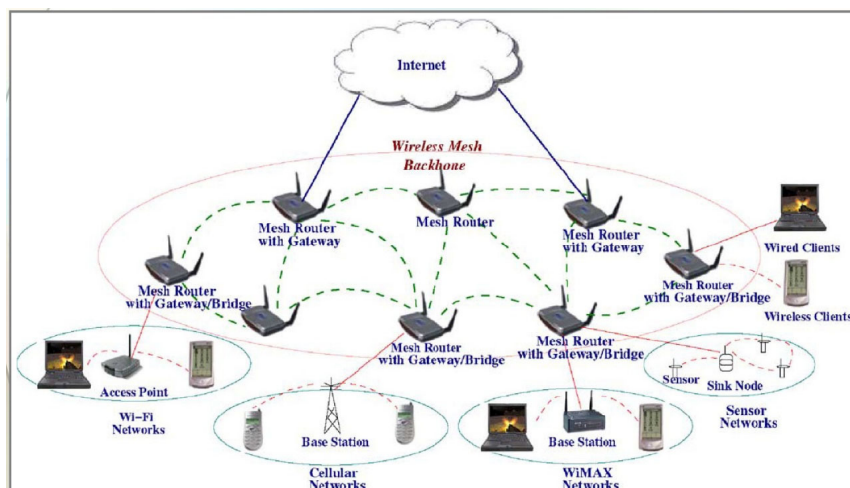
- Bandwidth is limited (e.g. 10s to 100s kbps)
- In most applications, fixed nodes
- Energy efficiency is an issue
- Resource constrained
- Traffic mainly node-to-gateway

## Wireless Mesh Networks

- Bandwidth is generous (e.g. > 1Mbps)
- Some nodes mobile, some nodes fixed
- Normally not energy limited
- Resources are not an issue
- Traffic mainly node-to-gateway

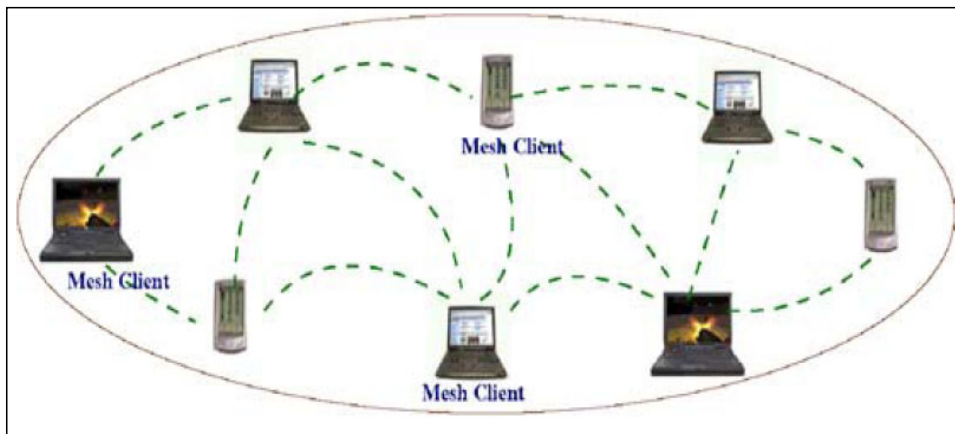
- Nodes are comprised of mesh routers and mesh clients
- Mesh routers:
  - Conventional wireless AP (Access Point) functions
  - Additional mesh routing functions to support multihop communications
  - Usually multiple wireless interfaces built on either the same or different radio technologies
- Mesh clients:
  - Can also work as a router for client WMN
  - Usually only one wireless interface
- Classification of WMN architecture:
  - Infrastructure/Backbone WMNs
  - Client WMNs
  - Hybrid WMNs

- Mesh routers form an infrastructure for clients that connect to them
- Mesh routers form a mesh backbone of self-configuring, self-healing links among themselves
- With gateway functionality, mesh routers can be connected to the Internet
- May use heterogeneous wireless technologies for the wireless links, typically one wireless technology for backbone mesh, and another for client-to-router links



# Client WMNs

- Client meshing provides peer-to-peer networks among client devices
- Client nodes constitute the actual network to perform routing and configuration functionalities as well as providing end-user applications to customers
- A mesh router is not required for these types of networks
- A packet destined to a node in the network hops through multiple nodes to reach the destination
- The requirement on nodes is increased when compared to infrastructure meshing; the nodes have to perform additional functions such as routing and self-configuration

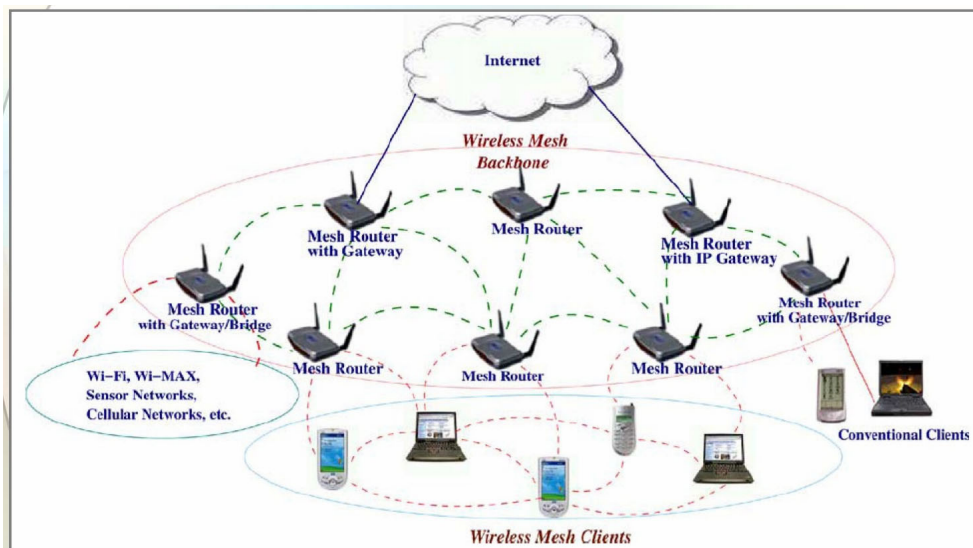


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# Hybrid WMNs

- This architecture is the combination of **infrastructure and client meshing**
- Mesh clients can access the network through mesh routers as well as directly meshing with other mesh clients
- While the infrastructure provides connectivity to other networks such as the Internet, Wi-Fi, WiMAX, cellular, and sensor networks; the routing capabilities of clients provide improved connectivity and coverage inside the WMN
- The hybrid architecture will be the most applicable case



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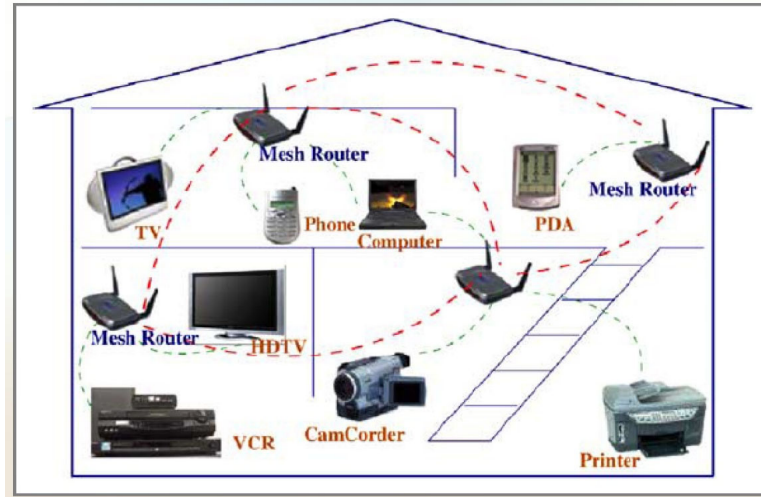
- Do not require centralized access points to mediate wireless connections
- Multihop feature:
  - Extend coverage with low transmission power
  - Provide non-line-of-sight (NLOS) connectivity
- Self-forming, self-healing and self-organization capability:
  - Low upfront investment
  - Easy deployment
  - Fault tolerant
- Comprises wireless nodes that can be fixed or mobile:
  - Mesh routers have minimal mobility
  - Mesh clients can be stationary or mobile
- Internetwork of heterogeneous wireless networks, e.g. WiFi, Zigbee, etc.
- Can be connected to:
  - Internet through gateways/routers
  - Other networks through gateways/bridges
- Traffic pattern:
  - Most traffic is node-to-gateway or gateway-to-node
  - In ad hoc networks, most traffic is node-to-node
- Not an energy-limited network:
  - Mesh routers are usually AC-powered
  - Energy efficiency is not an issue in protocol design

- Very low installation and maintenance cost
  - No wiring! Wiring is always expensive/labour intensive, time consuming, inflexible
- Easy to provide coverage in outdoors and hard-to-wire areas:
  - Ubiquitous access
- Rapid deployment
- Self-healing, resilient, extensible, scalable

# Application Scenario

## - Broadband Home Networking

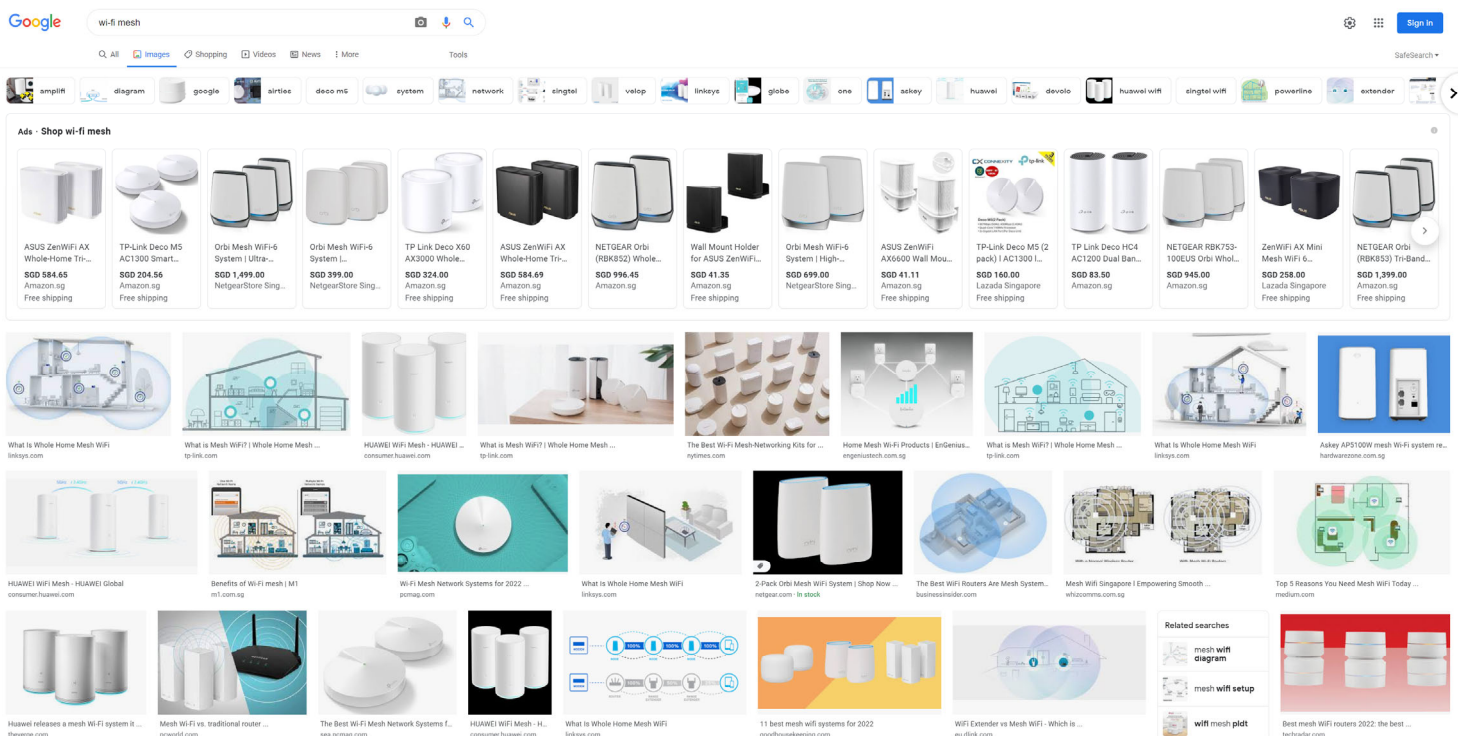
- Problems:
  - Homes have many dead zones without service coverage
  - Expensive to do site survey
  - Expensive to deploy multiple APs
  - Communications between nodes under 2 different APs have to go all the way back to access hub
- Mesh networking resolves these issues



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## Wi-Fi Mesh



The screenshot displays a Google search for "wi-fi mesh". The top section shows search filters and a row of product images. Below this, there are several product listings with images, prices, and shipping information. The listings include:

- ASUS ZenWiFi AX Whole Home Tri-Band (SGD 584.65)
- TP-Link Deco M5 AC1300 Smart Mesh System (SGD 204.56)
- Orbi Mesh WiFi-6 System (Ultra) (SGD 1,499.00)
- Orbi Mesh WiFi-6 System (SGD 399.00)
- TP-Link Deco X50 AX3000 Whole Home Mesh System (SGD 324.00)
- ASUS ZenWiFi AX (RBK532) Whole Home Mesh System (SGD 584.65)
- NETGEAR Orbi (RBK532) Whole Home Mesh System (SGD 596.45)
- Wall Mount Holder for ASUS ZenWiFi AX (SGD 41.35)
- Orbi Mesh WiFi-6 System (High-Speed) (SGD 699.00)
- ASUS ZenWiFi AX6600 Wall Mount Mesh System (SGD 41.11)
- TP-Link Deco M5 (2-pack) AC1300 Smart Mesh System (SGD 160.00)
- TP-Link Deco H4 AC1200 Dual-Band Mesh System (SGD 83.50)
- NETGEAR RBK753-100LUX Orbi Whole Home Mesh System (SGD 945.00)
- ZenWiFi AX Mini Mesh WiFi 6E (SGD 258.00)
- NETGEAR Orbi (RBK532) Tri-Band Mesh System (SGD 1,399.00)

Below the product listings, there are several informational articles and diagrams:

- "What is Whole Home Mesh WiFi" (linksys.com)
- "What is Mesh WiFi? | Whole Home Mesh" (tp-link.com)
- "HUAWEI WiFi Mesh - HUAWEI" (consumer.huawei.com)
- "What is Mesh WiFi? | Whole Home Mesh" (tp-link.com)
- "The Best Wi-Fi Mesh-Networking Kits for 2022" (rytmes.com)
- "Home Mesh Wi-Fi Products | EnGenius" (engeniustech.com.sg)
- "What is Mesh WiFi? | Whole Home Mesh" (tp-link.com)
- "What is Whole Home Mesh WiFi" (linksys.com)
- "Askey AP5100W mesh Wi-Fi system re..." (hardwarezone.com.sg)
- "HUAWEI WiFi Mesh - HUAWEI Global" (consumer.huawei.com)
- "Benefits of Wi-Fi mesh | MT" (mt.com.sg)
- "Wi-Fi Mesh Network Systems for 2022" (ponmag.com)
- "What is Whole Home Mesh WiFi" (linksys.com)
- "2-Pack Orbi Mesh WiFi System | Shop Now" (netgear.com - its stock)
- "The Best Mesh WiFi Routers Are Mesh Systems" (businessinsider.com)
- "Mesh WiFi Singapore | Empowering Smooth" (wholohome.com.sg)
- "Top 5 Reasons You Need Mesh WiFi Today" (medium.com)
- "Huawei releases a mesh Wi-Fi system it..." (theverge.com)
- "Mesh Wi-Fi vs. traditional router" (powerline.com)
- "The Best Wi-Fi Mesh Network Systems" (sea.ponmag.com)
- "HUAWEI Wi-Fi Mesh - HUAWEI" (consumer.huawei.com)
- "What is Whole Home Mesh WiFi" (linksys.com)
- "11 best mesh wifi systems for 2022" (goodhousekeeping.com)
- "WiFi Extender vs Mesh WiFi - Which is..." (eu.dlink.com)
- "Related searches" (mesh wifi diagram, mesh wifi setup, wifi mesh pldt)
- "Best mesh WiFi routers 2022: the best..." (techradar.com)

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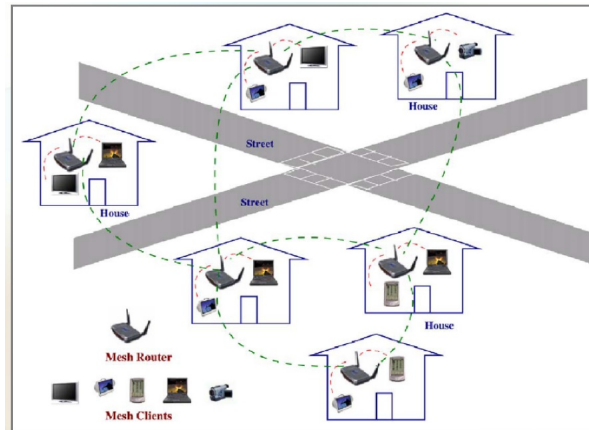
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# Application Scenario

## - Community & Neighborhood Networking

- In a community, the common architecture for network access is based on cable or DSL connected to the Internet, and the last-hop is wireless by connecting a wireless router to a cable or DSL modem.
- This type of network access has several drawbacks:
  - Even if the information must be shared within a community or neighborhood, all traffic must flow through Internet. This significantly reduces network resource utilization.
  - Large percentage of areas in between houses is not covered by wireless services.
  - An expensive but high bandwidth gateway between multiple homes or neighborhoods may not be shared and wireless services must be set up individually. As a result, network service costs may increase.
  - Only a single path may be available for one home to access the Internet or communicate with neighbors.



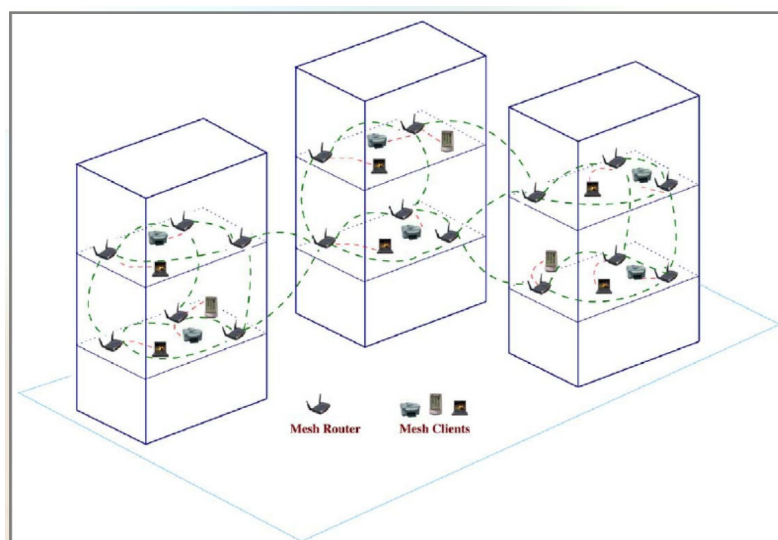
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# Application Scenario

## - Enterprise Networking

- Existing enterprise networks:
  - Usually interconnect islands of WLANs with a wired backbone network.
  - No robustness against local link failures.
  - Costly to scale.
- WMNs use multiple backhaul mesh routers can be shared by all nodes in the entire network, and thus improve the robustness and resource utilization of enterprise networks.
- WMNs can grow easily as the size of enterprise expands.



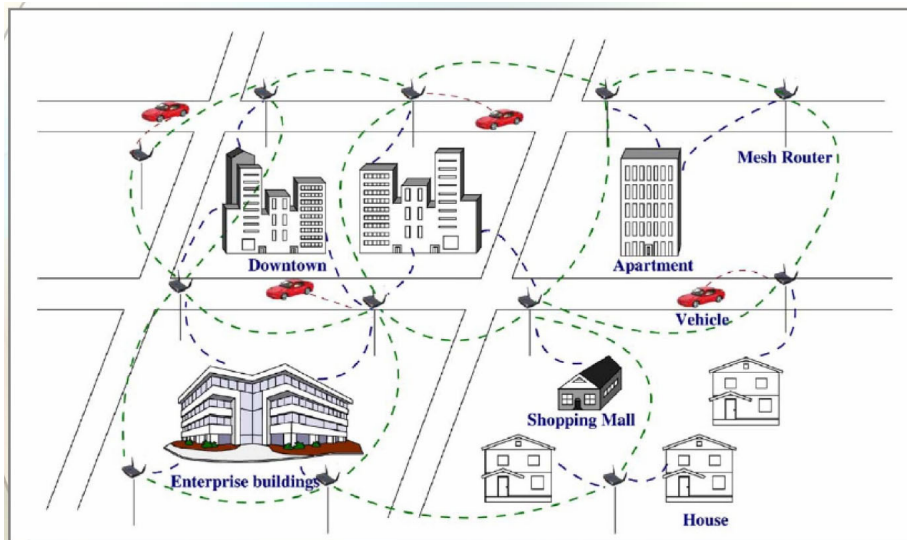
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# Application Scenario

## - Metropolitan Area Networking

- Communication between nodes in WMNs does not rely on a wired backbone.
- Compared to wired networks, e.g., cable or optical networks, WMN-MAN is an economic alternative to broadband networking, especially in underdeveloped regions.
- WMN-MAN covers a potentially much larger area than home, enterprise, building, or community networks.
- The requirement on the network scalability by WMN-MAN is much higher.

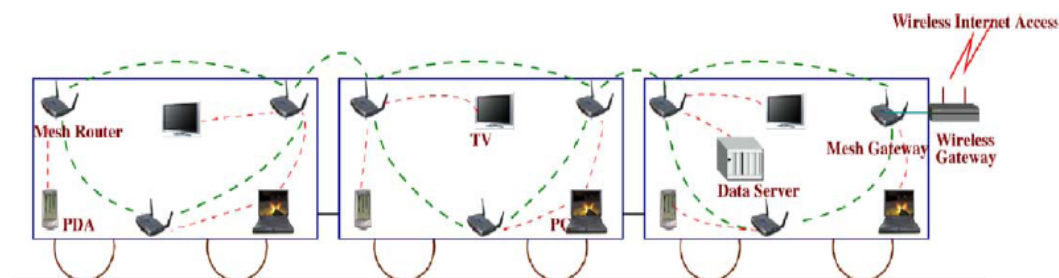


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# Application Scenarios

- Transportation systems
- Building automation
- Health and medical systems
- Security surveillance systems
- Spontaneous networking



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- Radio Techniques:
  - Directional and smart antennas
  - MIMO systems ← (Key Technology for IEEE 802.11n/ac/ax)
  - Multi-radio/multi-channel systems
  - Reconfigurable radios
  - Frequency agile/cognitive radios, and
  - Software defined radios
- Scalability
- Mesh Connectivity
- Broadband and QoS
- Compatibility and Inter-operability
- Security
- Ease of use

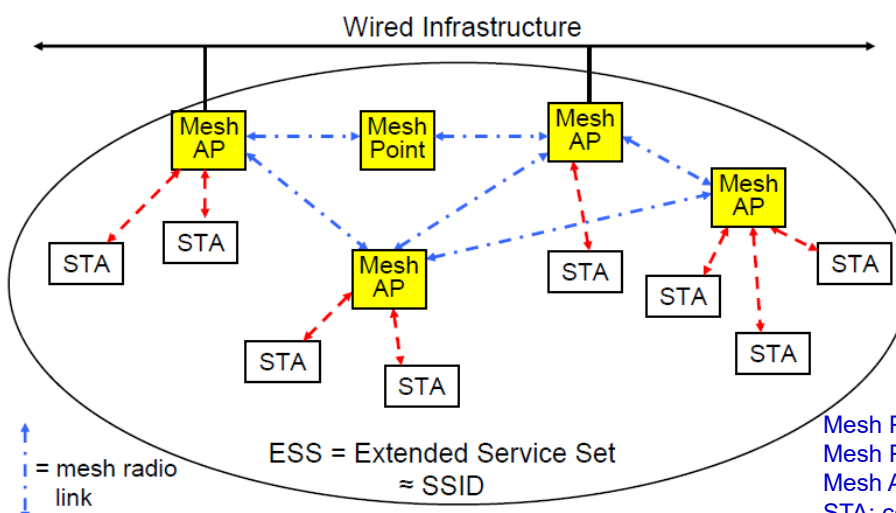
## MAC Layer – WMN MAC vs Other MACs

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- MACs for WMNs are concerned with multihop communication
  - Classical MAC – one hop: design is easier, since MAC and routing are transparent to each other
  - Does not work well in WMNs because of multihop transmission (e.g. hidden node problem)
- MAC must be distributed, cooperative, and work for multipoint-to-multipoint communication
- No centralized controller
- WMN nodes able to communicate with all its neighbours
- WMN is self-organizing
  - MAC should know topology to allow cooperation between nodes
  - Network self-organization based on power control may optimize network topology, minimize interference and improve capacity
- Mobility affects the performance of MAC
  - Network configuration is dynamic
  - Greater need to exchange network topology information
- Approaches:
  - Enhance existing MAC protocols or propose new MAC protocols to increase E2E throughput when only single channel is available in a network node
  - Allow transmission on multiple channels in each network node (this is an advanced topic; example protocols are Multi-channel MAC (MMAC) and Multi-Channel Routing Protocol (MCR))

- Scalability
  - Overhead is an issue in mobile WMNs
- Fast route discovery and rediscovery
  - Essential for reliability
- Mobile node 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)

- IEEE 802.11s is an IEEE 802.11 amendment for mesh networking, defining how wireless devices can interconnect to create a WLAN mesh network, which may be used for static topologies and ad hoc networks.
- 802.11s extends the IEEE 802.11 **MAC** standard by defining an architecture and protocol that support both broadcast/multicast and unicast delivery using “radio-aware metrics over self-configuring multi-hop topologies”.
- One active path selection protocol/metric in one mesh, but allow for alternative path selection protocols/metrics in different meshes; supports single or multi-channel mesh



- Default routing/path selection protocol in IEEE 802.11s
- It combines the flexibility of on-demand route discovery with efficient proactive routing to a mesh portal
- On demand routing offers great flexibility in changing environments
- Pro-active tree based routing is very efficient in fixed mesh networks
- This combination makes it suitable for implementation on a variety of different network configurations
- Simple mandatory metric based on airtime as default, with support for other metrics
- Extensibility frame framework allows any path selection metric (QoS, load balancing, power-aware, etc.)

## On demand routing

- Based on *Radio Metric AODV (RM-AODV)*: use the features of AODV (RFC 3561); extensions to identify best-metric path with arbitrary path metrics; Destinations may be discovered in the mesh on-demand.

## Pro-active routing

- Based on tree based routing: If a Root portal (=MPP) is present, a distance vector routing tree is built and maintained
- Tree based routing is efficient for hierarchical networks
- Tree based routing avoids unnecessary discovery flooding during discovery and recovery

# WMN metrics - 1

## 2.1. Expected Transmission Count (ETX)

$$ETX = 1 / (d_f \cdot d_r)$$

(1)

Where  $d_f$  and  $d_r$  denote the delivery ratio in the forward and reverse directions, respectively. The ETX does not consider the impact of varying transmission rates of different wireless links and sizes of data packets [8]. ETX also does not consider the impact of intra-flow and inter-flow interference.

## 2.2. Expected Transmission Time (ETT)

The expected transmission time (ETT) metric calculates the time required to transmit a packet of size  $S$  on a link with a data rate  $B$  using (2). The ETT of a link is the duration of time a node uses the medium to successfully deliver a packet to the next hop. The ETT of the  $i$ -th link is defined by:

$$ETT_i = ETX_i \cdot S / B_i$$

(2)

Where :

- $B_i$  : the data rate of the  $i$ -th link.
- $S$  : the packet size.

ETT and ETX not considers the presence of multiple channels. To resolve this problem WCET- T has been proposed in literature.

## 2.3. Weighted cumulative expected transmission time (WCETT)

The Weighted Cumulative Expected Transmission Time (WCETT) as a path metric for routing in multi-radio multi-channel WMNs[16]. To find paths with less intra-flow interference and channel diversity, the authors in [9] proposed WCETT metric for a path  $P$  of  $n$  hops by :

$$WCETT_p = (1 - \beta) \cdot \sum ETT_i + \beta \cdot \max_{1 \leq j \leq k} X_j$$

(3)

Where :

- $0 \leq \beta \leq 1$  :the tunable parameter,
  - $X_j$ : represents the sum of ETT for the hops that are in the channel  $j$ ,
  - $k$ : the number of orthogonal channels.
- The WCETT metric is composed by two components:
- The first defines the end-to-end delay experienced in a particular path,
  - And the second accounts for channel diversity along the path.

However, WCETT considers the interference between the distant nodes and does not consider the link quality. To consider this, Airtime metric has been proposed.

# WMN metrics - 2

## 2.4. Airtime

The Airtime metric  $c_a$  is the default routing metric specified in the draft of IEEE 802.11s [2] by:

$$c_a = [O + B_t / r] \cdot [1 / (1 - e_f)]$$

(4)

Where:

- $O$  : The channel access overhead,
- $B_t$  : test frame size in bytes,
- $r$  : data rate in Mb/s,
- $e_f$  : measured test frame error rate.

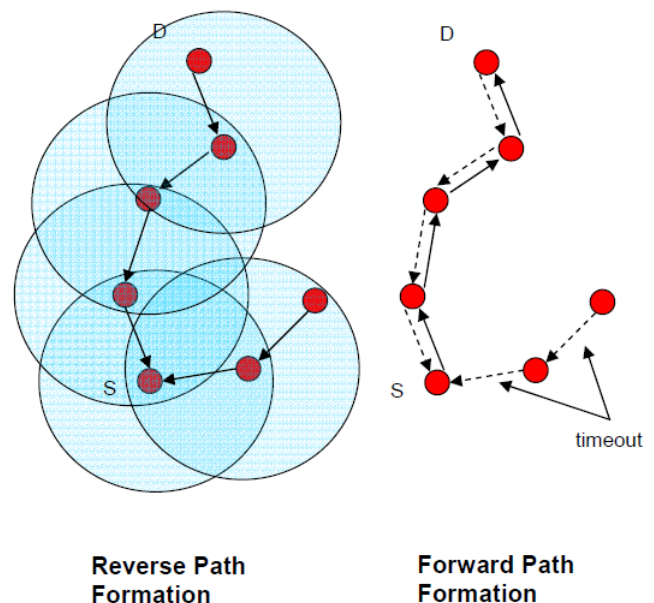
This metric defines the amount of channel resources consumed by transmitting the frame over a particular link, The path metric is the sum of metric values of all links in the path.

## HWMP Protocol Elements

- *Root Announcement* (broadcast): tells MPs about presence and distance of *Root MP*
- *Route Request* (broadcast/unicast): asks destination MP(s) to form a reverse route to the originator
- *Route Reply* (unicast): forms a forward route from the originator and confirms the reverse route
- *Route Error* (broadcast): tells receiving MPs that the originator no longer supports certain routes

## On-demand Routing in HWMP – Key Features

- Allows nodes to quickly obtain routes for new destinations (does not require nodes to maintain routes to destinations that are not in active communication)
- Route Discovery
  - Uses expanding ring search to limit the flood of routing packets
  - Reverse Paths are setup by *Route Request* packets broadcast (or unicast) from Originator
  - Forward Paths are setup by *Route Reply* packet sent from destination node or any intermediate node with a valid route to the destination





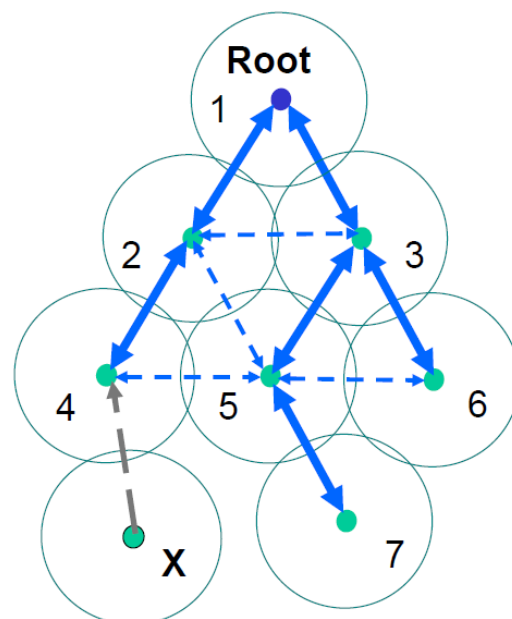
## On-demand Routing in HWMP – Key Features

- Route Maintenance
  - Nodes monitor the link status of next hops in active routes. When a link break in an active route is detected, a *Route Error* message is used to notify other nodes that the loss of that link has occurred.
  - Route Error message is a unicast message, resulting in quick notification of route failure
- Loop Freedom
  - DSDV and AODV principle
  - All nodes in the network own and maintain a destination sequence number which guarantees the loop-freedom of all routes towards that node

## Tree-based routing in HWMP – Key Features

### •Topology Creation

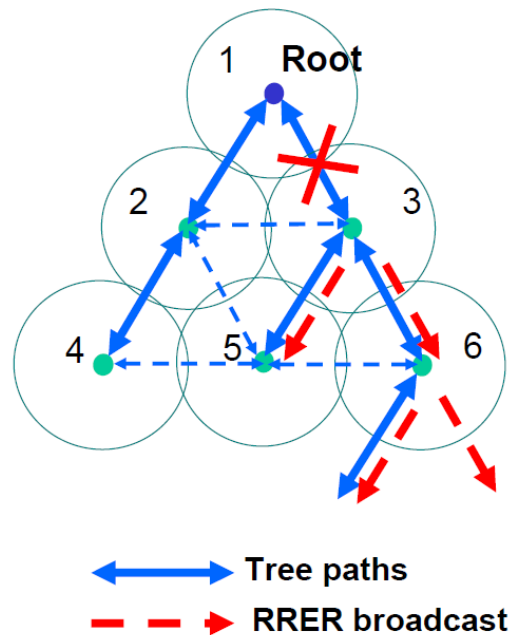
- Root MP may issue a “broadcast” RREQ; MPs may respond with RREP
- The Root MP may issue “Root Announcements” which contains information on path metrics to Root MP
- MPs may respond by a unicast RREQ to the Root (answered by RREP) (to establish bi-directional path)
- MPs select next hop to Root based on best path metric
- “Registration” of subtrees by MPs facilitates outward message routing
- *Drawback:* Packets between MPs are routed through Root MP even though a shorter path may exist



## Tree-based routing in HWMP – Key Features

### •Topology Maintenance

- MPs monitor their upstream links and may switch to back-up links using RREP; This avoids “re-building” the tree. Loss of upstream link **X** causes RERR to be sent down.
- This allows nodes to decide/select own back-up paths. It signals route holders that some route is broken.



**The End**  
Questions?