Wireless Mesh Networks Technologies: Architectures, Protocols, Resource Management and Applications

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NOTE: This 3 hours tutorial does not cover all aspects of the WMNs. Specific issues like QoS, security, detailed resource management and integration in E2E architecture are not contained. They will be added to a next version.

Acknowledgements

- **Main references**
  - **Acknowledgment:**
    - **Materials of this tutorial are based on several authors' work and literature; among the main ones are the following overviews and tutorials and studies:**

- **Akyildiz, I.F., Wang, X. and Wang, W., Wireless Mesh Networks: A Survey, Computer Networks Journal (Elsevier), March 2005**
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- **Addagada, B.K, et.al, A Survey: Routing Metrics for Wireless Mesh Networks, May 5, 2009, http://www.public.iastate.edu/~vkisara/Survey..**
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Acknowledgements

- **Main references (cont'd)**

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  - **J. C. Hou, et.al., Medium Access Control and Routing Protocols for WMN, Ch. in Wireless Mesh Networks Architectures and Protocols, Springer, 2008**
  - **A. Ting , and D. Chieng Design and Capacity Performance Analysis of Wireless Mesh Network**
  - **FACCIN, S.M.,et. al., MESH WLAN NETWORKS: CONCEPT AND SYSTEM DESIGN, IEEE Wireless Communications • April 2006**
  - **Yan Zhang et. al., WIRELESS MESH NETWORKING, Architectures, Protocols and Standards, Auerbach Publications, 2007**

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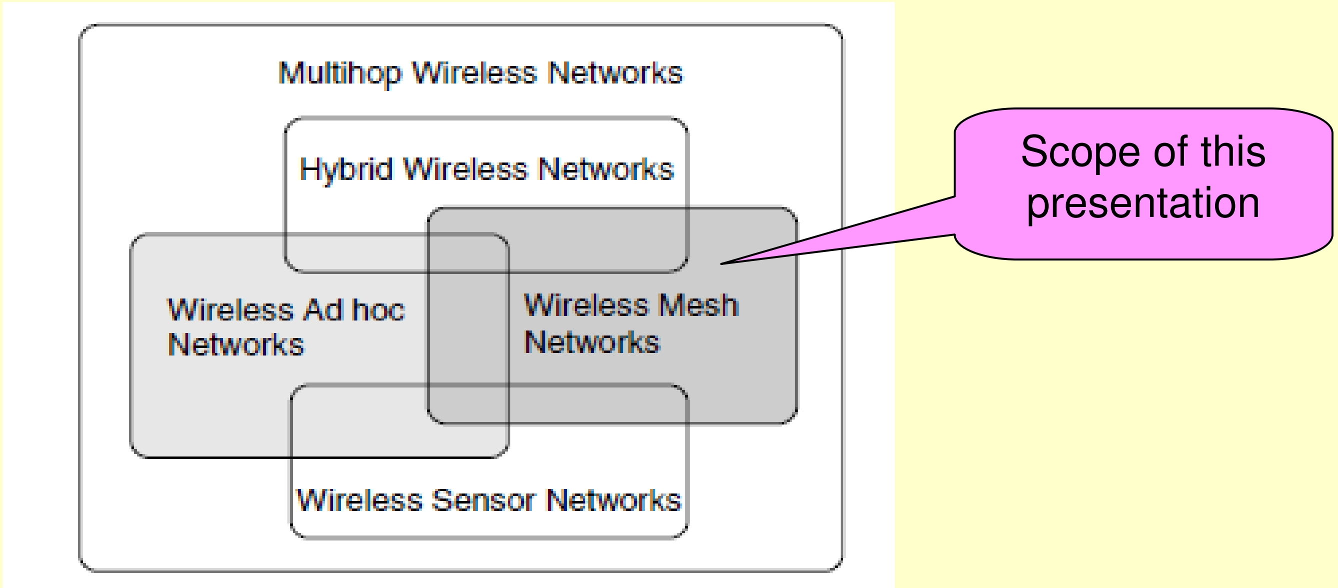
1. WMN Introduction

- **WMN general characteristics**
  - WMNs – can be seen as an extension of multi-hop Ad-Hoc networks; each node can communicate directly or inf=directly with one or more peer nodes
  - WMN relationship with other multihop wireless network
    - Source: Ed.Yan Zhang , Jijun Luo, Honglin Hu, WIRELESS MESH NETWORKING, Auerbach Publications, 2007



1. WMN Introduction

- **WMN general characteristics**
  - WMN do not require centralized access points to mediate the wireless connection
  - WMN Multi-hop feature – increases the coverage area and link robustness of existing Wi-Fi's; (if the correspondent nodes are not in the wireless transmission range of each other)
  - Hope to complement and improve the performance/costs for WPANs, MANETs, WLANs, WMANs
  - WMNs are in significant progress; numerous deployments already exist, to deliver wireless services for a large variety of applications in personal, local, campus, and metropolitan areas
  - WMNs wireless nodes: mobile or fixed
    - Basic types of nodes: *mesh routers* (MR) and *mesh clients* (MC), where MR – establishes an infrastructure backbone for clients
    - Actually one have: *Wireless Mesh routers*, *Gateways*, *Printers*, *Servers, Mobile or Stationary clients* (terminals)

1. WMN Introduction

- The WMN may be connected to:
  - the Internet through gateway/routers
  - Other networks through Gateways/Bridges
- End hosts and routing nodes might be distinct
  - Routers are usually stationary (except hybrid WMNs where they can be also mobile)
- Mesh clients
  - can be either stationary or mobile
  - can form a client mesh network among themselves and/or together with MRs
- Traffic: *user-to-gateway* or, *user-to-user*
- WMNs : dynamically self-organized and self-configured systems (one node can automatically establish and maintain the mesh connectivity)

1. WMN Introduction

- **Wireless Mesh Networks Technolgies**

- **WMNs technologies:**
  - Initially: extension of IEEE 802.11 WLANs
  - today hybrid technologies can cooperate in mesh topology
  - the APs are considered as the nodes of mesh; (they may be heterogeneous and inter-connected in a hierarchical fashion)

  - The integration and interconnection of different technologies in/with WMNs (Internet, cellular, IEEE 802.11, IEEE 802.15, IEEE 802.16, sensor networks, etc.), can be achieved through the gateway and bridging functions in the MRs

- **WMN: many open issues and research challenges related to (non-orthogonal list of issues):**
  - Architectures and Protocol layers
  - PHY and MAC specific issues
    - Scheduling, Multi-channel, multi-radio
    - Cognitive radio
    - MIMO, Directional and smart antennas systems
  - Capacity and coverage
  - Scalability (major point)
  - Routing
  - Resource management and QoS capabilities
  - Cross-layer optimization
  - Security, etc.

1. WMN Introduction

- **WMN usage scenarios**
  - **WMN economical advantage: low cost technology**
- **WMNs – Broadband Networking services**
  - Metropolitan Area
  - Home
  - Community and Neighborhood
  - Enterprise
  - Campus
- **High level services scenarios**
  - Security and Surveillance Systems
  - Building Automation
  - Health and Medical Systems
  - Transportation Systems
  - Community networks
  - City networks
  - …..

CONTENTS

2. Basic architectures and challenges

- **WMN taxonomy**
- Major architectural choices
  - **Topology based**
    - Flat
    - Hierarchical (clusters)
  - **Technology based**
    - Homogeneous (e.g. IEEE 802.11 only)
    - Heterogeneous (e.g IEEE 802.11, 16, 15)
  - **Node based**
    - Infrastructure/Backbone WMNs(fixed/nomadic infrastructure)
    - Client WMNs (host based)
    - Hybrid WMNs

2. Basic architectures and challenges

- **Infrastructure/Backbone WMNs**
  - **Mesh Routers (MR)** : compose together a mesh infrastructure/ bacbone for clients (connected to them) using different RT (mainly 802.11)
  - Actually one has a wireless distribution system replacing the wired one in 802.11
  - MRs form a mesh of self-configuring with self-healing links
  - MR/GW: additional gateway/bridge functionality, for connection to the Internet
  - Clients with Ethernet I/F can be connected to MRs via Ethernet links
  - Clients with the same radio technologies as MRs - can directly communicate with MRs
  - If different RT are used, clients must communicate with the base stations that may have Ethernet connections to mesh routers.

- **Infrastructure/Backbone WMNs (cont'd)**
  - Mesh Infrastructure/Backbone WMNs : currently the most used type.
  - *Example:*
    - community and neighborhood networks
    - The MRs can be placed on the roof of houses in a neighborhood, which serve as access points (APs) for users inside the homes and along the roads.
  - Typically, two radios are used in the routers,
    - for backbone communication
    - for user communication
  - The mesh backbone communication can be established using extended-range communication techniques including directional antennas.

2. Basic architectures and challenges

- **Client WMNs**
  - Similar to Ad hoc networks
  - P2P-style mesh networks among client devices
  - Client nodes should:
    - perform routing and configuration functionalities
    - provide end user applications to customers
  - A packet destined to a node in the network , hops through multiple nodes to reach the destination
  - Usually have a single type of radio on devices
  - The requirements on end-user devices
    - Higher when compared to infrastructure meshing since, the end-users must perform additional functions (e.g. routing and self-configuration)

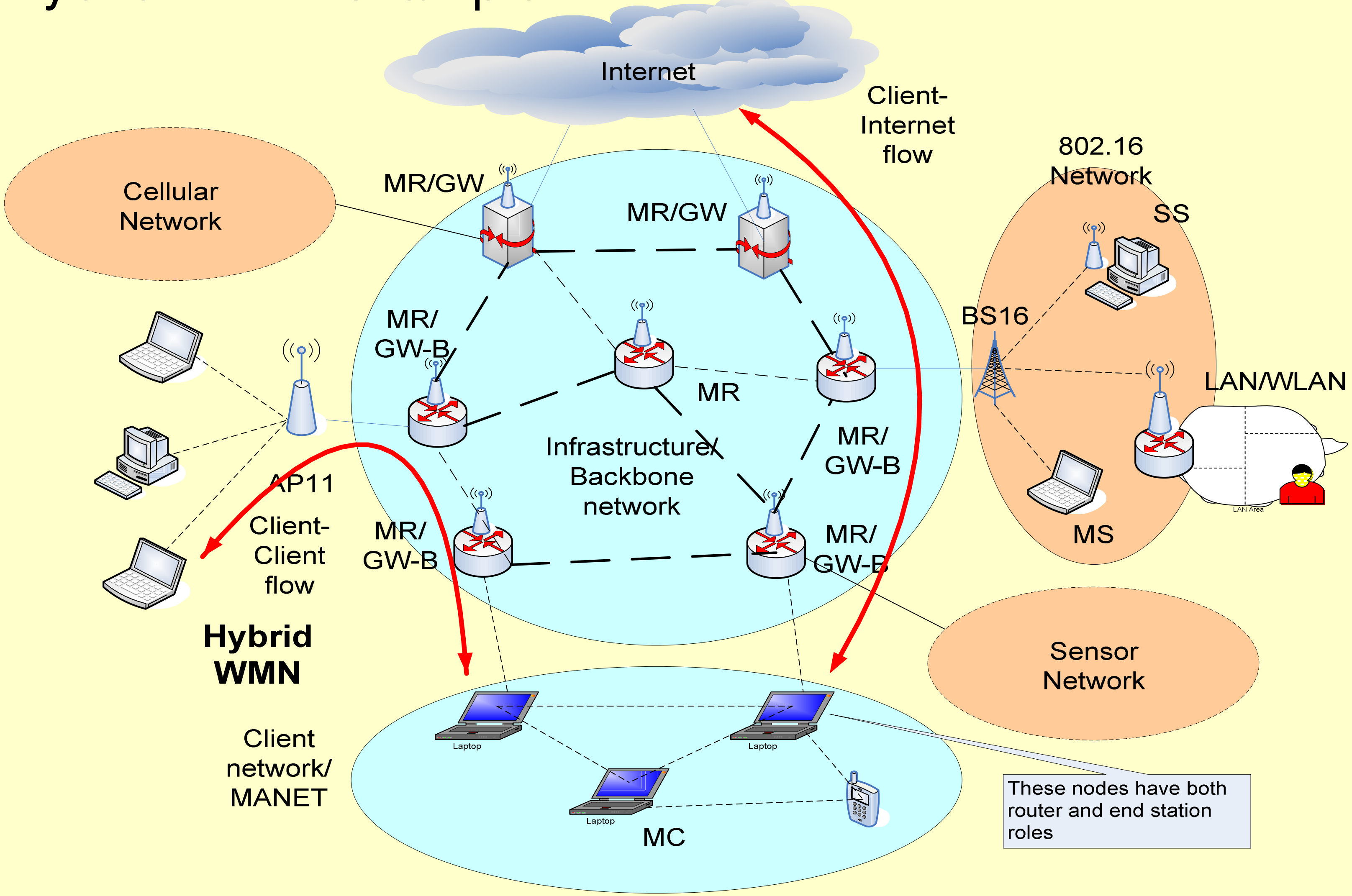
2. Basic architectures and challenges

- **Hybrid WMN**

  - It is a combination of infrastructure and client meshing.
  - Mesh clients can access the network through MR as well as directly meshing with other mesh clients
  -
  - The infrastructure may provides connectivity to other networks
    - Internet, Wi-Fi, WiMAX,cellular, and sensor networks
  - The routing capabilities of clients provide improved connectivity and coverage inside the WMN
  - The hybrid architectures will be probably, the most applicable case in the future

1. 2. Basic architectures and challenges

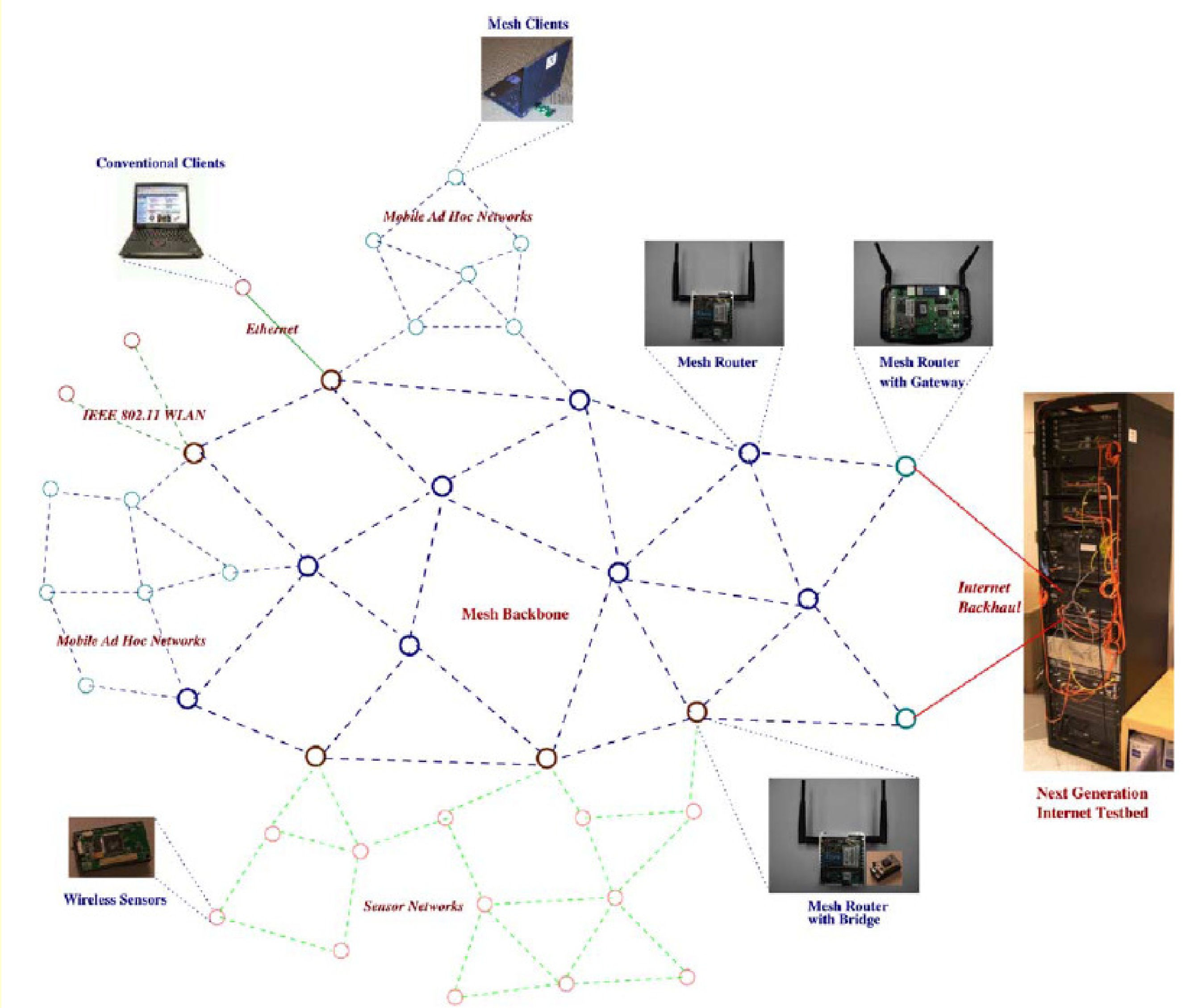
- Hybrid WMN- example



2. Basic architectures and challenges

- Hybrid WMN - real life example

- *Source: Akyildiz, I.F., Wang, X. and Wang, W., Wireless Mesh Networks: A Survey, Computer Networks Journal (Elsevier), March 2005*



2. Basic architectures and challenges

- **WMN elements: links**
- Link functions: intra-mesh, access (to/from stationary or mobile client stations), internet

- **Client-to MR links**
  - Link types
    - Wired: Bus (PCI, PCMCIA, USB), Ethernet, Firewire, etc.
    - Wireless: 802.11x, 802.16x, 802.15, proprietary
  - Link mode: Point-to-Point (PP) or Point-to-Multipoint (PMP)
  - Links should have enough capacity to avoid traffic saturation
  - In general- access links: connect entities different from MR-MR

- **MR to MR (backbone) links**
  - Link types
    - Wireless: 802.11x, 802.16, 802.15, Proprietary
  - Link mode: Usually multipoint to multipoint; set of point to point
  - Could be traffic saturated

- **WMN Gateway to Internet links (backhaul)**
  - Link types
    - Wired: Ethernet, TV Cable, Power Lines
    - Wireless: 802.16, Proprietary
  - Link mode: Point to Point or Point-to-Multipoint
  - Must be designed with enough capacity to avoid bottlenecks

- **WMN elements (cont'd)**
  - **Mesh Routers (MR)**
    - They contain additional routing functions to support mesh networking
    - They usually have multiple wireless interfaces built on the same or different RAT
    - Mobility: Stationary (e.g. rooftop) ; Mobile (e.g., airplane, busses/subway)
    - MRs can achieve the same coverage as a conventional router
      - with lower transmission power due to multi-hop feature
    - Do not originate/terminate data flows
    - For large WMNs, many MRs are needed, hence, cost can be an issue
    - Implementation: MRs may be based on different embedded systems, e.g.: PowerPC or Advanced Risc Machines (ARM)

WMN elements (cont'd)

Gateways (GW)

- The gateway/bridge (GW-B) functionalities enable the integration of WMNs with other wireline or wireless networks such as: Internet, cellular, wireless sensor, Wi-Fi, WiMAX
- Multiple interfaces (wired & wireless)
- Mobility: Stationary (e.g. rooftop) – most frequent; Mobile (e.g., airplane, busses/subway)
- Serve as (multi-hop) "access points" to user nodes
- Few GWs are needed, (they are more expensive)

2. Basic architectures and challenges

- **WMN elements (cont'd)**
  - **Clients/users**
    - The sources/destinations for data traffic flows in the network
    - Typically have one interface
    - Mobility: Stationary or Mobile
    - Connected to the WMN through MRs (or directly to GWs)
    - Examples of mesh clients: Laptop, PDA, Wi-Fi IP Phone and Wi-Fi RFID Reader
    - Nodes (e.g., desktops, laptops, PDAs, PocketPCs, phones, etc.) having wireless NICs can connect directly to MRs
    - Clients with wireline NICs can access MRs by connecting through, e.g., Ethernet
    - WMNs enable users be always-on-line anywhere, anytime

2. Basic architectures and challenges

- **WMN versus Ad-hoc Networks (MANET)**
  - **Routing and network configuration**
    - MANET: end-user devices additionally perform routing and configuration functionalities for all other nodes
    - WMN: Mesh routers perform routing and configuration
    - Consequence for WMNs
      - load on end-user devices is significantly decreased
      - lower energy consumption hence additional capabilities to mobile and energy constrained end-users.
      - limited end-user requirements (decreasing the cost of devices that can be used in WMNs).
  - **Mobility capabilities**
    - MANET: topology is frequently changing, depending on the users' movement -> additional tasks for routing protocols and network configuration
    - WMNs- MRs infrastructure : WMN can be easier managed and configured (MRs are usually fixed or nomadic)
    - Still the mobility of end-users is supported

- **WMN versus Ad-hoc Networks (MANET) (cont'd)**
  - **Usage of Multiple Radios (MRd)**
    - MRs can be equipped with multiple radios to perform routing and access functionalities.
    - Consequence: possibility to distinguish between two main types of traffic
      - routing and configuration traffic is performed between MRs
      - access traffic to the network from clients (can be carried in a different radio)
      - MRd can improve the WMN capacity versus MANET
  - **Relationship 802.11-MANET and WMN**
    - MANETs can be considered as a subset of WMNs.
    - IEEE 802.11 existing techniques developed for MANET are applicable to WMNs (with some modifications for better performance).

2. Basic architectures and challenges

- **Significant WMN design factors with impact on performance/cost**
- **PHY - Radio techniques and MAC**
  - Approaches have been proposed to increase capacity and flexibility of wireless systems
    - Directional and smart antennas, MIMO and multi-radio/multi-channel systems
    - MIMO : key technologies for IEEE 802.11n - high speed extension of Wi-Fi
    - Multi-radio chipsets and their development platforms are available on the market
    - Advanced RT such as reconfigurable radios, frequency agile/cognitive radios, software radios are in development – allowing dynamic control of PHY layer

2. Basic architectures and challenges

- **Significant WMN design factors with impact on performance/cost**
- **PHY - Radio techniques and MAC (cont'd)**
  - The above advanced wireless PHY RT all require a revolutionary design in higher layer protocols, especially MAC and routing protocols (close to PHY)
    - e.g. directional antennas applied to IEEE 802.11 networks
      - need a routing protocol to take into account the selection of directional antenna sectors
      - can reduce exposed nodes, but they also generate more hidden nodes. Thus, MAC protocols need to be re-designed to resolve this issue
    - For MIMO systems, new MAC protocols are also necessary
    - For software radios are considered, powerful MAC protocols, and programmable MAC, are needed

2. Basic architectures and challenges

- **Significant WMN design factors with impact on performance/cost**
- **Considerations on scalability**
  - Multi-hop wireless networking may have poor scalability; Performance (mainly throughput) decrease rapidly with number of hops
  - MAC protocols may experience significant throughput reduction
  - Routing protocols no more find a reliable routing path
    - Result: TCP may loose connections
    - E.g. IEEE 802.11b, 4 hops, TCP throughput < 1.0 Mbps)
  - The reason for low scalability is that the E2E reliability drops as the scale of the network increases

2. Basic architectures and challenges

- **Significant WMN design factors with impact on performance/cost**
- **Considerations on scalability (cont'd)**
  - However, in WMNs, centralized multiple access schemes such as TDMA and CDMA are difficult to implement (complex, need timing synchronization for TDMA and code management for CDMA - see IEEE 802.16 2004 mesh mode complexity)
    - In distributed multi-hop network accurate timing synchronization within the global network is difficult to achieve
    - Distributed multiple access schemes such as CSMA/CA are easier to use
    - But CSMA/CA has very low frequency spatial-reuse efficiency - which significantly limits the scalability of CSMA/CA-based multi-hop networks
  - To improve the scalability of WMNs, designing a hybrid MAC scheme with CSMA/CA and TDMA or CDMA is an interesting and challenging research issue.

2. Basic architectures and challenges

- **Significant WMN design factors with impact on performance/cost (cont'd)**
- **Mesh connectivity**
  - It depends on MAC and routing protocols
  - Network self organization and topology control algorithms are needed
  - Topology-aware MAC and routing protocols can improve the performance

- **Bandwidth and Quality of Services (QoS).**
  - Many applications on top of WMNs are related to broadband services with various QoS requirements

  - E2E delay, fairness, bandwidth assurance, delay jitter, aggregate and per node throughput, packet loss ratios - important design factors for the protocols

2. Basic architectures and challenges

- **Significant WMN design factors with impact on performance/cost (cont'd)**
- **Inter-operability and integration in E2E architectures**
  - WMNs usually support network access for both conventional and mesh clients.
  - WMNs need to be backward compatible with conventional client nodes
  - Integration of WMNs with other wireless/wireline networks requires appropriate routers/gateways/bridges
- **Control and Management issues**
  - Protocols are needed to make WMN to be autonomous: power management, self-organization, dynamic topology control, robust to temporary link failure, and fast network-subscription
  - user-authentication procedure- necessary
  - Network management tools are needed to
    - maintain the operation
    - monitor the performance
    - configure the WMNs parameters

- **WMN Main challenges/problems- examples**

- **Capacity/Throughput versus dimension**
  - **Major problem of WMN!!**
  - Ad hoc networks and WMNs initially - single-channel or single-radio interface
  - WMNs problem: significant network capacity limitation
  - Theoretical upper limit of the per node throughput capacity is asymptotically limited by $O(1/n^{1/2})$, n is the no. of network nodes
  - Theoretically max capacity to every node in a random static wireless ad hoc network, with ideal global scheduling and routing, is estimated as $O(1/(n\log n)^{1/2})$ – show a serious problem
    - *(P. Gupta and P.R. Kumar, "The Capacity of Wireless Networks." IEEE Transactions, on Information Theory, vol. 46, no. 2, March 2000)*
  - Worse for WMN: for real MAC, routing, and transport protocols and a realistic traffic pattern, the achievable capacity in a WMN, in practice, is still less

2. Basic architectures and challenges

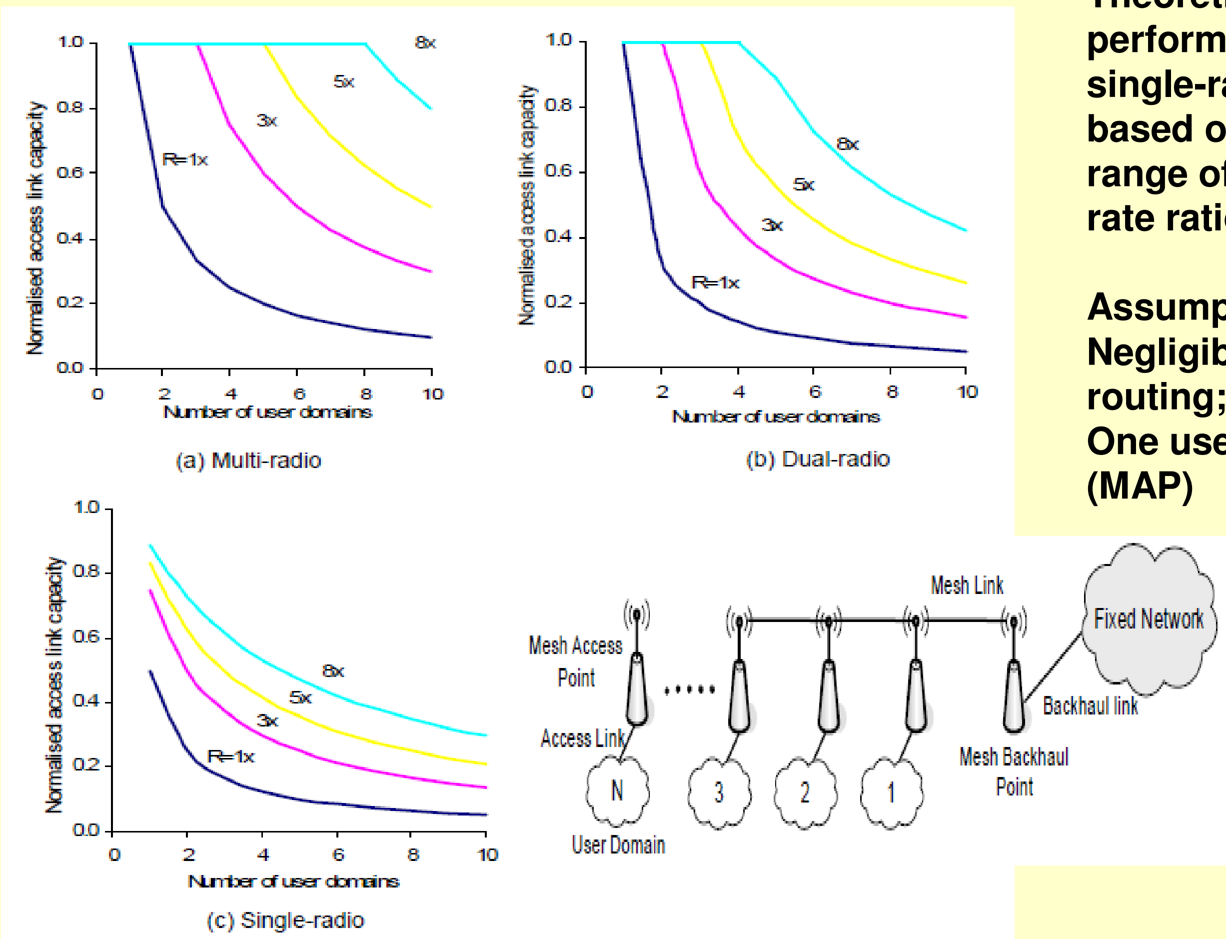
- **WMN challenges/problems - examples**
- **Capacity/Throughput versus dimension (cont'd)**

  - *J. Li, C. Blake, et.al., , "Capacity of Ad Hoc Wireless Networks," Proceedings of ACM Mobicom 2001, July 2001*
    - Experiments (CSMA/CA – MAC IEEE 802.11) on a string topology, have shown the throughput is ~ 1/n of the raw channel bandwidth
    - In general, the throughput capacity achievable in an arbitrary WMN is ~ $O(W/n^{1/d})$
    - d is the network dimension, W is the total bandwidth.

  - Important solution to increase capacity: **multiple radio interfaces**.
  - Recently, WMNs using multiple radio I/Fs are more and more used (lower costs)
    - But other problems arise: interference and channel assignments- increased complexity

2. Basic architectures and challenges

- **WMN challenges/problems - examples**
- **Capacity/Throughput versus dimension (cont'd)**
  - *Source: A. Ting ,D. Chieng, Design and Capacity Performance Analysis of Wireless Mesh Network*



(a) Multi-radio

(b) Dual-radio

(c) Single-radio

Theoretical upper-bound capacity performance limit of multi, dual and single-radio chain topology network based on the following assumptions for a range of different mesh-to-access link rate ratios (R).

Assumptions: Fair access capacity; Negligible RF interferences; Perfect routing;
One user domain per mesh access point (MAP)

The normalized access link capacity, C = 1 means all the user domains along the chain are able to access their respective access points at full theoretical link rate e.g. at full 11Mbps if IEEE802.11b access is used or 54Mbps in IEEE802.11g/a case

2. Basic architectures and challenges

- **WMN challenges/problems –examples (cont'd)**
- **Single channel - fairness problems**

•Q- flow – active ⇒ Node 2 – exposed

•Node 2 - silent

•Node 1: RTS, Node 2 does not answer

•Node 1 retries, ….

•Conclusion Q gets more capacity than P

Multiple exposure case

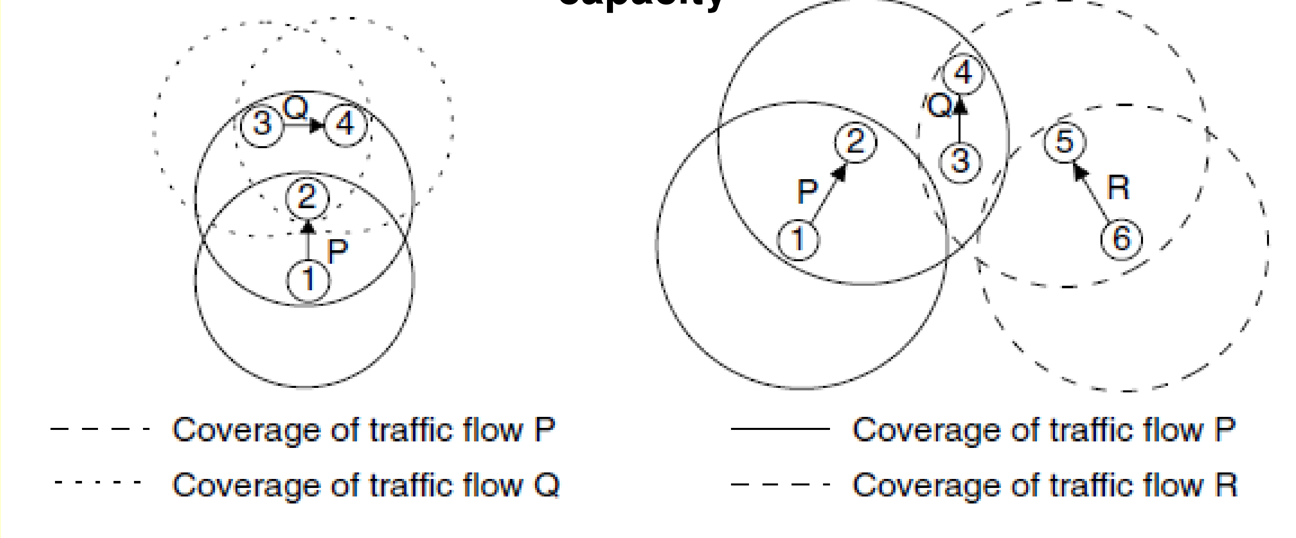
•flows P and R active and do not have info about other flows

•Q has information about both the other flows.

•Node 3 is double exposed w.r.t flows P, R

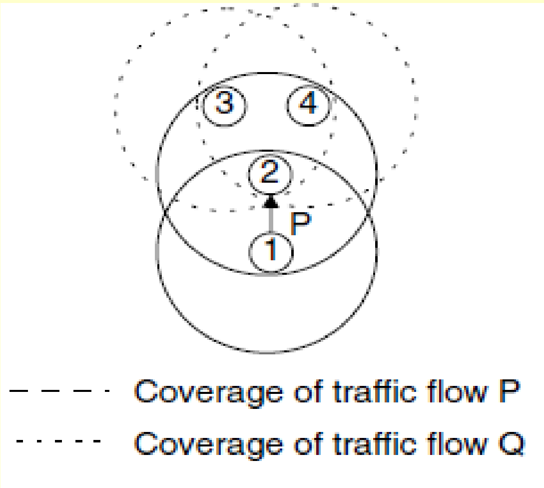
•Node 3 abstain for transmission and set NAV appropriately

•Conclusion : Flow Q may starve and get less capacity

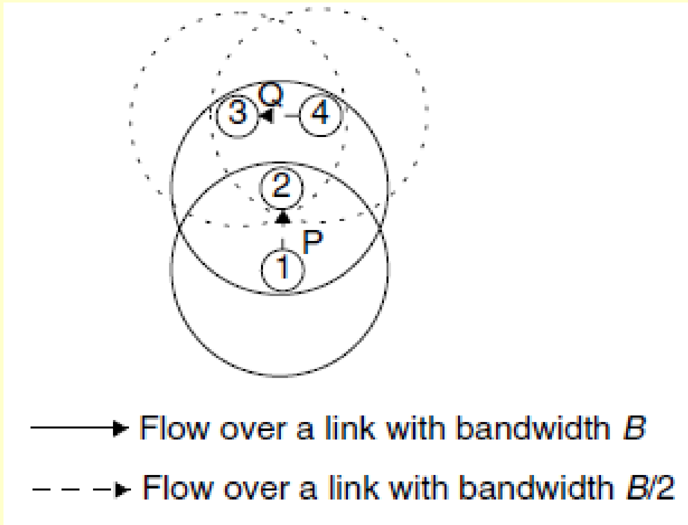


WMN challenges/problems- examples (cont'd)

- **Half duplex- problem**
  - No node can simultaneously receive and transmit.
  - A single half-duplex radio with a channel data rate of B bits/s is employed at a time
  - Example: only flow P could be transmitting while other nodes are waiting
  - In certain MAC CSMA/CA-based IEEE 802.11, there exists a strong chance of channel capture
  - So, a successful node keeps the channel busy more than others



- **Fairness improvement**
  - each node uses two radio interfaces with channel data rate of B/2 bits/s
  - two simultaneous flows, P and Q, could exist
  - though each channel has only half the bandwidth, the throughput fairness increases as found in experimental studies



2. Basic architectures and challenges

- **WMN challenges/problems- examples (cont'd)**
  - **Deployment examples (small partial list)**
  - **Several cities have partially deployed WMNs**
    - Bay Area Wireless Users Group (BAWUG) [3], Champaign-Urbana Community Wireless Network, (CUWiN), SFLan, SeattleWireless, Southampton OpenWireless Network, (SOWN), and Wireless Leiden (in Netherlands), etc.
    - **Academic/research WMNs**
    - MIT Roofnet project, the Rice University Technology for All project, \MSR Self-organizing neighborhood WMN project
  - **Comments on results and problems encountered in the above developments**
    - successes have been reported
    - but still problems identified- at lower layers
      - Excessive packet losses unpredictable channel behaviors
      - inability to find stable and high-throughput paths throughput degradation due to intra-flow and inter-flow interference, etc.

2. Basic architectures and challenges

- **WMN challenges/problems- examples (cont'd)**
-
- **Comments on results and problems (cont'd)**
  - **Main reason of the problems at lower layers**
    - the notion of a link is no longer well-defined in wireless environments
      - In WMN, the shared medium ranges among nodes is determined by several PHY/MAC attributes such as the transmit power he carrier sense threshold, and the channel on which an interface sends/ receives frames
      - intra- and inter-flow interference (which in turn is contingent upon how nodes and traffic are distributed in the spatial and temporal domains)
      - environmental factors (multi-path fading and shadowing effects, temperature and humidity variation, and existence of objects in the paths)
  - Effect:
    - the definitive metrics that usually characterize a link are no longer the old well-defined metric for a wireless link.
    - protocols designed for wireline networks may have poor performance or even fail in WMNs (e.g a routing protocol based on hop count metric)

WMN challenges/problems-examples (cont'd)

- Approaches to solve some of the above problems
  - MAC layer:
    - characterize how, and to what extent, wireless links are affected by PHY/MAC attributes and other environmental factors
    - identify control tools/means in the PHY/MAC layers with which the sharing range of a wireless link can be better controlled
  - Cross layer design and optimization (making available the PHY/MAC attributes to higher-layer protocols)

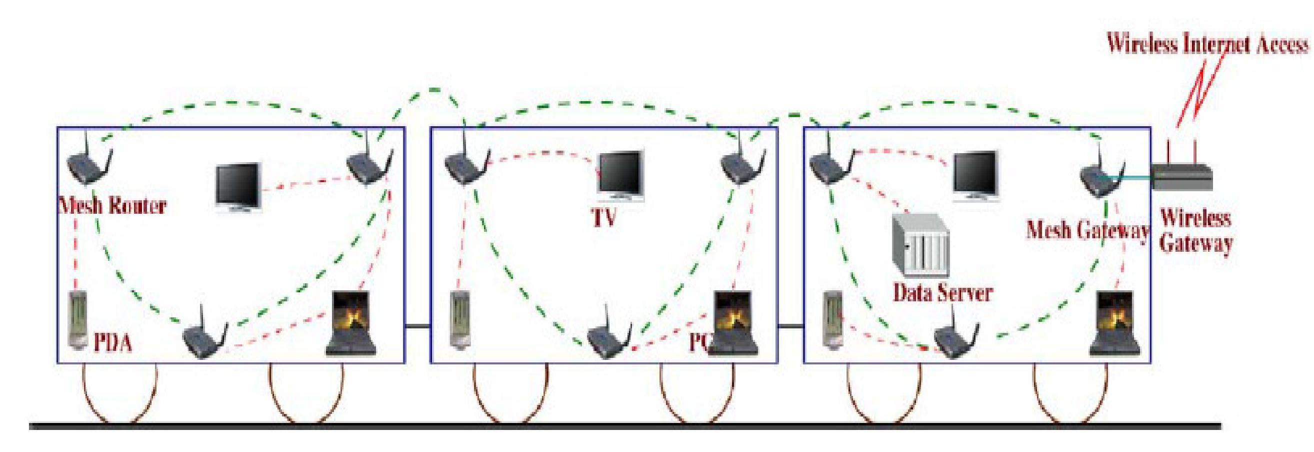
CONTENTS

3. WMN deployments and applications

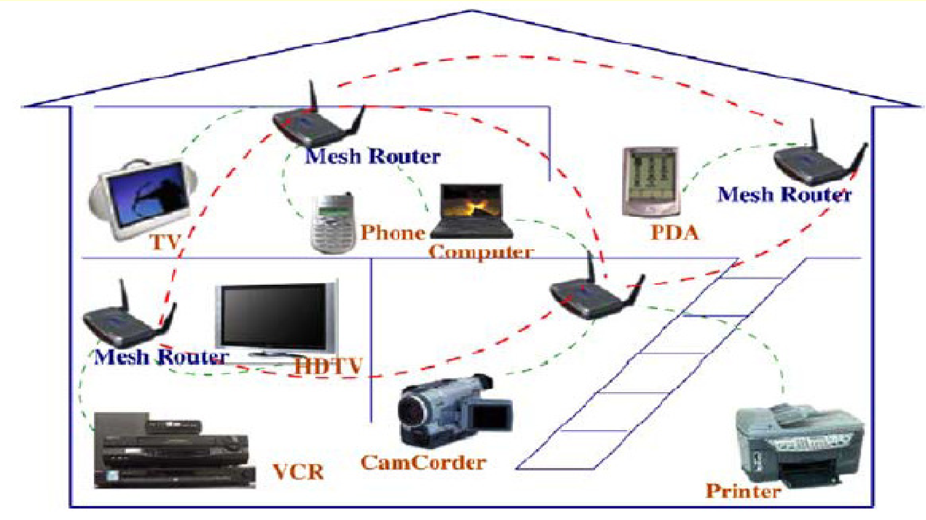
- Connectivity services
  - Broadband Internet access (fixed or mobile)
  - L2 connectivity between clients
  - Extended WLAN coverage
  - Metropolitan networks (usually 802.11 + 802.16)
- Use cases scenarios
  - General support for A/V, data and multimedia applications
  - Remote monitoring and control, Video surveillance
  - Emergency response
  - Military and field applications
  - Community networks
  - Enterprise networks
  - Public transportation Internet access
  - Multimedia home networking

3. WMN deployments and applications

- **Use cases examples**



Transportation system



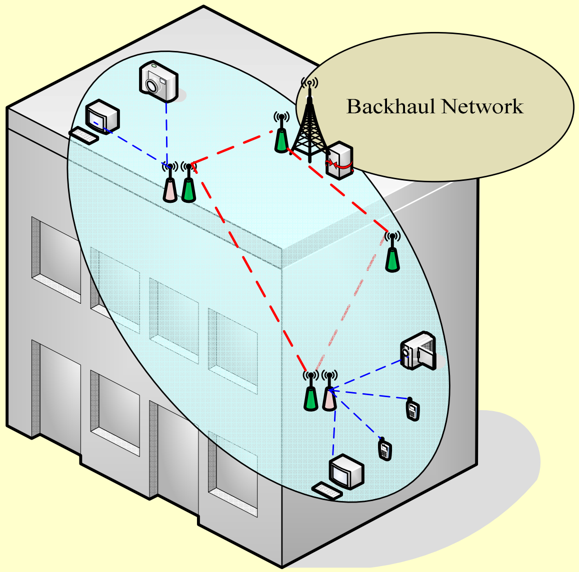
Broadband Home Networking

Source: Akyildiz, I.F., Wang, X. and Wang, W., Wireless Mesh Networks: A Survey, Computer Networks Journal (Elsevier), March 2005

3. WMN deployments and applications

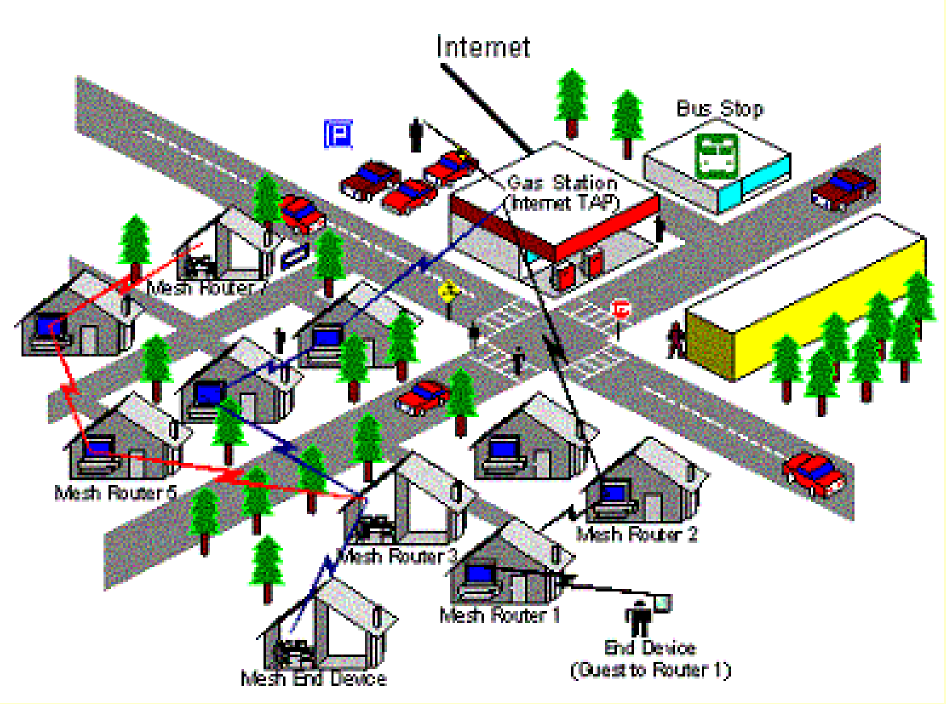
- **Use cases examples**

Enterprise network



Community network:

- WMNs are replacing DSL based solution

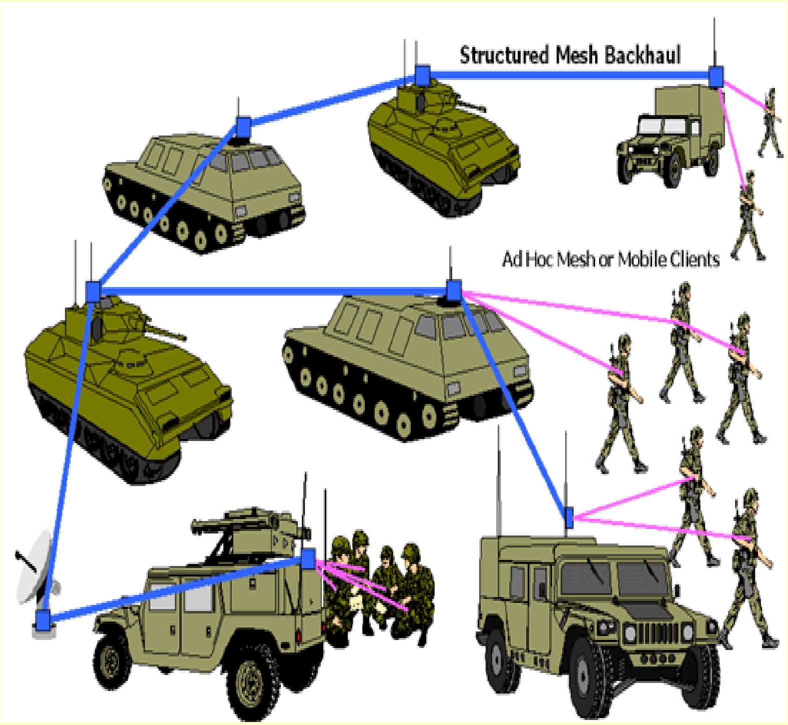


Source: research.microsoft.com/mesh/

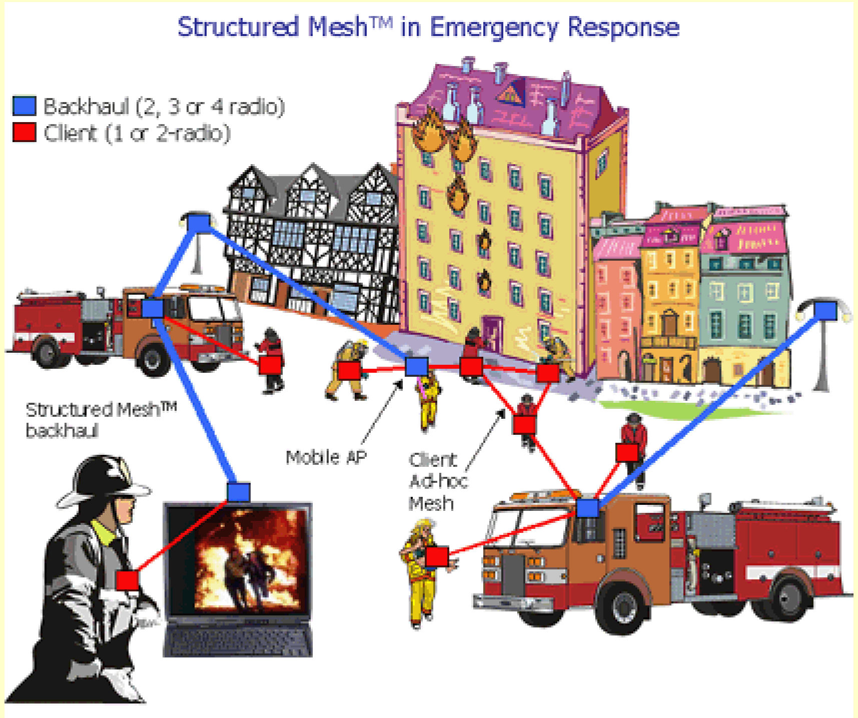
3. WMN deployments and applications

- **Use cases examples**

Military networks



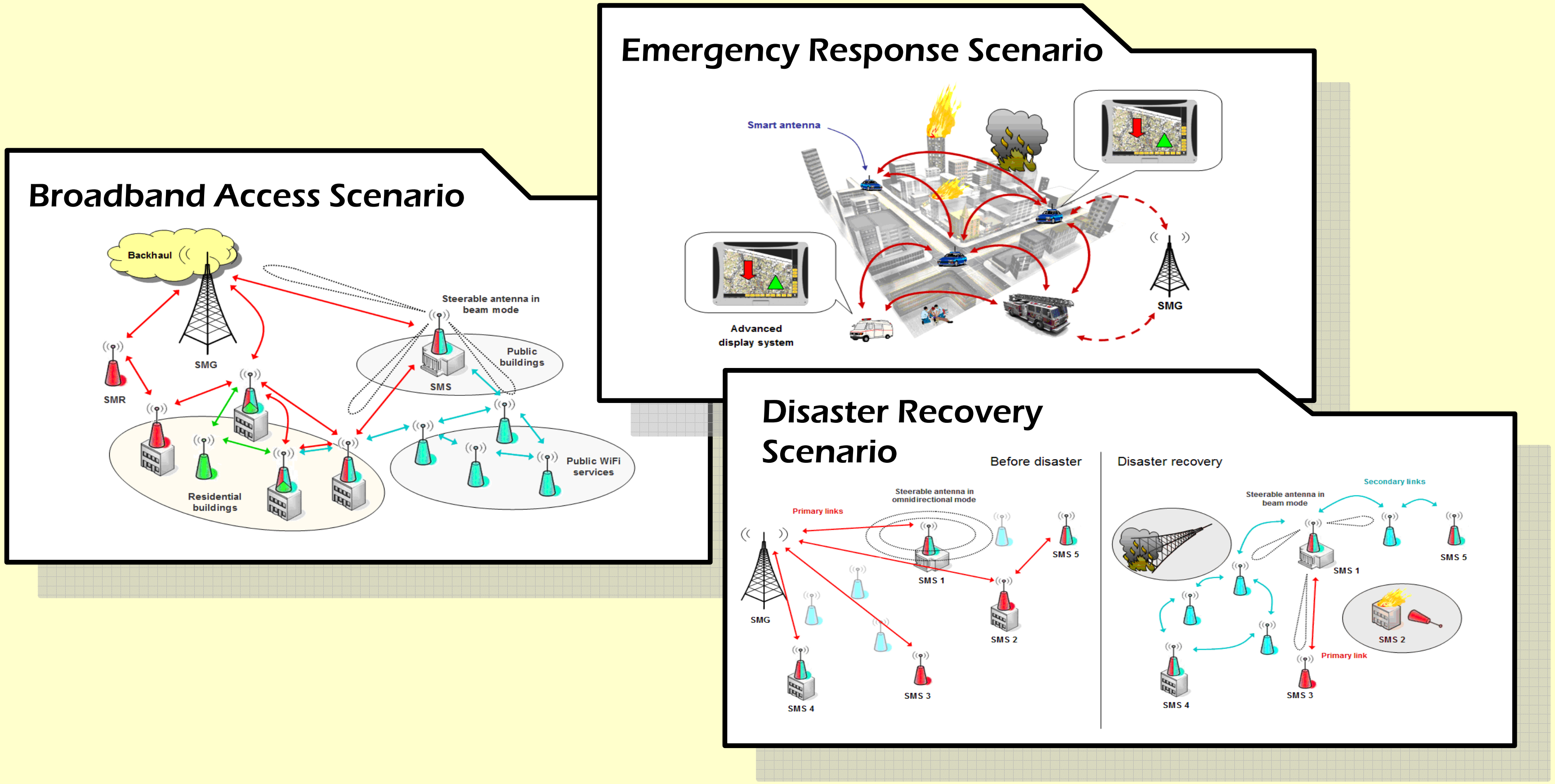
Emergency response



Source: www.meshdynamics.com

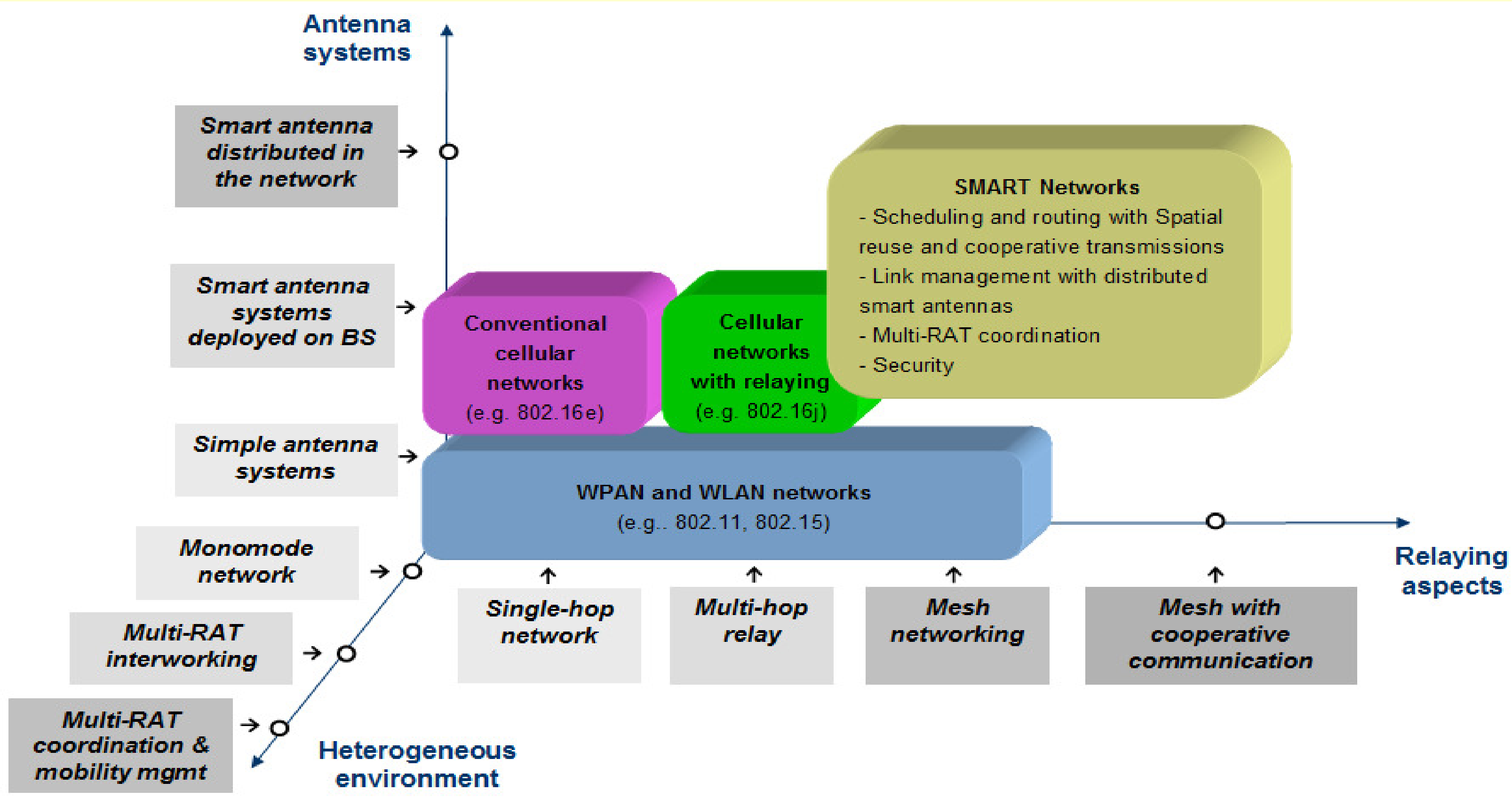
3. WMN deployments and applications

- **WMN- Example of a hybrid configuration**
  - **Source : SMART-Net FP7 project,** https://www.ict-smartnet.eu/
  - SMART-antenna multimode wireless mesh Network



3. WMN deployments and applications

- **WMN- Example of a hybrid configuration (cont'd)**
  - SMART-Net FP7 project- objectives



3. WMN deployments and applications

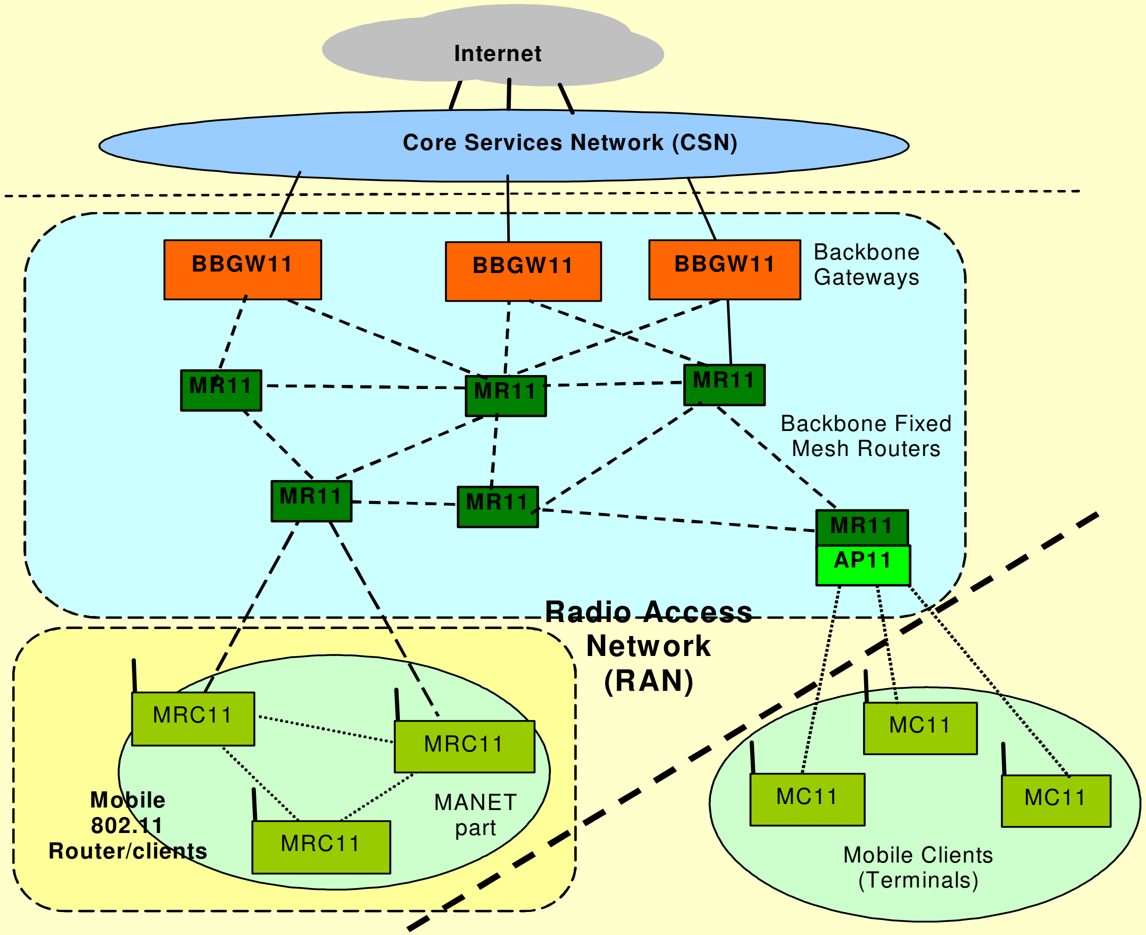
- **WMN- Example of a hybrid IEEE 802.11 configuration: RAN**
  - **Source : SMART-Net FP7 project,** https://www.ict-smartnet.eu/

MR- Mesh Routers

BBG- Backbone Gateway

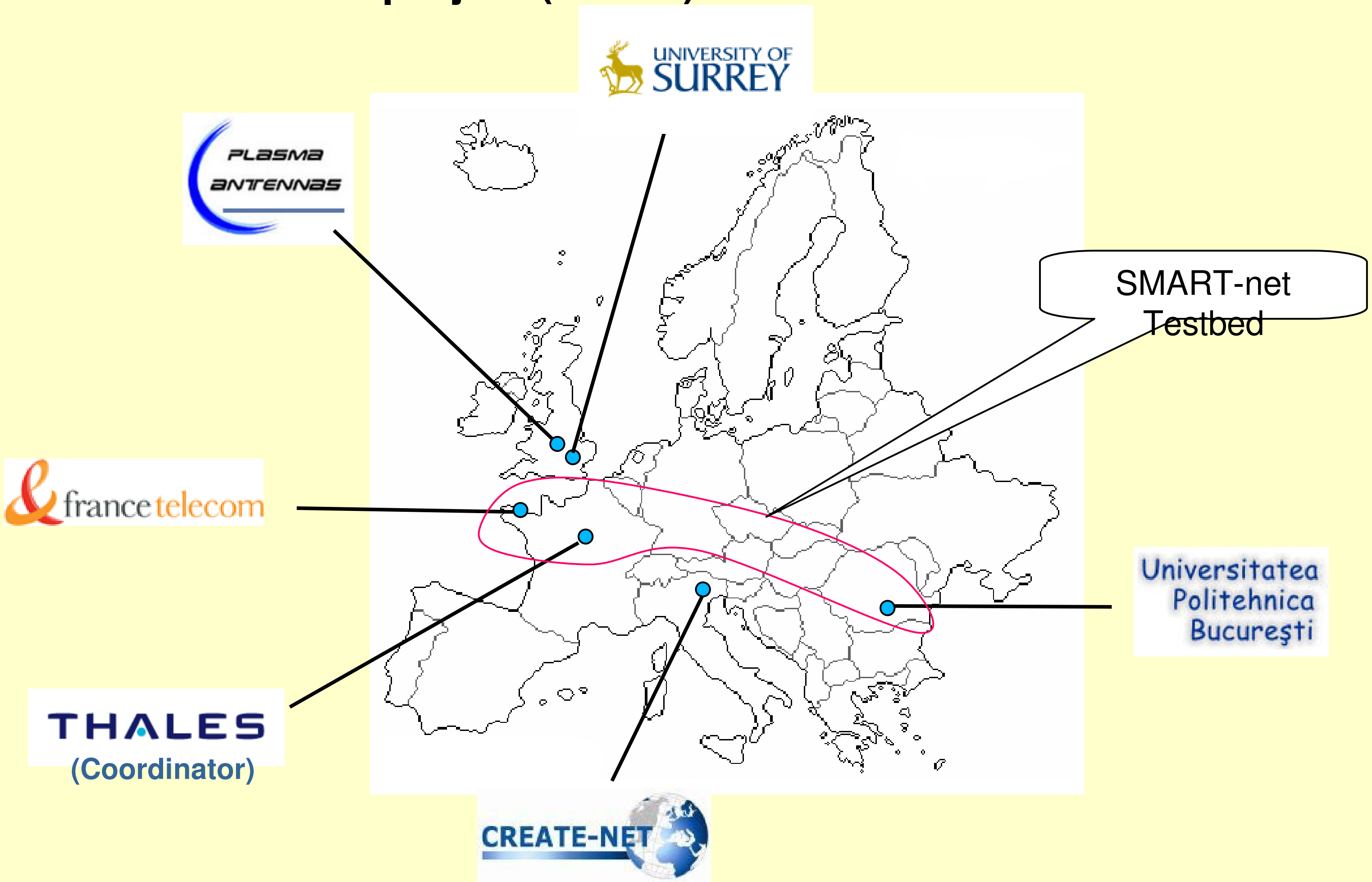
MRC – Mesh Router and Client

MC – Mesh client



3. WMN deployments and applications

- **WMN- Example of a hybrid IEEE 802.11 configuration**
  - **SMART-Net FP7 project (cont'd)**



3. WMN deployments and applications

- **Open research issues at application layer**
  - **Make existing Internet applications work better on top of the WMN architecture**
    - Lower layers WMNs protocols cannot provide perfect support (due to ad-hoc and multi-hop architecture)
    - Certain applications working smoothly in a wired network, especially those with time-critical may fail over WMNs.
    - Algorithms in the application layer must be developed to improve the performance of real-time Internet applications over WMNs
    -
  - **Application protocols for distributed information sharing** (e.g. P2P) –designed initially for wired context are not fully investigated how well work on WMNs
  - **Develop new applications that utilize the advantages of WMNs**
    - Example: wireless sensor networks may be are integrated with WMNs,
    - software tools can be developed for users in a home networking environment to remotely monitor, configure, and control all electronic devices

CONTENTS

4. Standard technologies: IEEE 802.11

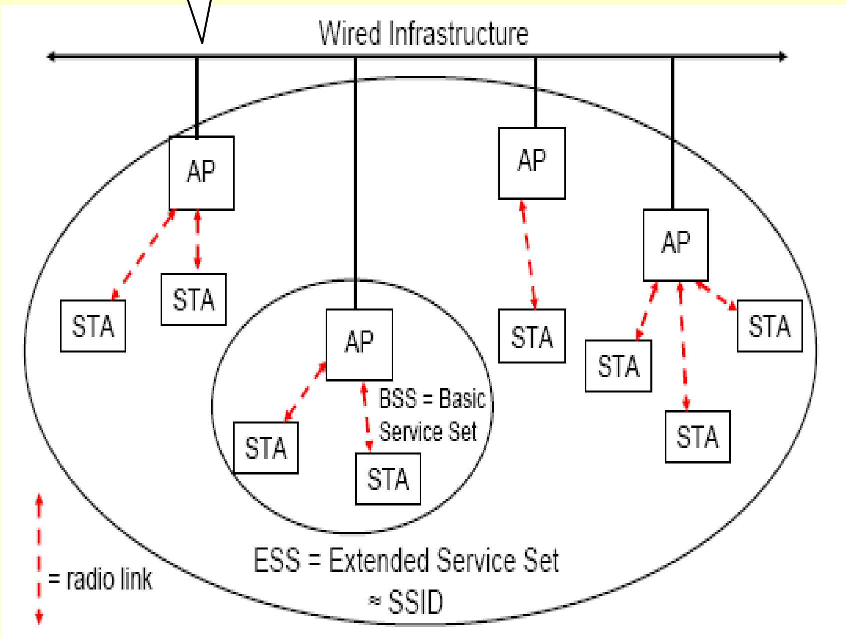
- **IEEE 802.11** standards (partial list):
  - 802.11a, 802.11b, 802.11g
  - 802.11e, MAC Quality of Service Enhancements
  - 802.11h, Spectrum and Transmit Power Management Extensions in the 5 GHz band in Europe
  - 802.11i, MAC Security Enhancements
  - 802.11j, 4.9 GHz–5 GHz Operation in Japan
  - 802.11- 2007 Part 11: Wireless LAN Medium Access Control (MAC), and Physical Layer (PHY) Specifications

- **Active Task Groups in the Wireless Local Area Network**
  - **Working Group, 802.11:**
  - 802.11k, TGk, Radio Resources Measurement
  - 802.11REV-ma, TGm, Maintenance
  - 802.11n, TGn, High Throughput
  - 802.11p, TGp, Wireless Access in the Vehicle Environment
  - 802.11r, TGr, Fast Roaming
  - **802.11s, TGs, Mesh Networking**
  - 802.11.2, TGT, Wireless Performance Prediction
  - 802.11u, TGu, Interworking with External Networks
  - 802.11v, TGv, Wireless Network Management
  - 802.11w, TGw, Protected Management Frames
  - 802.11y, TGy, 3850-3700 MHz Operation in the USA

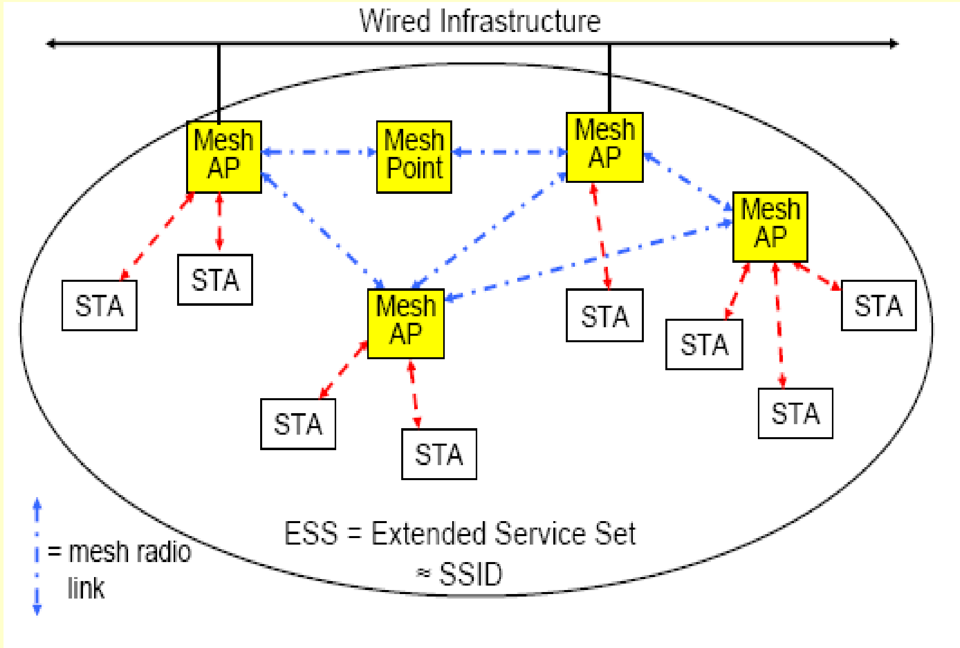
4.Standard technologies: IEEE 802.11

- **Classic WLAN – 802.11**

Wired connections!

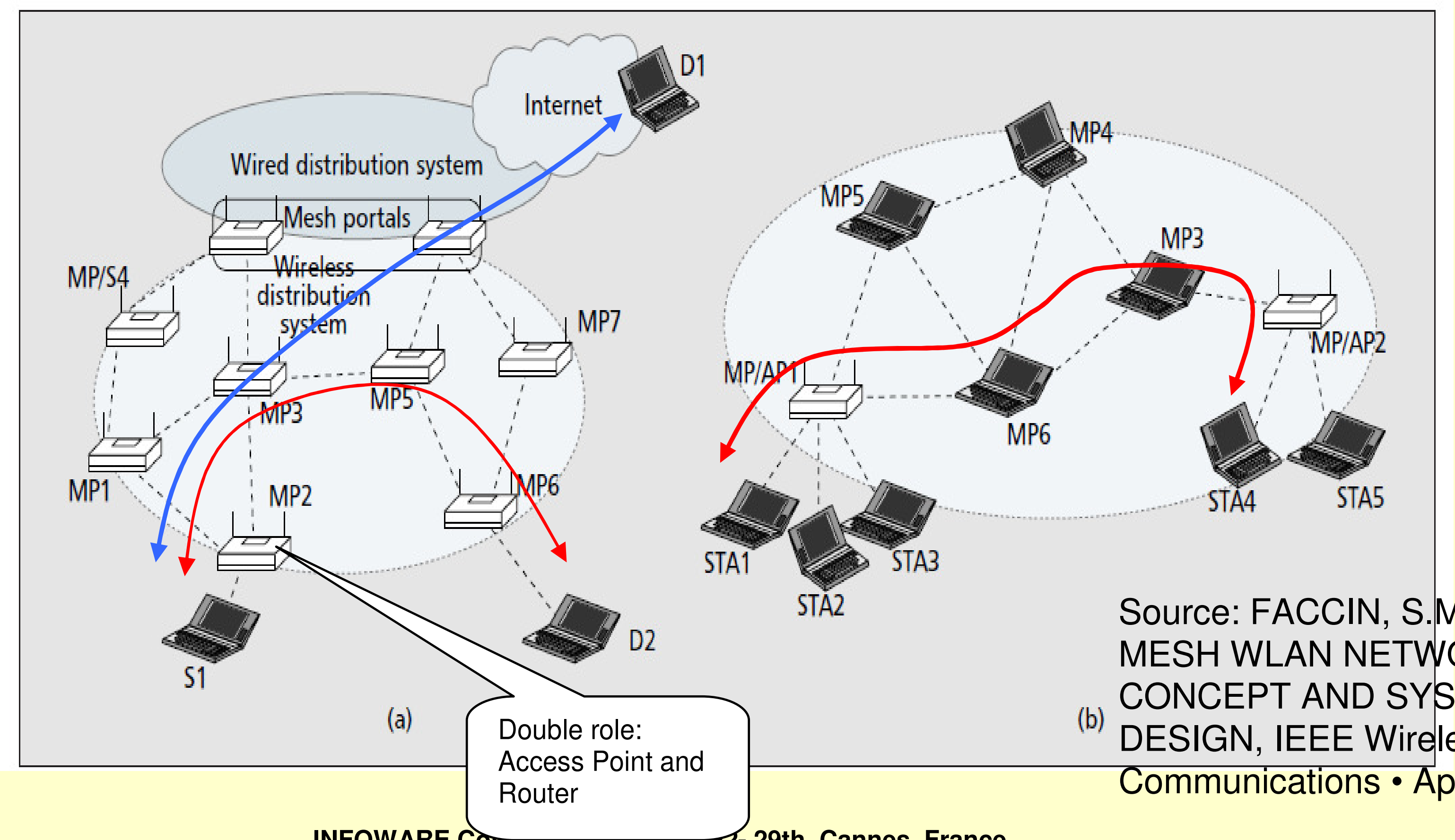


- **802.11s – mesh topology and infrastructure**
  - **Elements:**
    - **Mesh AP, Mesh Points (MP), Stations (STA)**
    - **Mesh radio links, access links**



4. Standard technologies: IEEE 802.11

- **WLAN – mesh topology and infrastructure: 802.11s (cont'd)**
- **Examples of mesh network topologies:**
- **a) 802.11 connected mesh; b) 802.11 mesh ad hoc**



Source: FACCIN, S.M.,et. al., MESH WLAN NETWORKS: CONCEPT AND SYSTEM DESIGN, IEEE Wireless Communications • April 2006

4. Standard technologies: IEEE 802.11

- **IEEE 802.11s scope**
- **802.11s is an amendment being developed to the IEEE 802.11 WLAN standard**
  - **Integrates mesh networking services and protocols with 802.11 at the MAC Layer**
- **802.11 Primary Scope:**
  - Amendment to IEEE 802.11 to create a Wireless Distribution System with automatic topology learning and wireless path configuration
  - Small/medium mesh networks (~32 forwarding nodes) – can be larger
  - Dynamic, *radio-aware* path selection in the mesh, enabling data delivery on single-hop and multi-hop paths (unicast and broadcast/multicast)
  - Extensible to allow support for diverse applications and future innovation
  - Use 802.11i security or an extension thereof
  - Compatible with higher layer protocols (~ broadcast LAN)

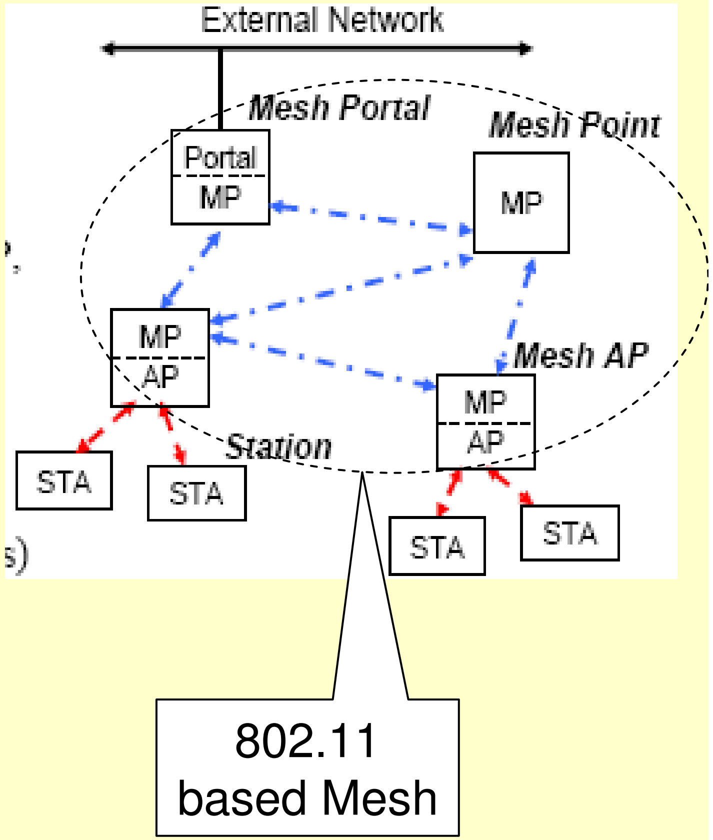
4. Standard technologies: IEEE 802.11

- **802.11s elements**

- ***Mesh Point (MP):*** establishes peer links with MP neighbors, full participant in WLAN Mesh services
  - **Light Weight MP participates only in 1-hop communication with immediate neighbors (routing=NULL)**
- ***Mesh AP (MAP):*** functionality of a MP, collocated with AP which provides BSS services to support communication with STAs

- ***Mesh Portal (MPP):*** point at which MSDUs exit and enter a WLAN Mesh (relies on higher layer bridging functions)

- ***Station (STA):*** considered in 802.11s to be outside of the WLAN Mesh,
  - They are connected via Mesh AP

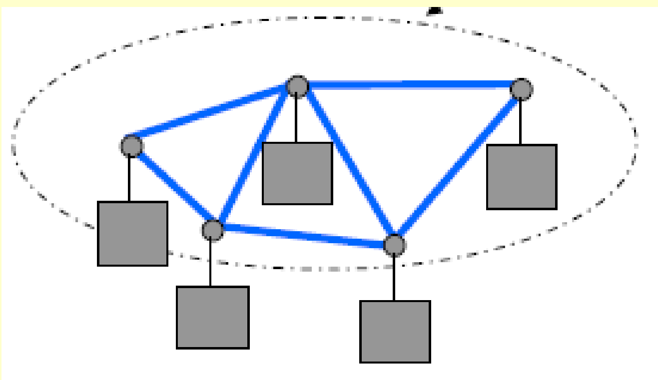


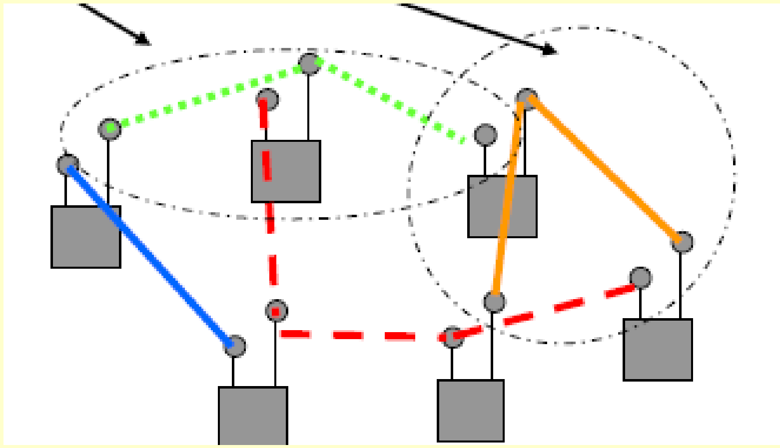
4. Standard technologies: IEEE 802.11

- **IEEE 802.11s**
- Topology Formation: Membership in a WMN
  - MPs discover candidate neighbors based on new IEs in beacons and probe response frames
    - WLAN Mesh Capability Element
      - Summary of active protocol/metric
      - Channel working mode information
    - Mesh ID
      - Name of the mesh
  - Mesh Services are supported by new IEs (in action frames), exchanged between MP neighbors
  - Membership in a WMN is determined by secure peer links with neighbors
  - Example
    - Mesh Profile:(link state, airtime metric)
    - Capabilities:
      - Path Selection: distance vector, link state
      - Metrics: airtime, latency

4. Standard technologies: IEEE 802.11

- **IEEE 802.11s**
- **Topology Formation:Support for Single &Multi-Channel Meshes**
  - Each MP : one or more logical radio interface:
  - Each logical interface on one (infrequently changing) RF channel, belongs to one “Unified Channel Graph”
  - Each Unified Channel Graph shares a channel precedence value
  - Channel precedence indicator – used to coalesce disjoint graphs and support channel switching for DFS
- **Examples of UCG :** Conner, S.W., IEEE 802.11s Tutorial, Overview of the Amendment for Wireless Local Area Mesh Networking, IEEE 802 Plenary, Dallas, Nov, 2006





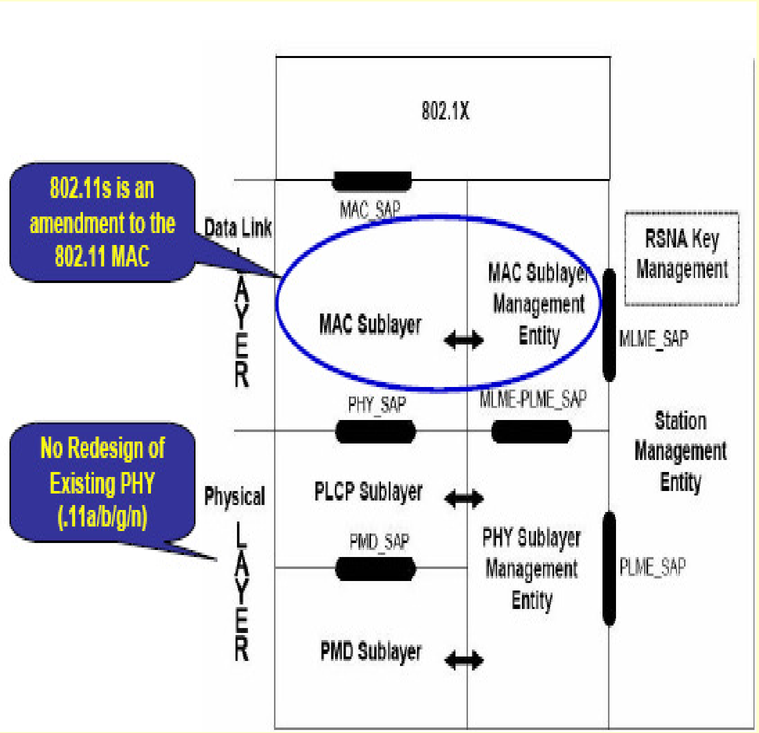
4. Standard technologies: IEEE 802.11

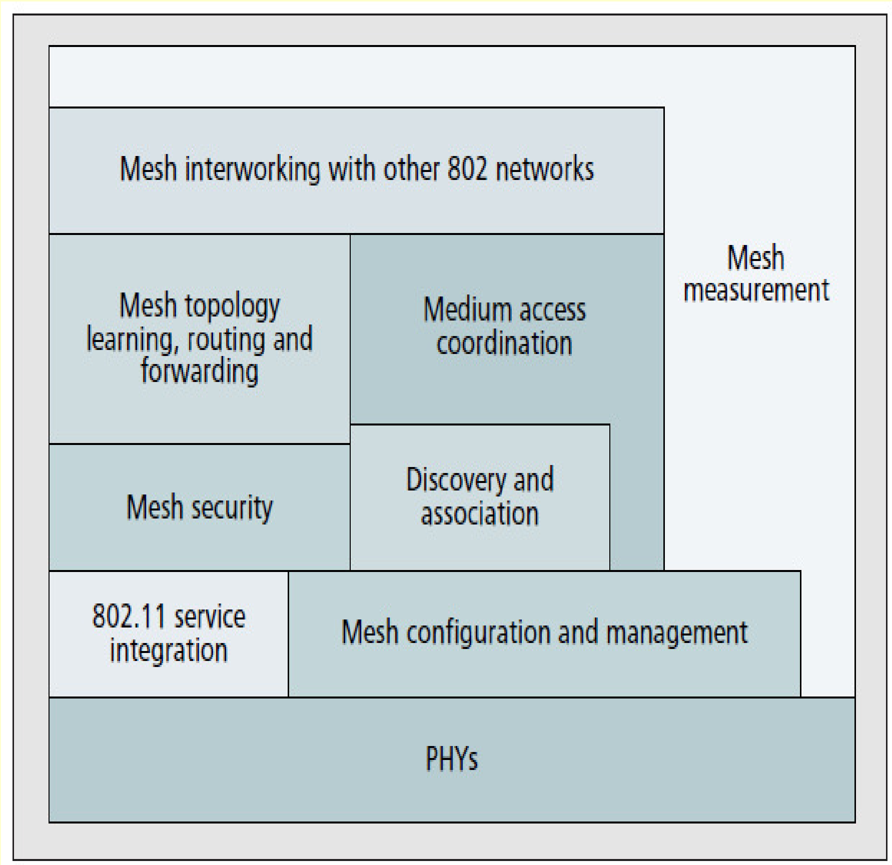
- **IEEE 802.11s**
- **Extensible Framework Support for Mandatory and Alternative Path Selection Protocols**

- 802.11s Draft defines one mandatory protocol and metric
  - Vendors may implement any protocol and/or metric within the framework
  - A particular mesh will have only one active protocol/metric on a particular link at a time
  - The protocol in use will be indicated by WLAN Mesh Capability IE
  - A mesh that is using other than mandatory protocol is not required to change its protocol when a new MP joins
  - But the algorithm to coordinate such a reconfiguration is out of 802.11 scope

4. Standard technologies: IEEE 802.11

- IEEE 802.11s MAC
- Source: MYUNG J. LEE, et.al., EMERGING STANDARDS FOR WIRELESS MESH TECHNOLOGY, IEEE Wireless Communications • April 2006





4.Standard technologies: IEEE 802.11

- **IEEE 802.11s**
- **Network entry**

  - 1. Mesh Point *X* discovers Mesh (WLANMesh_Home) with Profile (link state, airtime metric)
  - 2. Mesh Point *X* establishes peer link / authenticates with neighbors in the mesh, since it is capable of supporting the Profile
  - 3. Mesh Point *X* begins participating in link state path selection and data forwarding protocol

- 802.11s Security
- • Objectives• Scope • Role Negotiation • Authentication • Key Management

  - 802.11s Security Situation
  - • The MPs are no longer wired to one another
  - • There is no intrinsic node hierarchy
  - • MPs need to maintain secure links with many other MPs

4. Standard technologies: IEEE 802.11

- **IEEE 802.11s Routing(Layer 2)**
  - HWMP: Default Routing Protocol
  - RA-OLSR: Optional Routing Protocol

- *Hybrid Wireless Mesh Protocol (HWMP)* Default Routing protocol for Interoperability

  - Combines the flexibility of on-demand route discovery with efficient proactive routing to a mesh portal
  - Simple mandatory metric based on airtime as default, with support for other metrics

  - **On demand routing is based on Radio Metric AODV (RM-AODV)**
    - Based on basic mandatory 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 is based on tree based routing**
    - If a Root portal is present, a DV routing tree is built and maintained
    - Tree based routing is applied
      - efficient for hierarchical networks
      - avoids unnecessary discovery flooding during discovery and recovery

4.Standard technologies: IEEE 802.16/WiMAX

- **IEEE 802.16/WiMAX - Significant Broadband Wireless Access (BWA) technology**
  - Basically- cellular like systems
  - Main entities: *Base stations (BS), Subscriber Stations (SS)* – basic radial topology spanning several miles/kilometers

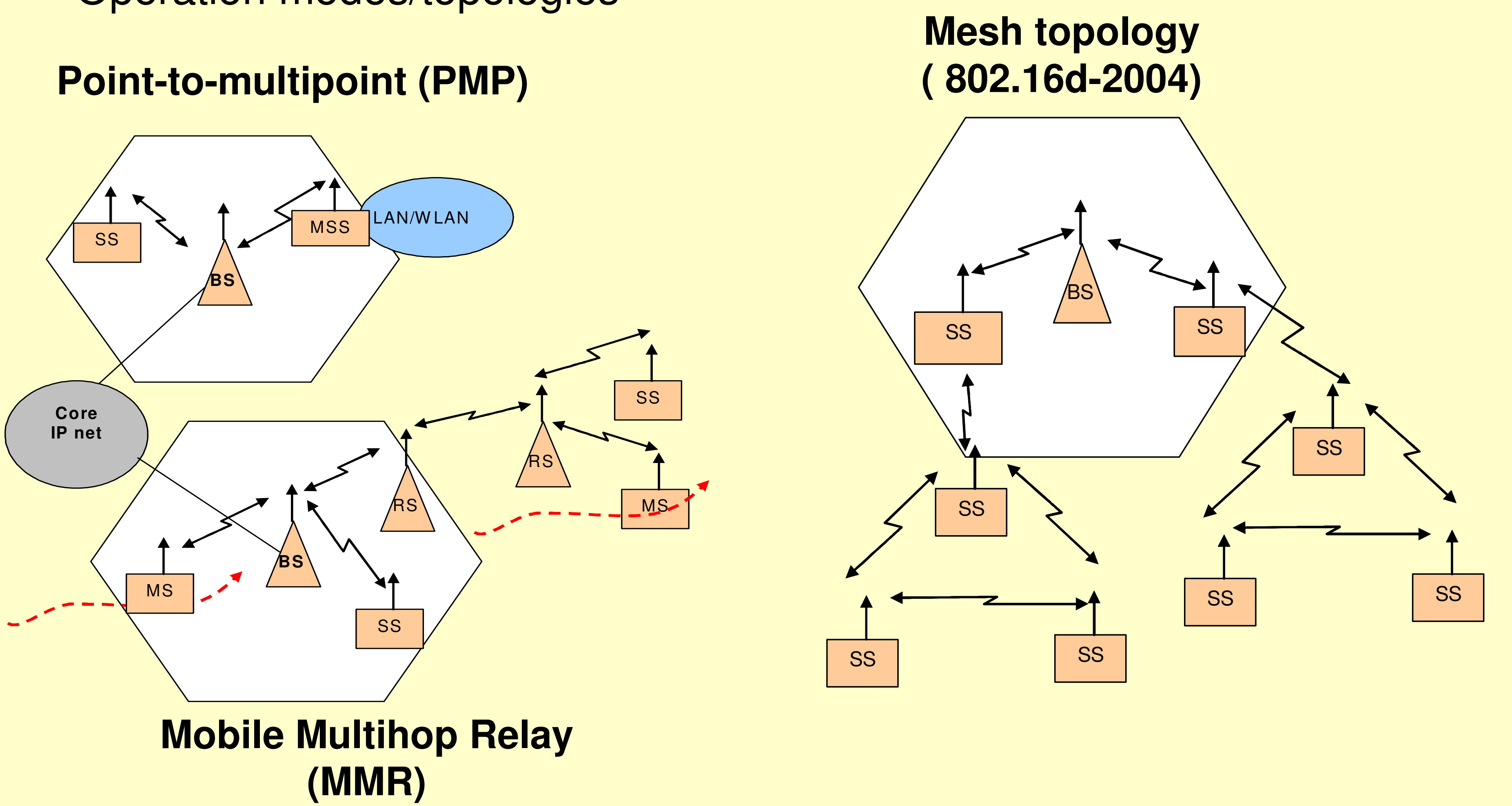
- **Goals:**
  - wireless high-speed Internet access to home and business subscribers, on metropolitan distances
  - BS can handle thousands of subscriber stations (SS)
  - Collision- free MAC (Uplink/downlink – UL/DL)
  - Support for : Data, Legacy voice systems, VoIP, TCP/IP, Appl. with different QoS, and different level of guarantees
  - Wireless Solution for “Last Mile” (or “First Mile”) problem

4. Standard technologies: IEEE 802.16/WiMAX

- **IEEE 802.16 Entities**
  - **BS- Base Station (**Usually out-door installation)
    - PHY and MAC are the main layers
    - Central role in point-to multipoint (PMP) modes
    - Partial coordination role in resource management
    - Connection/gateway point to other networks (backhaul, core IP, Internet)
  - **SS – Subscriber Station**
    - Single or Multiple user SS (role of an AP for LAN/WLAN)
    - Fixed, nomadic, mobile (MS)
    - may be installed in-door or out-door
  - **RS - Relay station**
    - **Used in Mobile Multihop Relay (MMR)**
- **Operation mode/topologies**
    - **Point to multipoint (PMP)/star topology**
    - **Mesh mode/mesh topology**
    - **(New) Mobile Multihop Relay/tree topology**
  - **MAC**
    - **allocates *uplink (UL)* and *downlink (DL)* bandwidth to SSes as per their individual needs**
    - **real time (rt) and non-real-time (nrt) classes of services**
  - **Duplex modes:**
    - ***Frequency/Time Division Duplex (FDD/TDD))***
  - **Frequency spectrum:**
    - **2-11 GHz, 10-66 GHz, Line of Sight (LOS) and Non LOS**

4. Standard technologies: IEEE 802.16/WiMAX

- Operation modes/topologies



802.16 relevant standards (selection)

- **802.16** (Dec. 2001)- basics std (obsolete).:
  - 10-66 GHz-licensed, single carrier (SC) ,LOS, fixed, PMP
  - Theoretical rates up to 134Mbit/s, real < 70Mbit/s, typical < 12MBit/s
  - Coverage – theoretically- 30-mile radius from BS (real ~20Km)

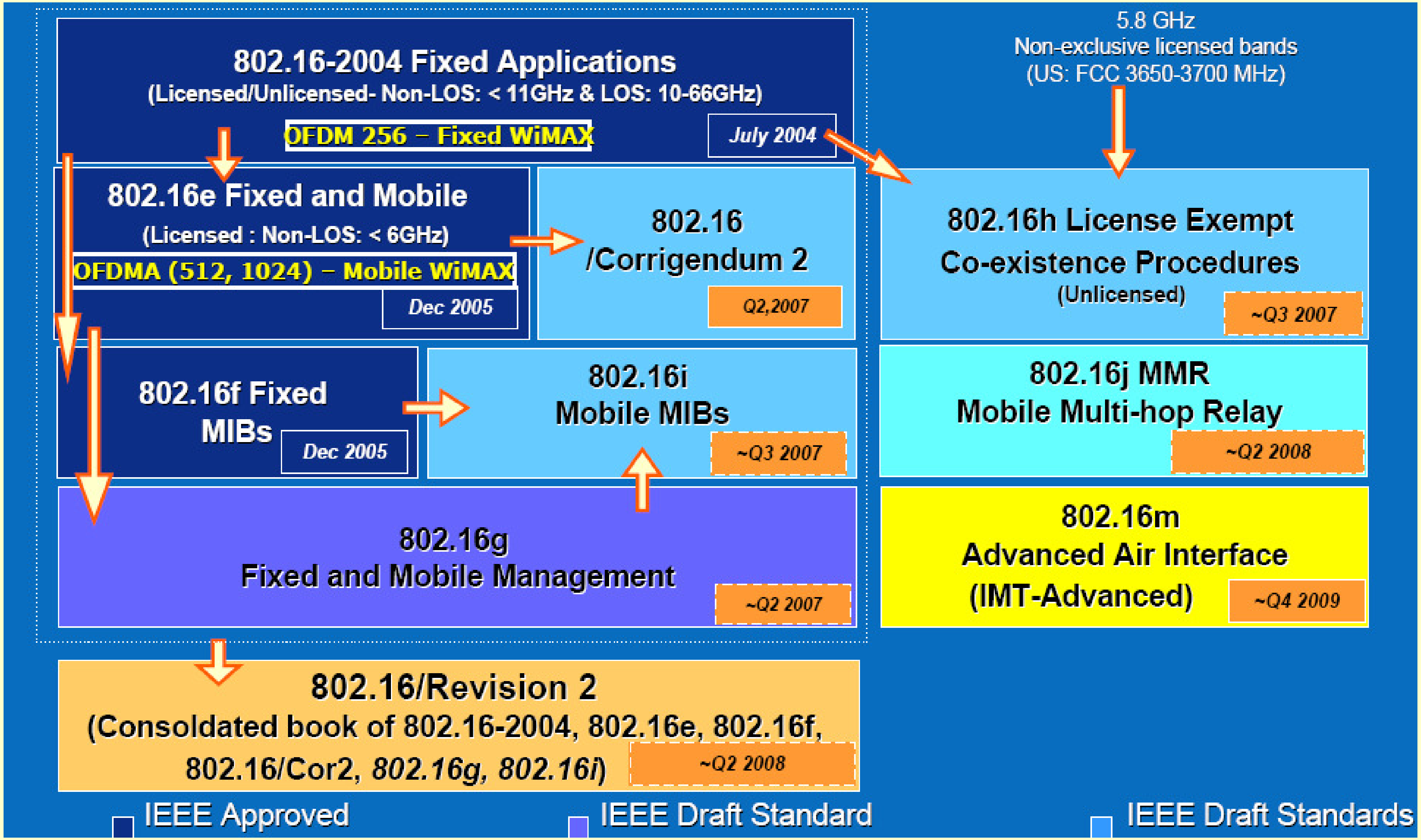
- **802.16a (2003)-** (obsolete)
  - 2-11 Ghz - licensed/unlicensed Channel size ranges: 1.75 – 20 MHz
  - PMP or Mesh topologies, LOS or NLOS
  - Rates <70MBps, distances up to 30 miles
  - Extension: Single Carrier (SC); 256 point FFT Orthogonal Frequency Division Multiplexing (OFDM); 2048 points transform OFDMA (OFD Multiple Access)
- **802.16d (2004) basic current fixed mode- standard**
  - Aligned with ETSI HIPERMAN std.
  - includes previous a/b/c amendments
  - Topologies: PMP and mesh,70 Mbps
- **802.16f, g -** Management

4. Standard technologies: IEEE 802.16/WiMAX

- **802.16 relevant standards (cont'd)**
  - **802.16e (Mobile Wireless MAN), 2005** "Mobile WiMAX"
    - Lower data rates of 15 Mbps, full nomadic and mobile use including handover
    - enhancements to 802.16-2004
      - better support for QoS
      - Scalable OFDMA
    - 2.3, 2.5 GHz bands
    - Supports devices as : mobile smart phones, PDAs, Notebooks, Laptops
  - **802.16j -** Multi-hop relay specification (2009)
  - **802.16k -** 802.16 bridging
  - **802.16m**
    - amendment for advanced air interface
    - looking to the future
    - it is anticipated that it will provide
      - data rates of 100 Mbps for mobile applications and 1 Gbps for fixed applications
      - cellular, macro and micro cell coverage, with currently no restrictions on the RF bandwidth although it is expected to be 20 MHz or more

4. Standard technologies: IEEE 802.16/WiMAX

- IEE 802.16 relevant standards evolution
  - Source: INTEL 2007



4. Standard technologies: IEEE 802.16/WiMAX

- **802.16 mesh mode (obsolete ??)**

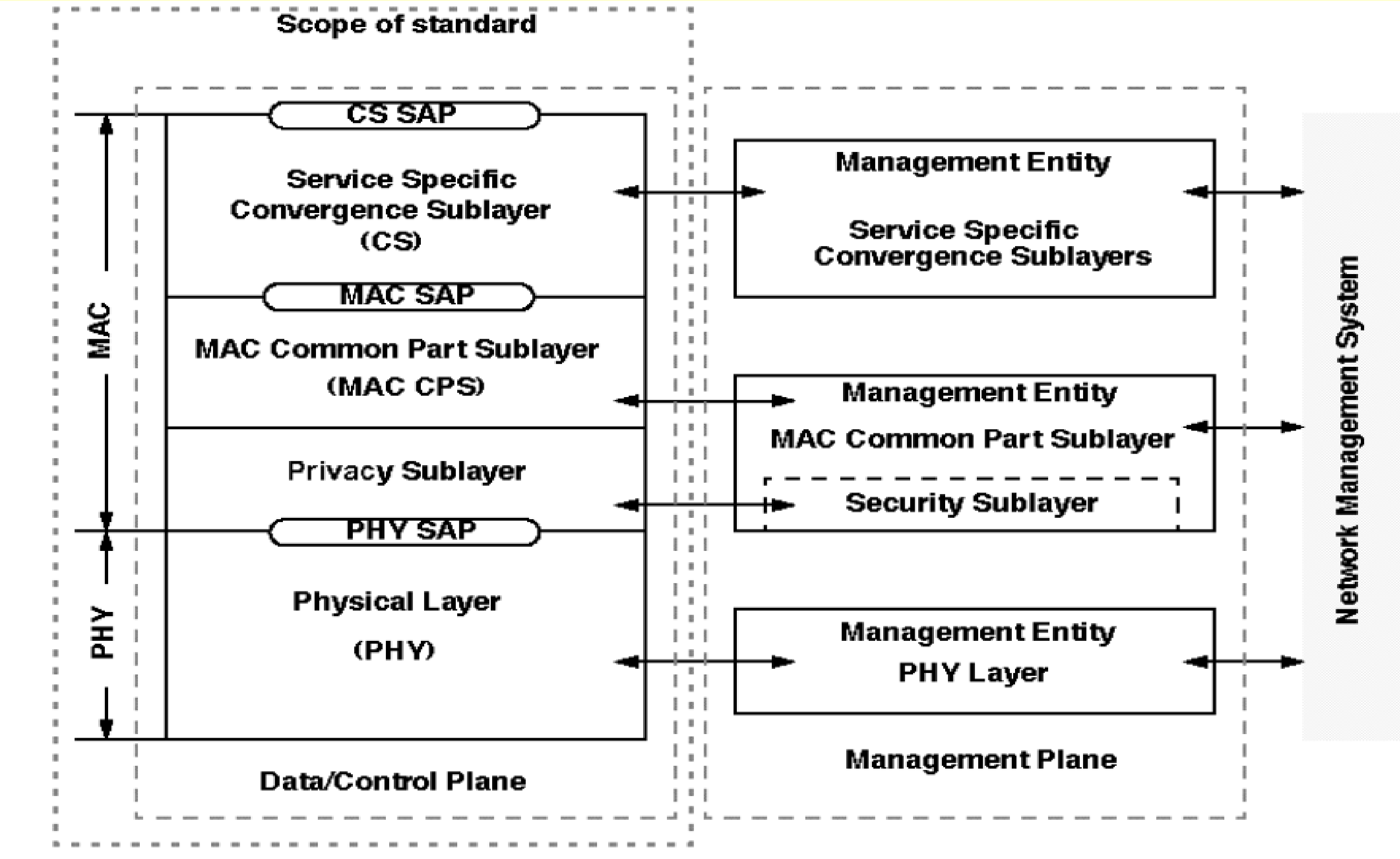
- **IEEE 802.16a** and **d (2004)** include the "mesh mode - MM" in addition to the PMP
  - Mesh mode enables *multihop communications*.
  - An SS in the MM serves as a router relaying traffic between the SSs, until it arrives at the target BS (also called the "mesh BS") that connects the mesh to backhaul link and other external networks.
  - Benefits: Higher coverage, Higher reliability, Multiple paths, Better scalability

- **Open issues/problems of the initial approach**
  - Not compatible with the original PMP mode
  - Fixed network solution
    - PHY:
      - Different frame structures-from PMP ones
      - Support only OFDM operation in both licensed and unlicensed bands
    - MAC
      - Network entry procedure is different w.r.t. PMP
      - It does not support mobility
  - Not so much deployed in the real world yet, still in development ??
  - Mesh mode – withdrawn from IEEE 802.16/2008 standard

- Alternative solution:
  - Mobile Multihop Relay (MMR) - Study Group
  - IEEE 802.16j TG – in development
  - IEEE 802.16j approved in 2009

4. Standard technologies: IEEE 802.16/WiMAX

- **IEEE 802.16 : PHY + MAC**
- **Multiple plane architecture: Data Plane(DPl), Control Plane (CPl), Management Plane (MPl)**



4. Standard technologies: IEEE 802.16/WiMAX

- **Mobile Multihop Relay 802.16j (MMR) mode**

- **IEEE 802.16j (MMR) targets**
  - Coverage extensions
  - Throughput enhancement
  - Develop new relay networking protocols
- IEEE 80216j Mobile Multihop Relay (MMR) – adopted in 2009
  - 802.16j specifies OFDMA PHY and MAC enhancement to IEEE Std. 802.16 for licensed bands to enable the operation of relay stations

- **IEEE 802.16j main characteristics**
  - Actually MMR topology is not mesh mode but tree topology
  - Multi-hop relay connections are established between SS/MS and BS
  - MMR mode
    - is backward compatible with PMP mode
    - Supports both OFDM and OFDMA operation
    - Support for fixed and mobile WiMAX terminals

- Subscriber station specifications are not changed.

4. Standard technologies: IEEE 802.16/WiMAX

- **Mobile Multihop Relay 802.16j (MMR) mode**
- **MMR Entities:**
  - **MMR** – Mobile multihop relay
  - **MMR-BS** - MMR Base Station - compliant with amendment IEEE 802.16j to IEEE 802.16e
  - **RS - Relay Station** – new definition of an entity which supports: PMP links, MMR links and aggregation of traffic from multiple RSs.
  - **RS types:**
    - fixed relay station (FRS): permanently installed at a fixed location.
    - nomadic relay station (NRS): has a fixed location for periods of time comparable to a user

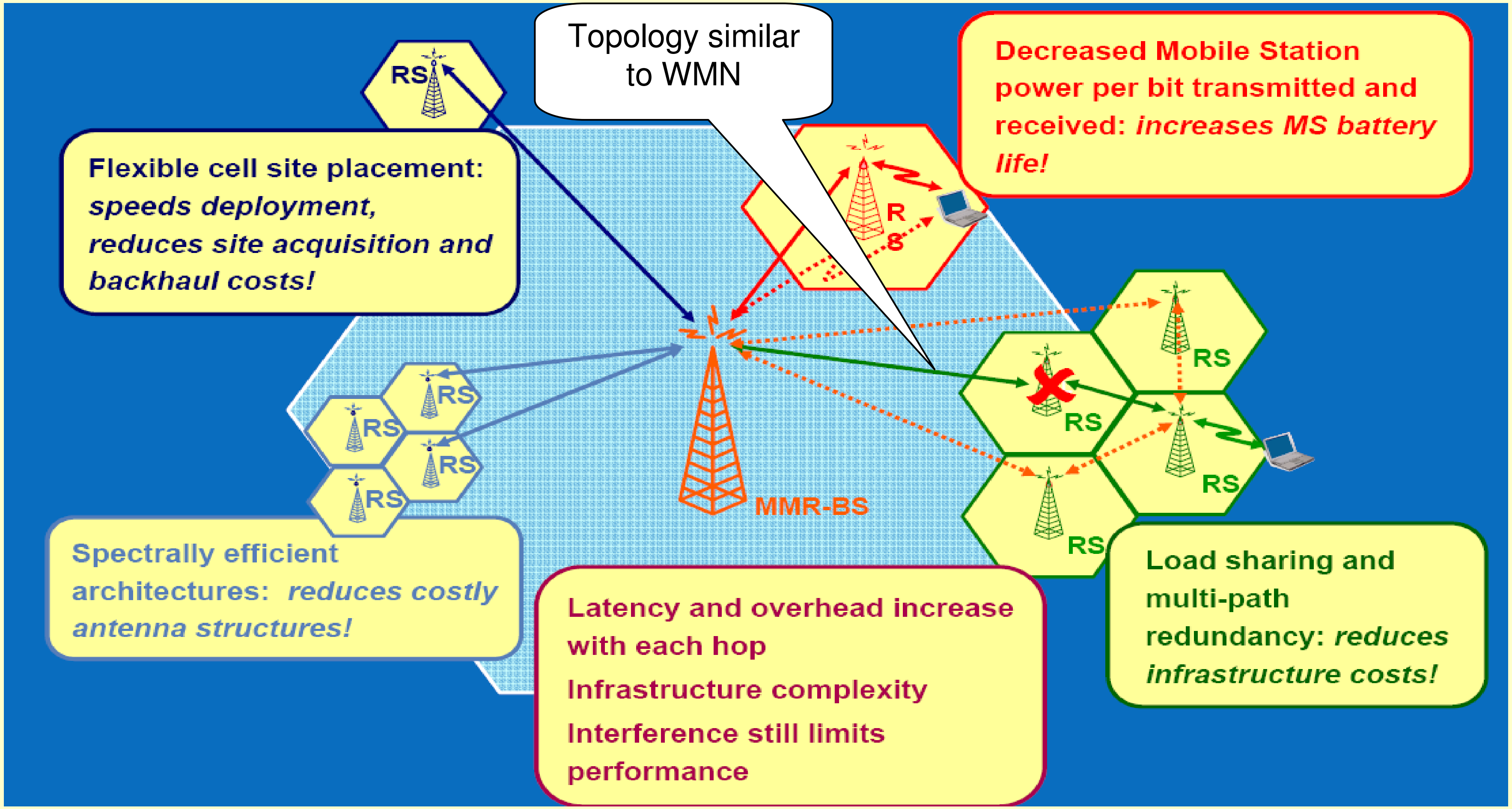
    session
    - mobile relay station (MRS): is intended to function while in motion.
  - **SS/MS** – SubscriberStation/Mobile Station

  - **Access link:** An 802.16 radio link that originates or terminates at an MS. The access link is either an UL or DL (IEEE Std. 802.16-2004 and IEEE Std. 802.16e-2005)

  - **Relay link (R-Link):** An IEEE Std. 802.16j radio link between an MR-BS and a RS or between a pair of RSs. This can be a relay uplink or downlink.

4. Standard technologies: IEEE 802.16/WiMAX

- **Mobile Multihop Relay 802.16j (MMR) mode**
  - Expected MMR Benefits and Limitations
    Improves Coverage, Capacity, QoS at Reduced Cost



Source: IEEE® 802.16 based Mobile WiMAX : A Strategic Overview, INTEL, 2007

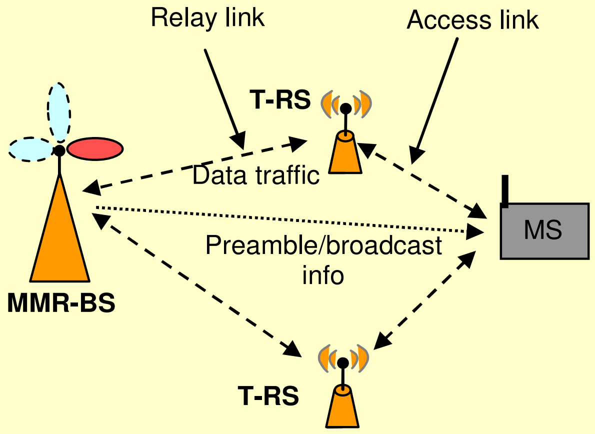
4. Standard technologies: IEEE 802.16/WiMAX

- **Mobile Multihop Relay 802.16j (MMR) mode**
- **Key design points:**
  - Changes to BS:
    - Add support for MMR links
    - Add support for aggregation of traffic from multiple RSs
  - No changes to SS/MS
  - No changes to 802.16e OFDMA PMP (access) links
  - Definition of new "802.16j Relay" link air interface
  - Support fixed, portable, and mobile RSs
  - Based on OFDMA PHY
  - MAC to support multi-hop communication (BS -> RS and RS -> RS)
  - Security and Management- revisited

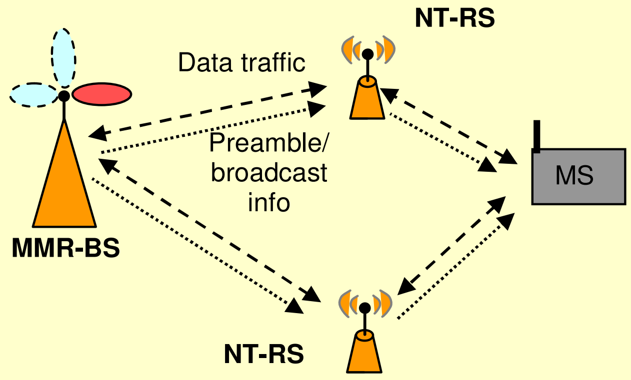
- **In-band and out-of-band RS**
  - *In-band RS:* the same carrier is used on MMR-BS links and RS links (note that half-duplex mode should be applied in RS).
  - *Out-of-band RS:*
    - MMR-BS uses one carrier for SS and RS
    - RS uses a separate carrier for its subordinate links

4. Standard technologies: IEEE 802.16/WiMAX

- **Mobile Multihop Relay 802.16j (MMR) mode**
- **RS types**
  - **Criteria for RS classification, PHY, MAC: scheduling, security**
  - **PHY processing:**
  - **T-RS – transparent mode**
    - RS does not transmit preamble and broadcast message as DL-MAP
    - MMR-BS transmits the control messages to MS
    - MS is not aware of RS; it is logically connected to MMR-BS
    - T-RS relays data traffic
  - **NT-RS – non-transparent mode**
    - NT-RS operates as BS for MS
    - NT-RS transmits preamble and other broadcast messages and also data
    - MS – physically and logically connected to NT-RS



a. Transparent mode



b. Non-transparent mode

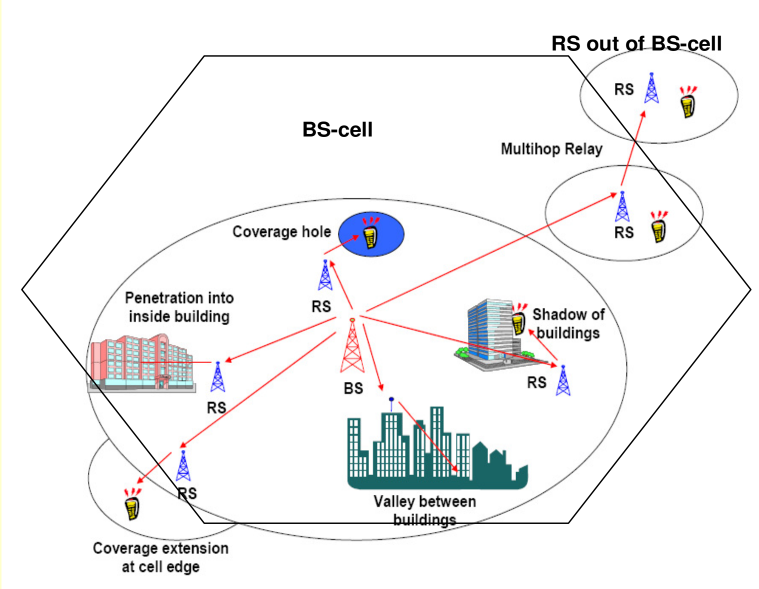
4. Standard technologies: IEEE 802.16/WiMAX

- **Mobile Multihop Relay 802.16j (MMR) mode**
- **Open MMR issues**
  - **MAC:** Enhanced Frame structure, Fast multi-hop route selection, Security, Scheduling policies
  - **PHY:** Synchronization, Interference management, Frequency reuse strategy
  - **Cross-layer issues**
    - Seamless handover
    - Backward compatible network entry procedure
    - Cross-layer optimization
  - **Topology:**
    - Choosing relay placement and carrier/channels assignment for best perf.

- **Use cases of relay mode**
  - The *Usage Models (UM)* are categorized from the perspective of the infrastructure, specifically according to where coverage is being provided
  - UMs differ in terms of the manner in which RSs are deployed, types of services or perf. goals.
  - From MS point of view, the coverage provided within the different usage models is the same.
  - A MS may encounter different UMs and may move from one UM to another.
    - For example, an MS can move from a building – to the outdoors- to a train, while being served by different RSs

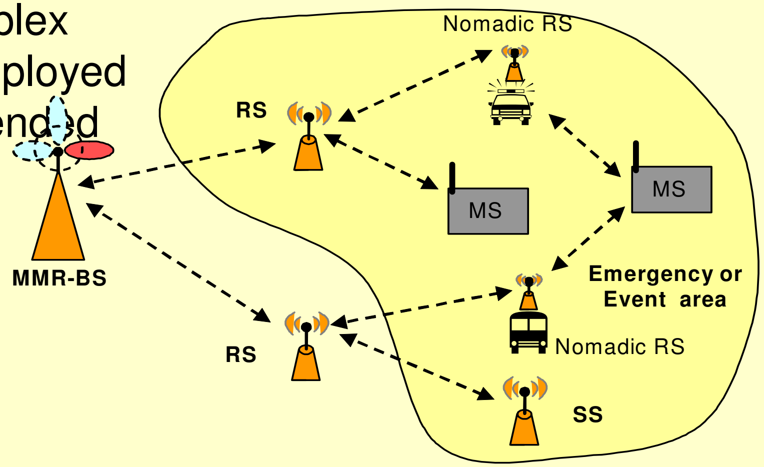
4. Standard technologies: IEEE 802.16/WiMAX

- **Mobile Multihop Relay 802.16j (MMR) mode**
- **Usage models**
- **Fixed Infrastructure Usage Model**
  - A Connectivity Service Provider (CSP) deploys RSs and MMR-BSs within their network
    - to improve coverage, capacity or per user throughput in areas which are not sufficiently covered in the MMR-BS cell
    - or to extend coverage to areas that are beyond the boundaries of the MMR-BS coverage area
  - This UM uses Fixed relay stations (FRS) owned by the CSP are utilized in this model
  - RSs can range from simple to complex
    - They can be mounted on towers, poles, tops or sides of buildings, lamp posts, etc.
    - The MMR-BS and RSs can work in LOS/NLOS mode
- Another usage: integrate small, simple RSs with stationary client devices (private and business stationary systems, hot-spots owned by utilities, municipalities, etc.) mounted on rooftops or within buildings
- In general, RSs will enter the network when they are deployed and remain in the network under the CSP management



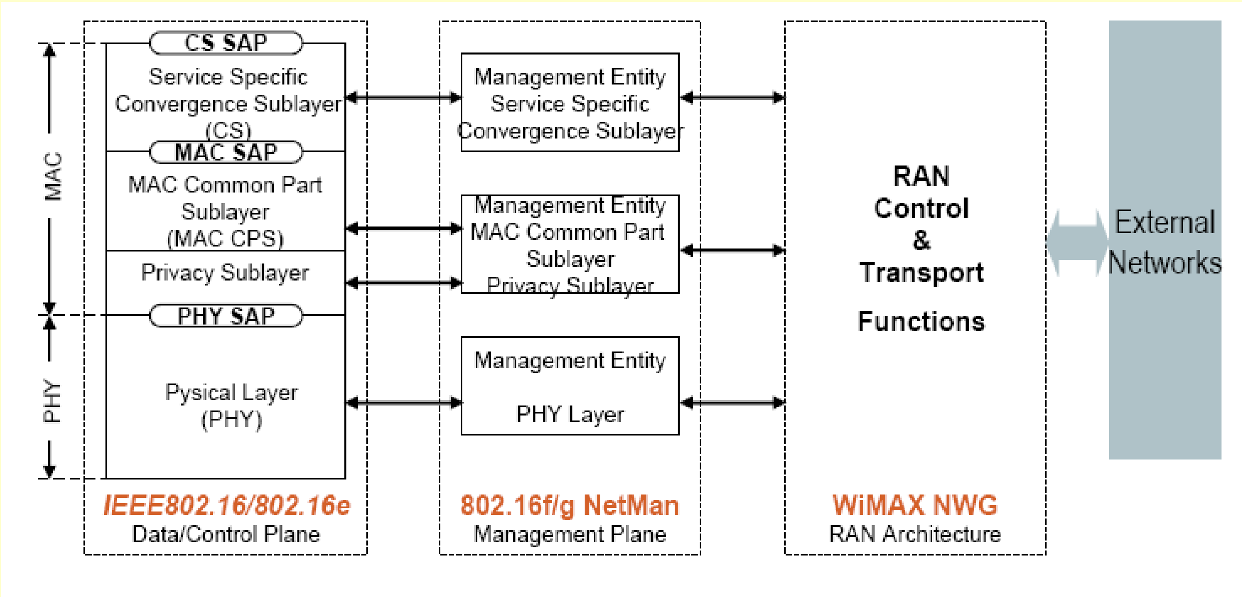
4. Standard technologies: IEEE 802.16/WiMAX

- **Mobile Multihop Relay 802.16j (MMR) mode**
- **Usage models examples**
- **In-Building Coverage Usage Model**
  - One or several low cost RSs are deployed to provide better coverage and higher throughput in a building, tunnel or underground such as on a subway platform
- **Coverage inside a vehicle (e.g train)**
  - A mobile RS mounted on the vehicle is connected to an MMR-BS/RS via a mobile link
- **Temporary Coverage Usage Model (Emergency)**
  - Nomadic RSs are deployed temporarily to provide additional coverage or capacity in an area where the MMR-BS and fixed RSs do not provide sufficient coverage or capacity
  - RSs can range from small to large and complex
  - RSs will enter the network when they are deployed
  - RSs exit when the temporary situation has ended
  - Links (MMR-BS) - RSs : LOS or NLOS
  - RSs : powered by a source, or battery
  - **Scenarios**
    - Emergency / Disaster Recovery
    - Temporary Coverage for some Events



4. Standard technologies: IEEE 802.16/WiMAX
IEEE 802.16/ WiMAX Forum NRM relationship

- IEEE802.16-2004 & 802.16e : define only DPI and CPI
  - 802.16f & g (NETMAN): MPI functions
  - IEEE P802.16 does not deal with functions usually provided by the RAN
  - WiMAX NWG objective: std. of the missing parts of a portable/mobile WiMAX access network
  - MPI: provide conformant 802.16 equipment with procedures and services to
    - enable interoperable and efficient management of network resources, mobility, and spectrum,
    - to standardize management plane behavior in 802.16 fixed and mobile devices



4. Standard technologies: IEEE 802.16/WiMAX

IEEE 802.16/ WiMAX ForumNRM relationship

- (IEEE 802.16g-05/008r2, December 2005)
  - Network Control and Management System : different functional entities
  - centrally located or distributed across the network
  - exact functionality of these entities and their services is outside the 802.16 scope (but shown here for illustration purposes)

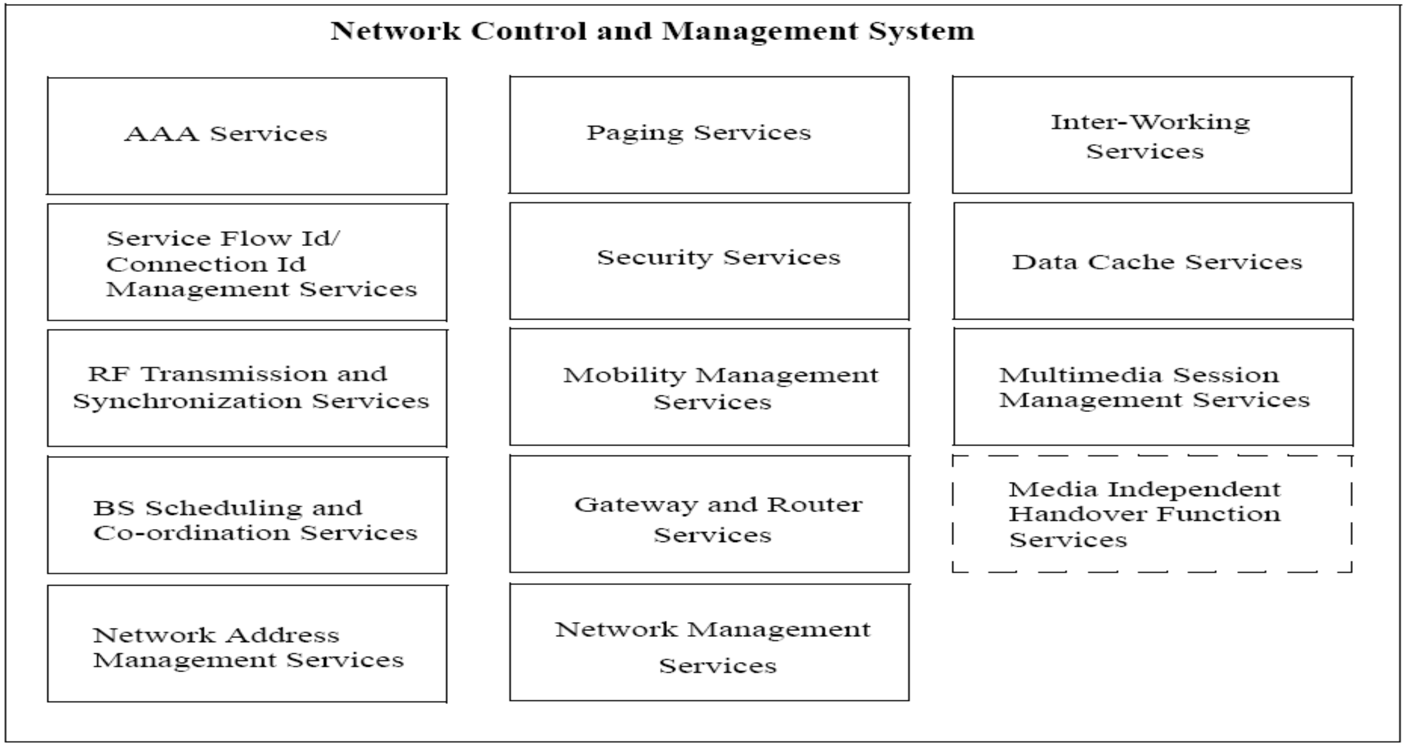
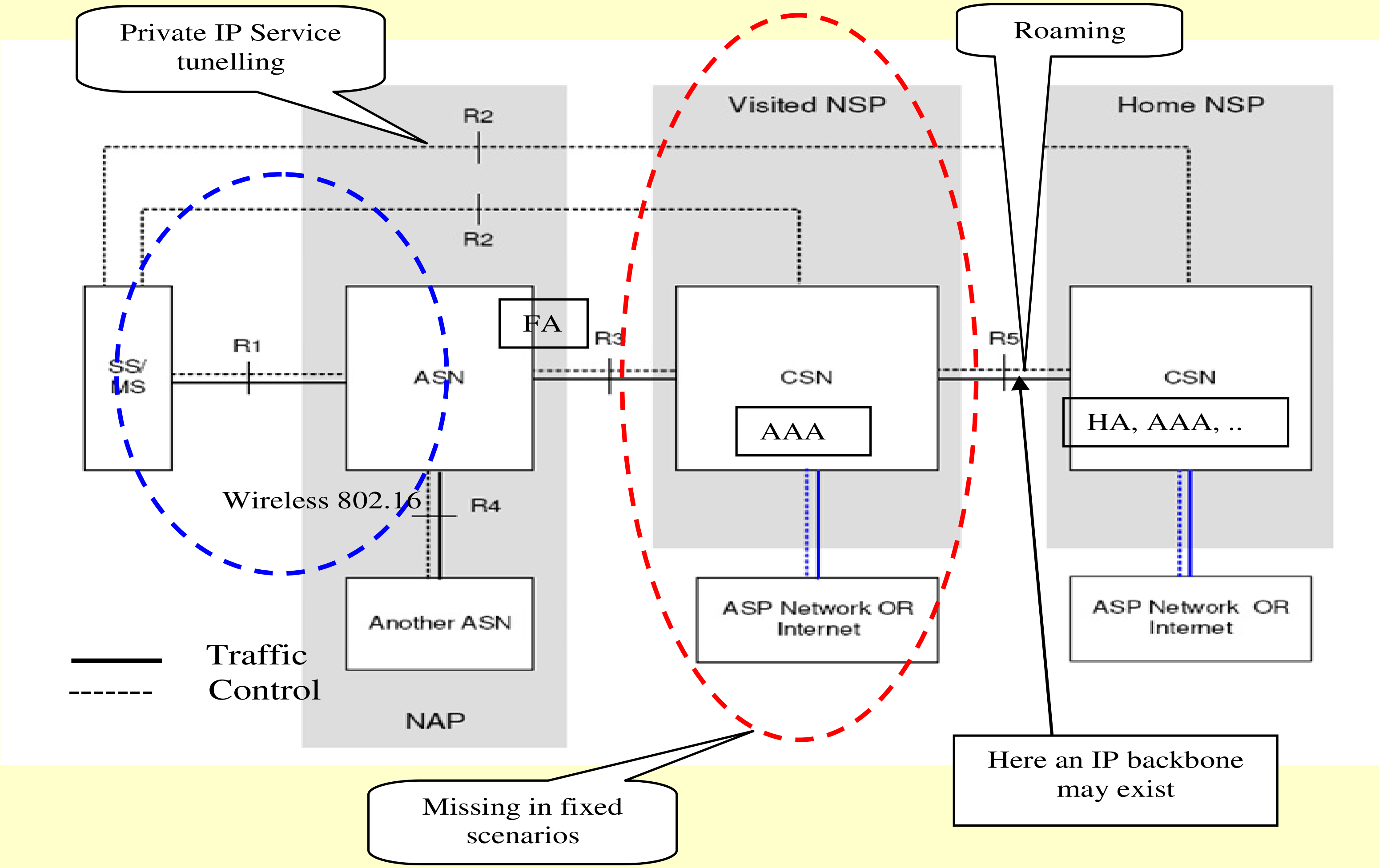


Figure 303—Illustration of the Network Control and Management System (Informational)

WiMAX Forum Reference Model



4. Standard technologies: IEEE 802.16/WiMAX

- **WMF Reference Points**
  - Defines protocols and procedures for:
- **R1 :** air I/F (PHY and MAC) (IEEE P802.16e/D12 and IEEE P802.16-2004); R1 may include protocols related to the management plane

- **R2** (logical): Authentication, Services Authorization and IP Host Configuration management running between the MS and the CSN (operated by H-NSP or V-NSP)
- **R3**
  - *Control plane (CPl)* protocols between the ASN - CSN to support AAA, policy enforcement and mobility management capabilities
  - *Bearer (data) plane (DPl)* methods (e.g., tunneling) to transfer user data between the ASN and the CSN
- **R4**
  - ASN-ASN, or beteween ASN-GWs)
  - set of CPI and DPI plane protocols originating/ terminating in ASN functional entities to coordinate MS mobility between ASNs and ASN-GWs.
  - R4 is the only RP between similar or hetero - ASNs
- **R5 :** R5 - set of control plane and bearer plane protocols CSN – CSN, operated respectively by the H-NSP and V-NSP

CONTENTS

5. Specific PHY issues in WMNs

- *Note: some problems/solutions will involve both PHY and MAC layers*
- **General aspects: rates**
  - High data rates are necessary for WMNs
  - Sophisticated modulations: DSS, OFDM, OFDMA, SOFDMA, etc. work well in 802.11, 802.16, …
  - PHY rates increased to 100 Mb/s (IEEE 802.11n) and will reach soon 1 Gb/s.
  - 802.16m/WiMAX promises: Advanced Air Interface with data rates of 100 Mbit/s mobile & 1 Gbit/s fixed
  - Higher transmission rate with ultra-wide band (UWB) techniques. for short distance (WPANs). If a transmission speed as high as that of UWB is desired in a wider area network such as WLANs or WMANs, new PHY is needed.

5. Specific PHY issues in WMNs

General aspects: rates

- Intelligence of the PHY layer is higher, allowing different modes of working
  - Better error performance can be obtained by using link adaptation
  - But note that in a frequency selective fading environment, a link adaptation algorithm cannot take directly the values of (SNR) or carrier-to-interference ratio (CIR) as a input from the PHY , because SNR or CIR alone does not adequately describe the channel quality

- In real-world the actual rates can be much much lower than theoretical ones
  - SNR decreases with distance, producing more errors at receiver, depending on signal constellation
  - intra flow and interflow interference (increasing with no. of nodes in WMN)
  - external interference

5. Specific PHY issues in WMNs

- **General aspects: interference**
- **Example Interference in 802.11**
  - ***Intra-flow I:*** the radios of two or more links of a single path or flow operate on the same channel
    - it can be reduced by increasing channel diversity. Interference range of a node is typically bigger than a single hop
  - ***Inter-Flow I:*** caused by other flows that are operating on the same channels and are competing for the medium

- ***External I:*** a link experiences interference outside of the control of any node in the network:
- *Controlled Interference*: other nodes external to the network use networking technologies that overlap with those used by the network,
- Uncontrolled I: caused by any other source of radio signals emitted in the same frequency range, but not having the same MAC protocol

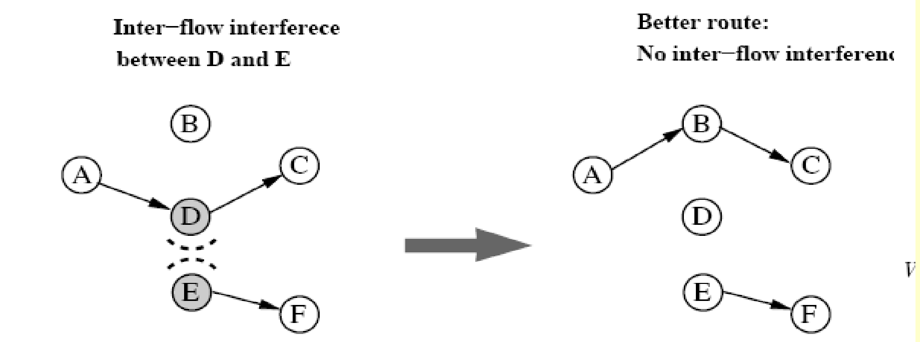
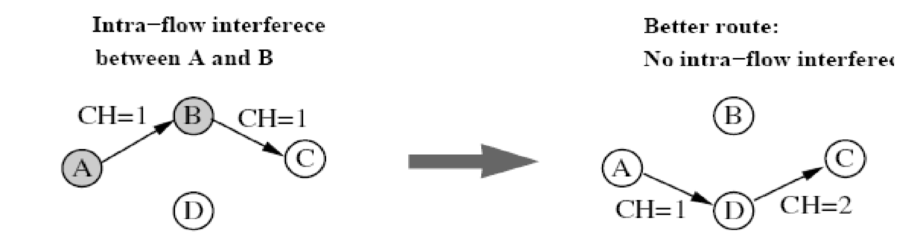


Fig. 1. An example for inter-flow interference.

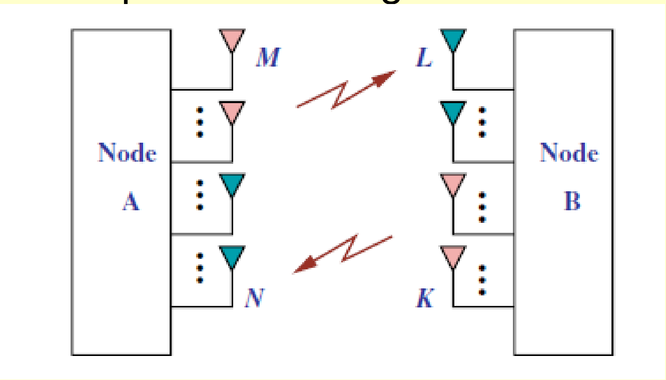


5. Specific PHY issues in WMNs

- **General aspects**
  - Omni-directional antennas assure uniform coverage but severely reduces the achievable throughput because of interference.
  - Solutions:
    - **Multiple radios** that can be operated on non-interfering channels
      - channel assignment problem arises
    - **Directional antennas** - add advantages
      - better spatial frequency reuse (possible due to directionality)
      - reduces inter-flow interference
      - But create new problems
        hidden and exposed stations
        difficult to use in mobile context (need tracking)
  - Recent developments in *multiple input multiple output (MIMO)* antenna technologies and *smart antennas* can help in decoding wireless signals with low SNR, thereby increasing the achievable bandwidth
  - Multiple radios can be used to significantly improve the throughput gains
    - note that improper placement may render them ineffective.
    - E.g. two antennae with a gain of 5 dBi used in one access point (AP), are disturbing each other unless one has a distance of 3ft separation
    - antennas placement relative to ground is important

5. Specific PHY issues in WMNs

- **General aspects**
- MIMO
  - Multiple-antenna system:
    - further increase capacity and mitigate the impairment by fading, delay-spread, and co-channel interference,
  - Different values of M, N, K, L result in various multiple-antenna systems
  - If K = 1, M = 1 (one Tx antenna) and either L > 1 or N > 1 techniques such as antenna diversity and adaptive/smart antennas can be used for a multi-antenna system.
  - They have been proposed for PMP one-hop cellular networks.
  - Antenna diversity is based on the fact that signals received from uncorrelated antennas have independent fading.



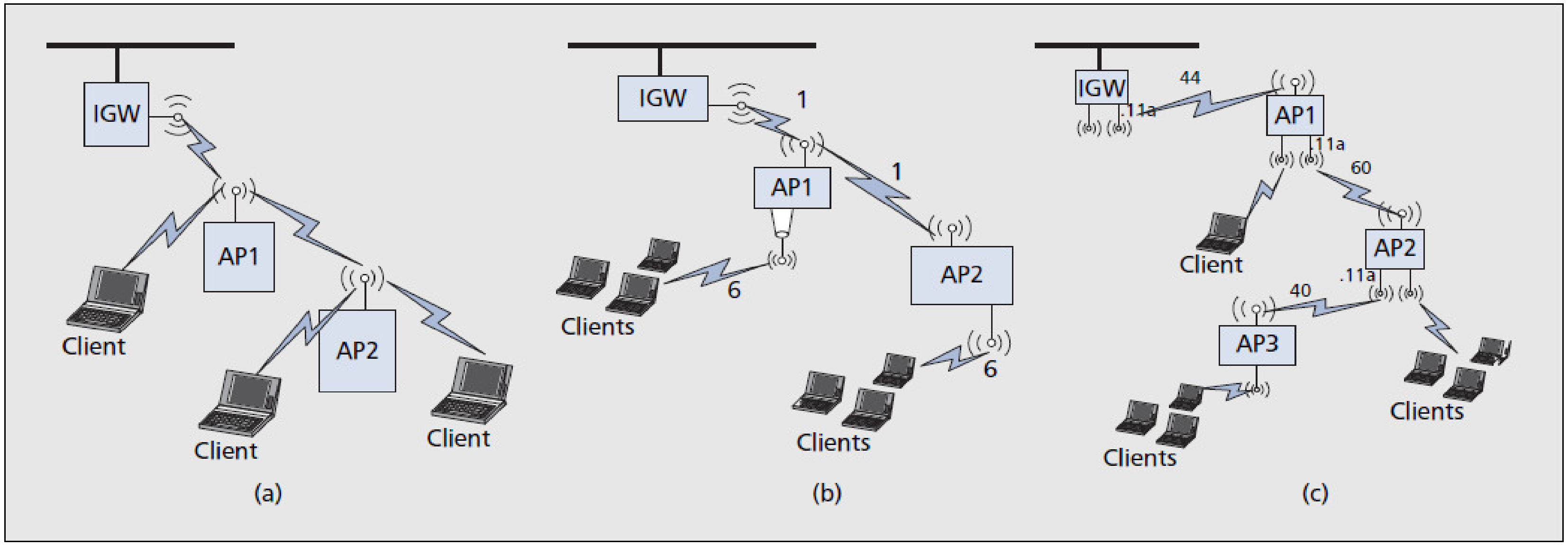
- Antenna diversity and smart antenna are also applicable to WMNs and other ad hoc networks but their performance needs more evaluation

5. Specific PHY issues in WMNs

- **General aspects**
- **MIMO**
- Multiple-antenna system (cont'd):
  - If N = 1, L = 1 (single Rx antenna) and either K > 1 or M > 1, antenna diversity or smart antenna cannot be applied unless the channel state information (CSI) is available.
  - Usually partial information of channel state is available at the transmitter.
  - The diversity is obtained by using the space–time coding (STC) technique: signals transmitted at different antennas in different symbol periods are processed with a certain coding technique.
  - The received signals are then combined at the receiver through an appropriate algorithm such as maximum likelihood detection (MLD).
  - STC is a promising technique that achieves second order diversity without bandwidth expansion.
  - If M > 1, L > 1 or K > 1, N > 1, the multiple-antenna system is an MIMO system, whith both diversity and simultaneous transmissions.
    - MIMO can potentially increase the system capacity by three times or even more
    - MIMO is being adopted into IEEE 802.11n and IEEE 82.16m
    - MIMO systems taxonomy: receiver processing only, transmitter processing only, and both transmitter and receiver processing MIMO systems
    - The processing techniques can be based on maximum likelihood detection (MLD), vertical Bell Lab Layered Space–Time (V-BLAST), singular value decomposition (SVD) [13], and space–time coding.

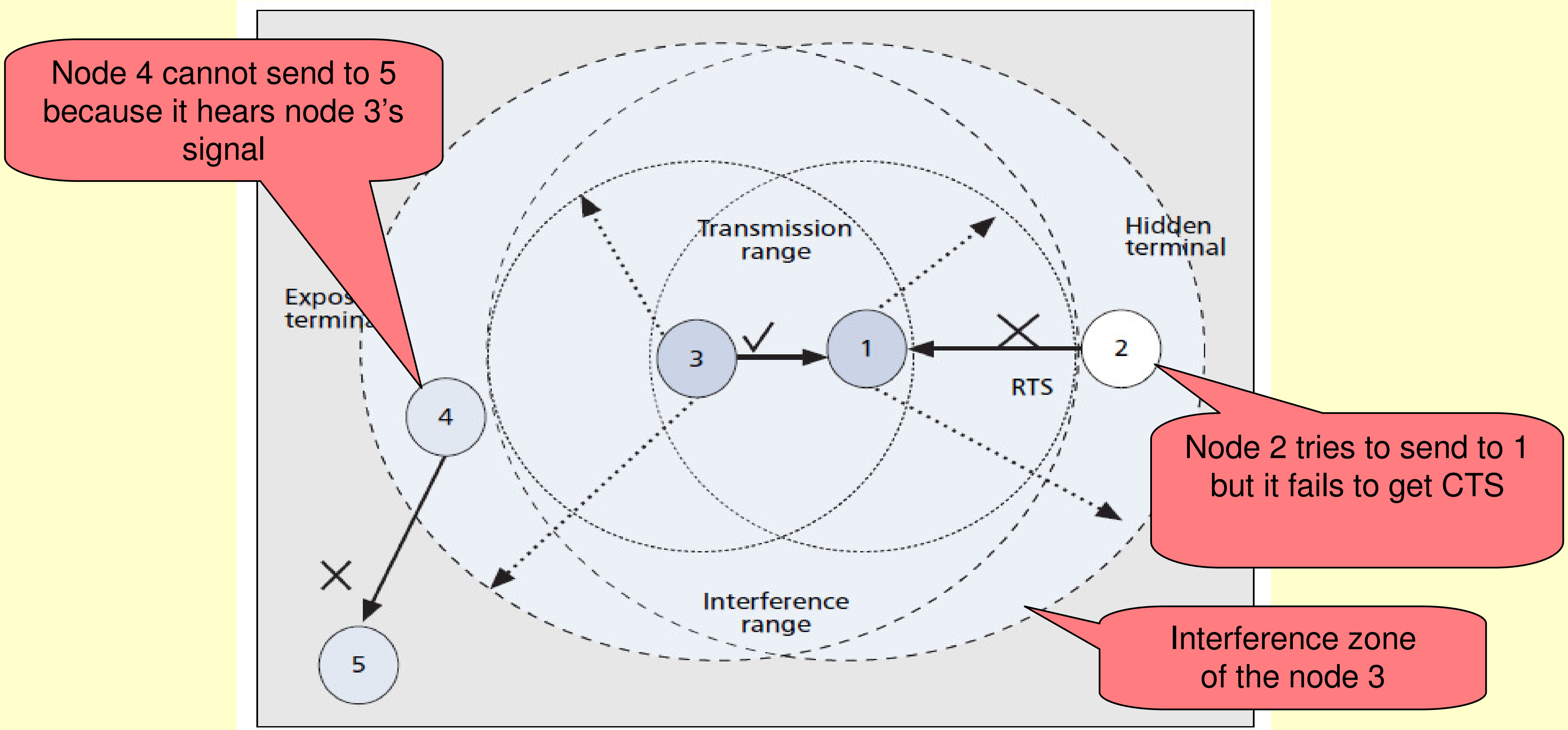
5. Specific PHY issues in WMNs

- **General aspects**
- **Single or Multiple Radios and Channel Taxonomy**
  - criterion : no. of radios/node and the number of channels per node.
  - Cases: Single Radio Single Channel ; Single Radio Multi Channels; Dual radio Single channel per radio; Multi Radio Multi Channels
- Figure: a) Single-radio single-channel WMN; b) dual-radio single-channel WMN; c) multiradio multichannel WMN
  - But need an appropriate MAC(s) !!
- Source: N.NANDIRAJU, et.al, WIRELESS MESH NETWORKS: CURRENT CHALLENGES AND FUTURE DIRECTIONS OF WEB-IN-THE-SKY IEEE Wireless Communications • August 2007



5. Specific PHY issues in WMNs

- **Omni-directional antenna: The hidden and exposed terminal problems in 802.11**
- Single radio single channel example
- Figure: Source:N.NANDIRAJU, et.al, WIRELESS MESH NETWORKS: CURRENT CHALLENGES AND FUTURE DIRECTIONS OF WEB-IN-THE-SKY IEEE Wireless Communications • August 2007



5. Specific PHY issues in WMNs

- **Smart and Directional Antennas issues**
- TYPES OF SMART ANTENNAS, [ ]

- **ADAPTIVE ARRAY ANTENNA:**
  - **Adaptively steers beams and possibly nulls, to maximise performance across immediate links or potentially the local network**
  - **Relatively expensive, especially as full phased arrays**
  - **Difficult to quantify results as environment dependent and no control over the adaptive process (except changing the algorithms)**

- **MIMO ANTENNA ARRAYS:**
  - **As adaptive arrays, but with spatially distributed antennas, (usually simple omni-directional antennas), capable as a configuration of simultaneous Tx/Rx operation**
  - **Usually they exploit multipath to improve performance but can also steer nulls**
  - **Cheaper than adaptive arrays as they usually use low cost omni-directional antennas**
  - **Difficult to quantify results as they are highly environment dependent**

- **MULTI-BEAM ANTENNAS:**
  - **Either selectable single beam, simultaneous multiple beams or subset of both**
  - ***Less expensive* that adaptive arrays and rely on low sidelobes to suppress intererence**
  - **Easier to quantify link performance as antennas do not exploit multipath**
  - **They can be wideband and work up to millimetre wave frequencies**

5. Specific PHY issues in WMNs

- **Smart and Directional Antennas issues**
- **Advantages**
- Lower power needed for transmissions
  - Battery not a big concern in many applications
  - Enables better spatial reuse and, hence, increased network capacity
- Better SNR
  - Better data rates
  - Better delays (less hops on a path)
  - Better error rates (at a given Tx power, due to spatial concentration)

- **Directional Antennas – new problems/challenges**
  - Specialized hardware needed
  - Specialized MAC (difficult to design)
    - Hidden and exposed stations- new problems
  - Difficult to track mobile data users

5. Specific PHY issues in WMNs

- **Open research issues on PHY layer**
- Further improve the transmission rate and the PHY performance
  - New wideband transmission schemes other than OFDM or UWB are needed in order to achieve higher transmission rate in a larger area network
  - Multiple-antenna systems – still too complex and expensive- not widely accepted in WMNs
  - Low-cost directional antenna implementation is attractive
  - Frequency agile techniques are still in the early phase.
- Better use of the advanced PHY features by the higher layer protocols (MAC, routing)
  - For directional and smart antennas many MAC protocols have been proposed for ad hoc networks
  - For multi-antenna systems, an efficient MAC protocol to achieve significant throughput improvement is still needed.
  - Communication protocols for cognitive radios - open issue
    - Efforts are needed to make cognitive-radio based WMNs become more practical

CONTENTS

6. Medium Access Control

- **General MAC issues**
- **WMN – MAC**
- **MAC WMNs differences compared to classical wireless networks**
  - MAC for WMNs – multi hop communication.
  - Classical MAC –one hop: design is easier, since MAC and routing are transparent to each other
  - This does not work well in WMNs, because data Tx/Rx at a node is influemced by two or more hops away. (example - hidden node issue in a WMN)
  - MAC is distributed and cooperative and works for MP2MP mode
  - In WMNs, no centralized controller is available.
  - MAC must ensure all nodes to cooperate in transmission
  - Any mesh network node is able to communicate all its neighboring mesh nodes

  - Network self-organization is needed for the MAC.
    - MAC should know the net topology to allow cooperation between neighboring nodes and nodes in multi-hop distances.
    - This can improve the MAC performance in WMNs.
    - network self-organization based on power control may optimize network topology, minimize the interference between neighboring nodes, and thus, improve the network capacity.

6. Medium Access Control

- **General MAC issues**
- **WMN – MAC**
- **MAC WMNs differences versus classical wireless networks (cont'd)**
  - Mobility affects the performance of MAC.
    - Network configuration is dynamic and affects the performance of the MAC
    - In order to be adaptive to mobility or even to utilize the mobility the network nodes need to exchange network topology information.
- The above differences must be considered in order to design a scalable MAC for WMNs.
  - Approaches:
  - 1. Enhance existing MAC protocols or propose new MAC protocols to increase E2E throughput when only single channel is available in a network node
  - 2. to allow transmission on multiple channels in each network node
- Conclusion: single-channel and multi-channel MAC protocols are needed to be studied separately.
- IEEE 802.11 is a widely accepted in WMN : most of the issues studied are for it, i.e., for CSMA/CA with RTS/CTS.

- **Single-channel MAC**
- Three approaches :
  - *Akyildiz, I.F., Wang, X. and Wang, W., Wireless Mesh Networks: A Survey, Computer Networks Journal (Elsevier), March 2005*
  - 1. Improving existing MAC
    - Currently several MAC protocols have been proposedfor multi-hop ad hoc networks by enhancing the CSMA/CA protocol
    - These schemes usually adjust parameters of CSMA/CA such as contention window size and modify backoff procedures.
    - They may improve throughput for one-hop communications
  - For multihop WMNs, still one have a low E2E throughput, because they cannot significantly reduce the probability of contentions among neighboring nodes.
  - Any method to modify backoff and contention resolution, cannot solve the throughput problem due to the accumulating effect on the multihop path.

6. Medium Access Control: IEEE 802.11

- **Single-channel MAC**
- **Three approaches (cont'd) :**
- **2 Cross-layer design with advanced PHY techniques**
  - Two major schemes proposed
  - MAC based on directional antenna (MAC-DAn)
  - MAC with power control

- 1.MAC-DAn
  - It eliminates exposed nodes if antenna beam is assumed to be perfect.
  - But more hidden nodes are produced in this case.
  - New solutions must be developed to reduce the number of hidden nodes. Moreover,
  - MAC-DAn additional problems: cost, complexity, and practicality of fast steerable directional antennas.
- 2.The purpose is of reducing power consumptions
  - These schemes reduce exposed nodes problem, especially in a dense network, improve the spectrum spatial-reuse factor in WMNs
  - However, hidden nodes still exist and this may be worse because lower transmission power level

6. Medium Access Control: IEEE 802.11

- **Single-channel MAC**
- **Three approaches (cont'd) :**
- **3. New MAC protocols.**
  - Current CSMA/CA are not a scalable and efficient solution in WMN multi-hop
  - Revisiting the MAC protocols based on TDMA or CDMA- open issue
  - To date, few TDMA or CDMA MAC protocols have been proposed for WMNs
  - Reasons:
    - One is the complexity and cost for developing a distributed and cooperative MAC with TDMA or CDMA
    - Compatibility of TDMA (or CDMA) MAC with existing MAC protocols.
  - E.g. IEEE 802.16, the original MAC protocol is a centralized TDMA scheme.
  - A distributed TDMA MAC for IEEE 802.16 mesh is still being researched.
  - In WMNs based on IEEE 802.11, how to design a distributed TDMA MAC overlaying CSMA/CA – open and challenging issue
  - For distributed TDMA or CDMA MAC protocols, network self-organization based on topology control and/or power control must also be considered.

- **Multi-channel MAC**
- Variants:
- **Multi-channel single-transceiver MAC**
  - from point of view cost and compatibility one transceiver on a radio is a preferred hardware platform
  - Since only one transceiver is available, only one channel is active at a time in each network node
  - However, different nodes may operate on different channels simultaneously To coordinate transmissions between network nodes multi-channel MAC are necessary
  - Example: seed-slotted channel hopping (SSCH) scheme
  - SSCH is actually a virtual MAC on top of IEEE 802.11 MAC and does not need changes in the IEEE 802.11 MAC.

6. Medium Access Control: IEEE 802.11

- **Multi-channel MAC**
- Variants:
- **Multi-channel multi-transceiver MAC.**
  - The radio includes multiple parallel RF front-end chips and baseband processing modules to support several *simultaneous* channels.
  - On top of the PHY, there is only one MAC layer to coordinate the functions of multiple channels.
  - Example: Engim multi-channel wireless LAN switching engine
  - the design an efficient MAC for this type of PHY platform - is still an open research topic
- **Multi-radio MAC**
  - A network node has multiple radios each with its own MAC and PHY.
  - Communications in these radios are totally independent.
  - A virtual MAC protocol such as the multi-radio unification protocol (MUP) is required on top of MAC to coordinate communications in all channels.
  - In fact one radio can have multiple channels.
    - *However, for simplicity of design and application, a single channel is used in each radio.*
- Examples of multichannel MAC protocols
  - Multi-channel MAC (MMAC)
  - Multi-radio unification protocol (MUP

- **Multi-channel MAC (MMAC)**
- MMAC has three main functions:
  - Maintaining data structure of all channels in each node. Channels of a node are classified into three types depending on its status of allocation
  - Negotiating channels during ad hoc traffic indication message (ATIM) window. Negotiations are done through a pre-defined channel known to all nodes
  - Selecting a channel. The criterion is to use a channel with the lowest count of source–destination pairs that have selected the channel.

- **MMAC problems and open issues**
  - It is assumed that RTS/CTS is active in DCFbut Actually, this is an option for DCF
  - Global synchronization in the network is difficult to achieve in an ad hoc network with alarge number of hops and nodes
  - The channel switching time may be much larger than 0.22 ms [ ]. A larger channel switching time will significantly degrade the performance of a multi-channel MAC protocol
  - Channel selection criterion based on the lowest number of source–destination pairs for eachchannel is not always appropriate. Using pending packets as a metric to select a channel may achieve better performance
  - The MMAC eliminates multi-channel hidden nodes, but it also generates many exposed nodes because of using RTS/CTS and ATIM/ATIMACK (for default channel) procedures

6. Medium Access Control: IEEE 802.11

- **Multi-radio Unification Protocol (MUP)**

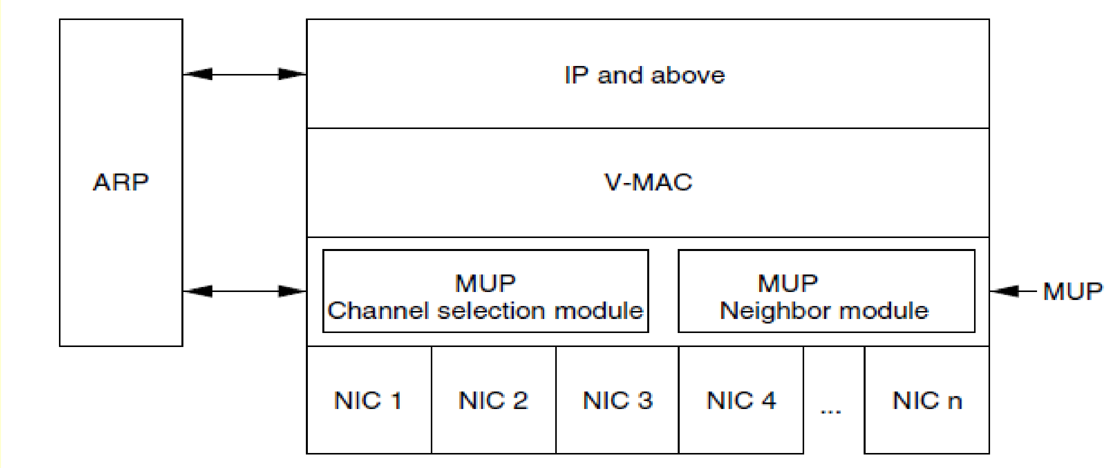
- Multiple wireless network interface cards (NICs) on each node
- Channels on all NICs are orthogonal and fixed
- The major functions of MUP include:
  - Discovering neighbors and their classification into MUP enabled and legacy nodes.
  - Selecting a NIC based on one-hop (RTT) measurements. MUP selects the NIC based on shortest RTT
  - Utilizing the selected NIC for a long period. This period is determined by a random process and in the order of 10–20 s.
  - Switching channels. After the random time period, all NICs are measured again through one-hop probe messages. If an NIC has a certain amount of quality improvement than the existing NIC, then it is selected for sending packets

- **MUP open issues**
  - Hidden node issue is not effectively solved. The channel quality measurement is based on one hop RTT. However, measurements based on shortest RTT do not guarantee that there exists no hidden nodes.
  - NIC switching mechanism is not justified. MUP allocates a random time period for each selected NIC. Performance of this scheme cannot be guaranteed, because the time of having the best quality in a NIC is not randomized but related to the wireless channel characteristics and interference from nodes using the same channel.
  - Packet re-ordering is needed after NIC switching. MUP relies on TCP to handle this issue. However, this will cause low E2E throughput in a WMNs.
  - Fixed channel assignment on each NIC also limits the flexibility of MUP.

Multi-radio Unification Protocol (MUP)- details

- *A. Adya,et.al.,"A Multi-radio Unification Protocol for IEEE 802.11 Wireless Networks," Proceedings of IEEE Broadnets 2004, October 2004*
- MUP : L2 solution to provide a virtual layer that controls multiple radio interfaces in order to optimize local spectrum usage in MR-WMNs
- MUP design goals for efficient spectrum management
  - to minimize hardware modifications,
  - to avoid making changes to the higher layer protocols; L3, .. need no changes to efficiently use multiple radio interfaces; MUP offers a single virtual interface to the L3, .. concealing the multiple PHY I/Fs and channel selection mechanisms
  - to operate with legacy (non-MUP) nodes
  - independency on the global topology information.

Source: Yan Zhang et. al., Wireless Mesh Networking: Architectures, Protocols and Standards, Auerbach Publications, 2007



6. Medium Access Control: IEEE 802.11

- **Multi-radio unification protocol (MUP)** (cont'd)
- MUP layer has complex tasks:
  - Monitoring the channel quality between a node and its neighbors such that the node can choose the best possible interface
  - In order to virtualize multiple radio interfaces having a different MAC address, MUP uses a virtual MAC address that conceals the multiple PHY address
  - At network start-up, every node tunes its radio interfaces to orthogonal channels and this channel setting on an interface is permanent.
  - Tasks of channel selection or switching of radio interfaces.
    - Requirement to have every node in the network to use the same set of orthogonal channels for its interfaces
    - This, however, leads to a limitation on the no. of radio I/Fs that can be attached to any node in the network, due to limited by the number of orthogonal channels in the system (e.g. channels 1, 6, and 11 out of a total of 11 channels in North America)

6. Medium Access Control: IEEE 802.11

- **Multi-radio unification protocol (MUP)** (cont'd)

- Two schemes for the selection of radio interfaces (or channel as each interface is statically assigned a channel) : MUP-Random, MUP-Channel-Quality

- **MUP-Random** (basic one scheme)
  - A node randomly chooses an interface for transmitting a packet with a destination node.

  - Advantages : simple, implement, it does not require channel state information, it provides a system wide uniform distribution of traffic across the available interfaces

  - Disadvantages: a channel which is already congested may be chosen over other idle channels and thus may lead to a degraded link level throughput and performance

- **MUP-Channel- Quality** (complex scheme)
  - Maintain the channel state information (channel quality metric) between nodes and choose the best possible channel based on the channel state information.

  - The channel quality metric is derived from the neighbor table that is maintained by the MUP

  - Over each interface, probe messages are sent to the neighbors periodically and the round-trip delay on link is estimated.

  - The use of probe messages enables the MUP layer to obtain the channel state information independently

6. Medium Access Control: IEEE 802.11

- **Multi-radio unification protocol (MUP) (cont'd)**

- **MUP advantages**
  - it can work with legacy nodes that have either a single interface or multiple interface without MUP
  - it removes the higher layers in the protocol stack from knowing the complexities in handling multiple radio interfaces,
  - it improves the spectrum efficiency and system throughput.
- **Disadvantages**
  - Channel assignment is coarse and hence MUP may not make the best use of the available orthogonal channels
  - the requirement of prioritized queuing for the probe packets makes MUP unusable with WMNs based on popular MAC protocols such as IEEE 802.11b, IEEE 802.11a, and IEEE 802.11g
  - MUP makes a local decision on choosing a channel and that may sometimes be suboptimal as far as global resource usage is concerned

- Additional issue : allocation of orthogonal channels for the nodes in the network
  - Since the network has multiple orthogonal channels
  - So, a new starting-up node should find out which channels are to be assigned for its interfaces

- **Channel Assignment Taxonomy**
  - The routing and channel assignment (ChA) in WMNs are strongly related especially in the case of multi-radio multi-channels case.
  - Circular dependence
    - usually the channel assignment is done at MAC layer and depends on the expected load on each virtual link
    - the load depends on routing
    - routing depends on capacity of virtual links
    - which is determined by the ChA (because the capacity of a virtual link depends on the number of other links that are in the interference range and are using the same channel.
  - The circular dependence -> need of *cross layer optimization strategies*.
- Channel Assignment Taxonomy:
  - *Fixed ChA, Hybrid ChA, and Dynamic ChA*.
    - depending on how frequently the CA scheme is modified
    - In fixed ChA the allocation is almost constant while in dynamic ChA the allocation scheme is continuously updated.

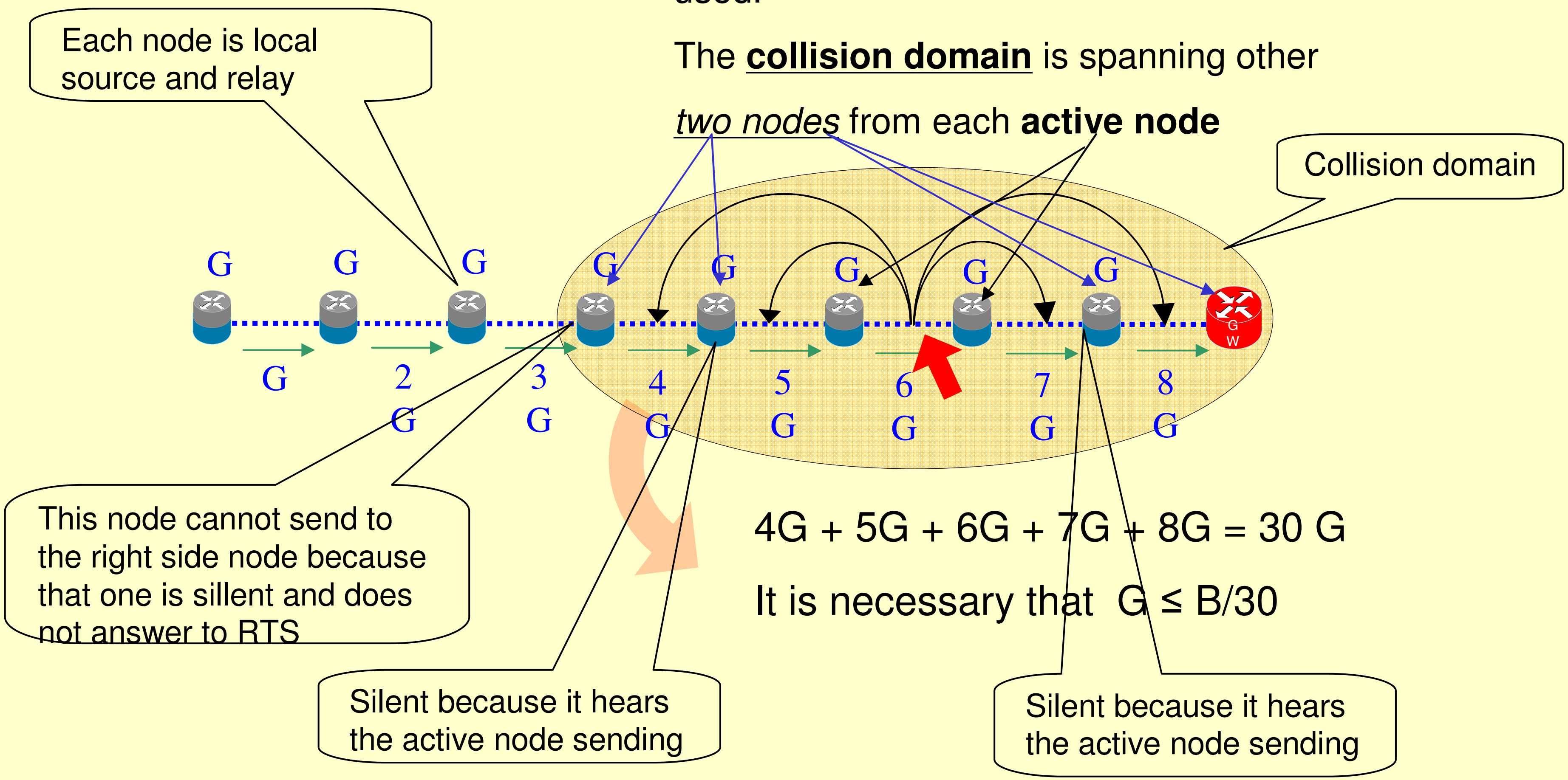
6. Medium Access Control: IEEE 802.11

- MAC specific issues: Collision domains problem- chain topology- example

The collision appears if only one channel is used.

The **collision domain** is spanning other

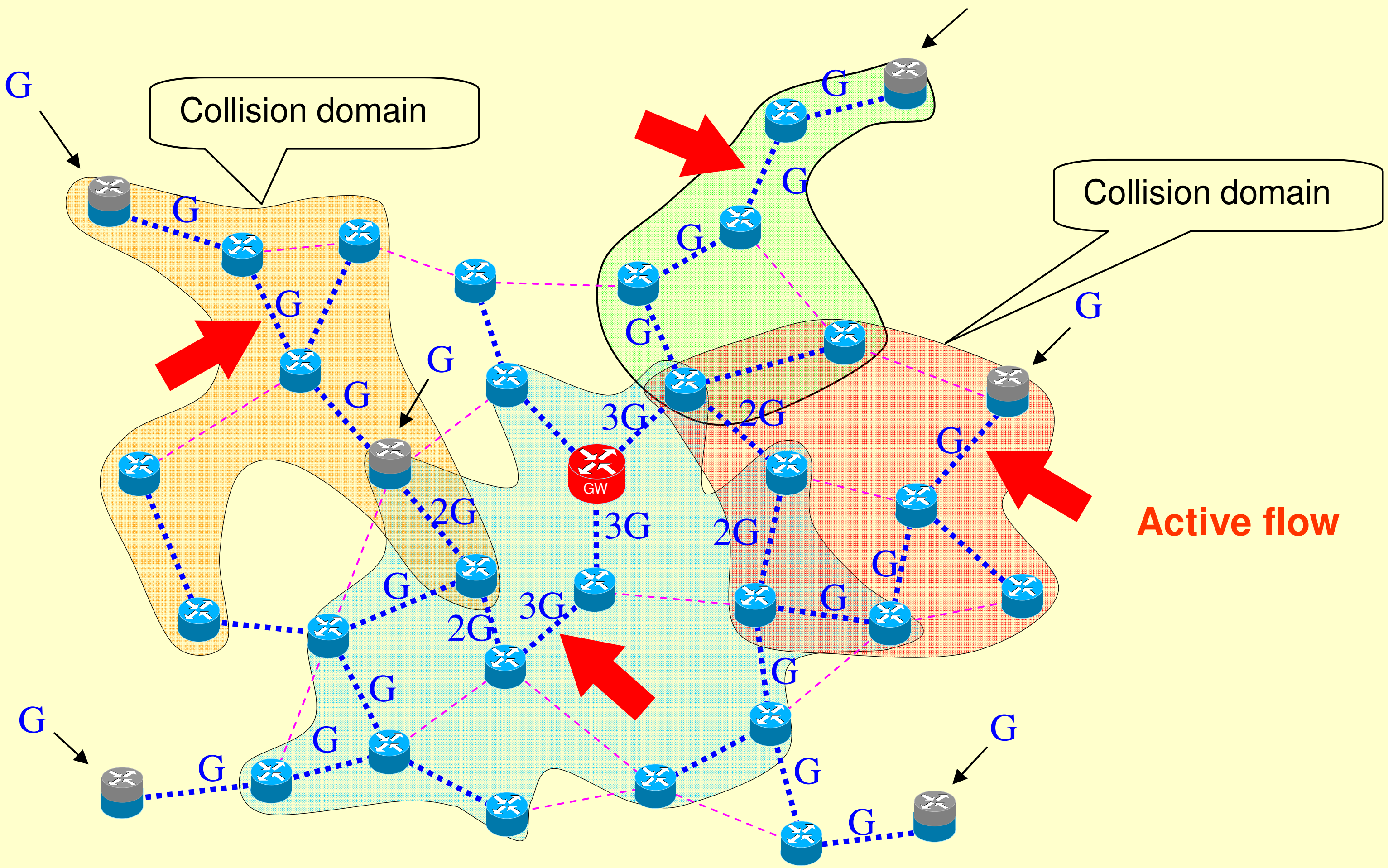
two nodes from each **active node**



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

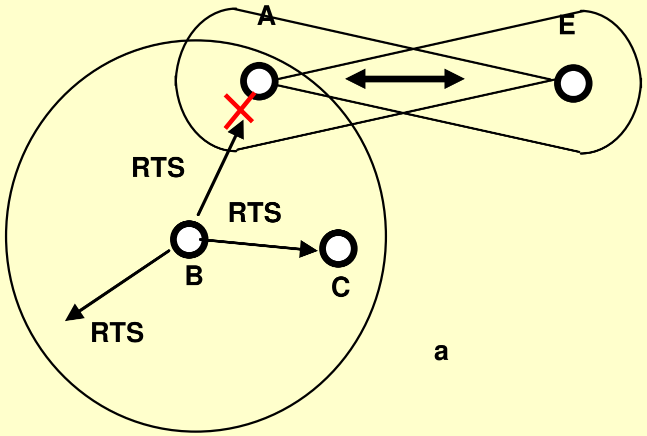
It is necessary that $G \leq B/30$

- Collision domains problem- chain topology

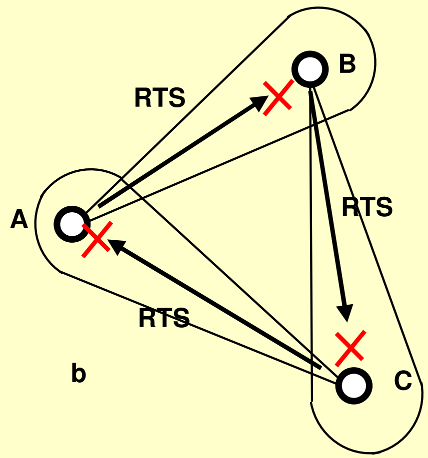


6. Medium Access Control: IEEE 802.11

- **Smart and Directional Antennas issues**
- **Directional Antennas problems: 802.11- deafness**
  - A node using a DAn is considered *deaf* in all the directions except that of its its main beam
  - The deafness problem can propagate throughout the network and cause low performance, unfairness, and even deadlock
  - **Example a :**
    - A (D mode) and E (D mode) are communicating
    - A is deaf for RTS sent in O mode by B
    - no RTS/CTS dialogue B-A happens ;
    - B eventually times out
    - The exposed C node (to B) receives RTS from B and stops its possible initiative to transmit to anybody (bad propagation effect)

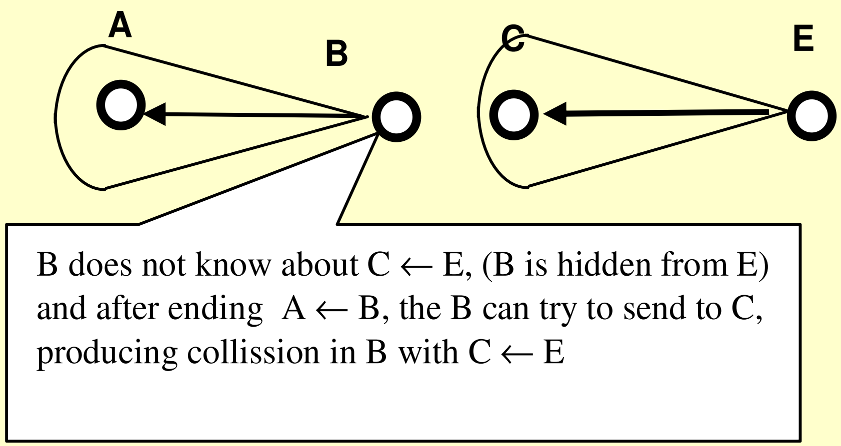


- **Example b: circular deadlock**
  - each node A, B, C try to send RTS to respectively B, C, A
  - But all nodes are deaf for these RTS; circular deadlock results
  - One node switching to O mode could solve such a deadlock
  - Idea : better work by using of mixed modes O/D for RTS/Data/CTS in different combinations
  - Optimization of such modes is an open issue.



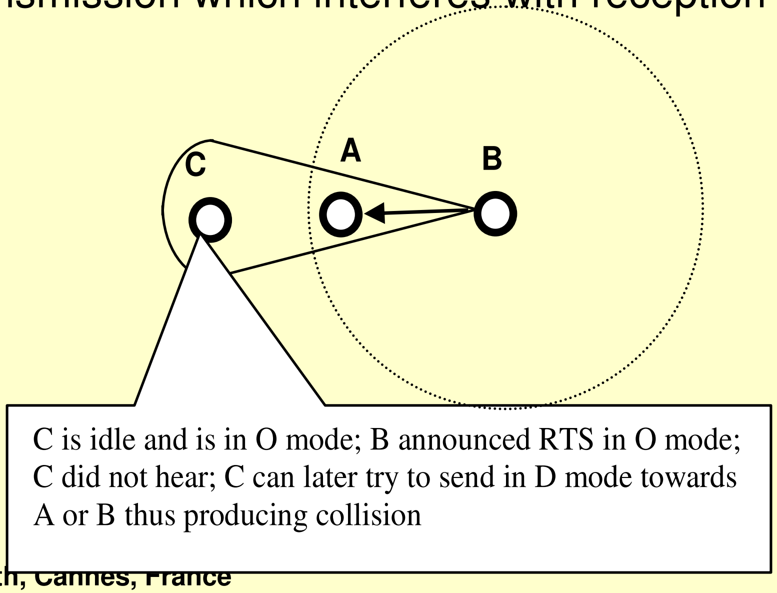
- **Smart and Directional Antennas issues**
- **Directional Antennas problems: hidden node**
  - DAn might aggravate the hidden node problem

- **Example:**
  - *Cause: deafness of node B w.r.t to RTS/CTS of C, E, because DAn mode in B*
  - Beamforming enables existence of two simultaneous transmissions of B to A and E to C (this is good!)
  - Node B is sending to A using D (directional) mode
  - Node E is sending to C in D mode
  - B is in interference range of E but because its DAn mode it does not hear the CTS of C
  - if the A←B is ended and B wants to send to C or E then it tries it and collision results at C, despite C and E made the RTS/CTS exchange.



Hidden node caused by unheard RTS/CTS by B

- **Smart and Directional Antennas**
- **Directional Antennas problems: hidden node (cont'd)**
  - Example:Hidden node due to asymmetric gain in O mode and D mode
  - Nodes remain in O mode while idle and/or Physical Layer Sensing (PCS) CS,
  - They only switch to D mode for active transmission
  - Node C is out of transmission range of B in O mode but not in D mode
  - While idle, C is unaware of the A ← B in D mode.
  - Assume that C has a packet destined to either A or B
  - Node C switches to D mode for this transmission which interferes with reception of A's packet at Node B



6. Medium Access Control: IEEE 802.11

- **Smart and Directional Antennas**
- **Omni and Directional Antennas MAC modes**
- O : Omnidirectional; D: Directional
- D/O: Directional transmission and Omnidirectional reception

- Combinations of modes D/O are proposed when transmitting/ receiving RTS/CTS and data packets.
  - There are advantages and also disadvantages, so this problem is an open issue

- ***Transmission of RTS/CTS in Omni-directional mode***
  - reduces deafness
  - but also reduces spatial reuse
    - as the nodes hearing RTS/CTS will defer their channel irrespective that maybe they would want to send in other directions than the current used one.
  - To allow spatial reuse while minimizing interference,
    - the neighboring nodes need to have information regarding the data transmission direction
    - in order to decide whether their intended sending will interfere with the on-going ones. RTS/CTS can include such information that can be used to estimate the location of the nodes..Examples:
      - Ex.1.each node is equipped with GPS and uses O-mode RTS/CTS to exchange node position information
      - Ex.2: A semi-omni transmission of RTS/CTS is proposed which can be performed using sector antennas. Nodes maintain multiple NAVs for different directions (sectors) and transmit RTS/CTS in all directions the channel is believed to be idle

- **Smart and Directional Antennas**
- **Omni and Directional Antennas MAC modes**
- ***Transmission of RTS/CTS in directional mode***
  - It can increase the spatial reuse and transmission range
  - but need prior knowledge of the direction of the nodes
  - capacity improvement is achievable even with the transmission power adjusted such that there is no increase in transmission range
  - Example:
    - neighbor aware antenna steering heuristic
      - Each node maintains tables containing the overheard info of who is communicating with whom
      - as well as the info on the direction of each of its neighboring nodes
      - At the Tx time, the node adjusts its beam-width
        to be wide enough so that the nodes recently involved in transmission with the destination node receive the current communication
      - Need a very accurate trs angle estimation and imposes high requirements on antenna adaptability.

- **Smart and Directional Antennas**
- **Omni and Directional Antennas MAC modes**
- O : Omnidirectional; D: Directional
- D/O: Directional transmission and Omnidirectional reception

- ***Hybrid transmission of RTS/CTS***
  - combine O and D transmission of control messages
    - one of RTS and CTS packets is transmitted (D- mode)
    - the other omni-directionally.
- *Comparison of modes for control messages transmission*
  - D-mode exchange of RTS and CTS
    - can increase in spatial reuse
    - but need prior knowledge of the intended transmission direction
    - Such knowledge may be obtained through neighbor discovery process but can be outdated even in low mobility scenarios due to node rotation.
  - O-mode or hybrid transmission of RTS/CTS
    - can inform a bigger number of neighbors of the on-going transmissions
    - They can also be used to estimate the direction of the nodes
    - O-mode reduces deafness and improves performance especially if RTS/CTS are modified to include information regarding the direction of the transmission to follow (might require a network-wide common reference direction).

6. Medium Access Control: IEEE 802.11

- **Smart and Directional Antennas**
- **Omni and Directional Antennas MAC modes**
  - Combinations of O/D modes for RTS, CTS, Data, Ack packets
  - Performance studies of various MAC schemes and O/D transmission of control messages show that:
    - O-mode RTS/CTS produces the min number of transmitted packets and collisions,
    - D-mode RTS/CTS results in max number of transmitted data packets and

Protocol	Physical Carrier Sensing (PCS)	RTS	CTS	Data	Ack	Tones
Directional MAC (D-MAC)	O	D/O	O/O	D/O	D/O	No
Tone-based Directional MAC (Tone-DMAC)	O	D/O	O/O	D/O	D/O	Yes
Directional Virtual Carrier Sensing (DVCS)	D	D/D	D/D	D/D	D/D	No
Circular directional RTS	O	Circular D/O	D/O	D/D	D/D	No

6. Medium Access Control: 802.16j

- **IEEE 802.16j MAC issues**
- **MAC perspective: (scheduling and/or security)**
  - RS has capabilities of security and scheduling and operates in distributed/centralised mode
  - **Distributed scheduling:**
    - RS creates DL-MAP/UL-MAP to allocate bandwidth to its subordinate MSs
    - RS may operate with distributed or centralised security mode
  - **Centralised scheduling:**
    - RS does not have scheduling capabilities
    - RS works usually in centralised security mode
  - Table (next slideshows a comparison of RS types.
    - Throughput: All modes increase the throughput
    - Coverage: For T-RS the coverage is limited by the coverage of the MMR-BS cell
    - Signalling overhead/latency: higher overhead in the centralised scheduling mode because all MS/access link information should be uploaded to MMR-BS
    - Higher BW efficiency: Only NT-RS/Distributed-scheduling/distributed-security can optimise the bandwidth usage because it can decrypt packets and decide proper fragmentation or packing of the data segments

6. Medium Access Control

- **IEEE 802.16j MAC issues:** Comparison of RS types
- **(Transparent) T-RS**
  - limited intra-cell throughput improvement, low-cost, no coverage improvement
  - It improves the link budget or to reduce the MS power in the given conditions of a BS cell radius
  - T-RS does fully support for mobility. It is a good low cost solution for fixed and nomadic applications.
- **(Non-transparent) NT-RS, with centralised scheduling mode**
  - throughput improvement and also coverage extension
  - but usable in low MS mobility environment, because of high latency
  - cost effective in comparison with distributed scheduling type, but the number of RSs associated to a MMR-BS cell is limited by the MMR-BS processing power and also signalling overhead leads to a limit
  - The MMR-BS scheduler should be highly complex.
  - **NT-RS with distributed scheduling mode:** the most performant approach (throughput/coverage/latency/efficiency) but having higher cost of RS.

Mode	T-RS	NT-RS		
Scheduling Mode	Centralised	Centralised	Distributed	
Security Mode	Centralised	Centralised	Centralised	Distributed
Characteristics				
Throughput increasing	Y	Y	Y	Y
Coverage extension		Y	Y	Y
Signalling overhead/latency reduction			Y	Y
Higher BW efficiency				Y

6. Medium Access Control

- **IEEE 802.16j**
  - R-MAC sub-layer : efficient MAC PDU relaying/ forwarding and control
  - is applicable to the links between MR-BS and RSs and between RSs
  - Figure 2a
    - example protocol stack for MS traffic relaying
    - MS connection and privacy managements is on an E2E basis (between MR-BS and MS).

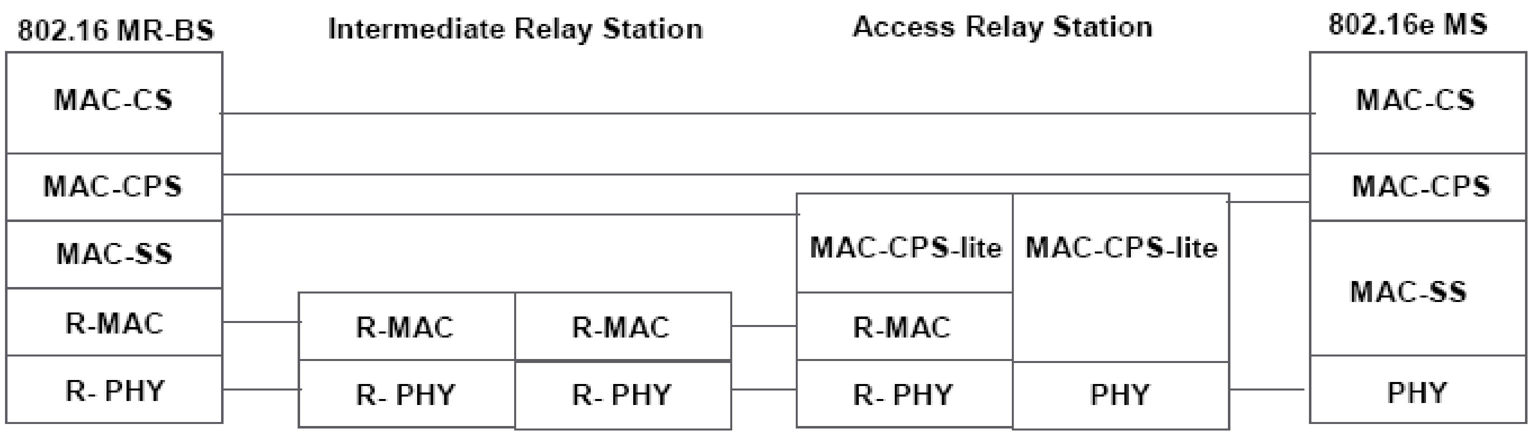


Figure 2a—Example MR data protocol stack for simple RS (MS traffic relaying).

6. Medium Access Control

- **IEEE 802.16j**
  - Figure 2b
    - protocol stack for MS traffic relaying
    - the MS connection and privacy management are managed by the RS and the RS connection and privacy management are controlled by MR-BS

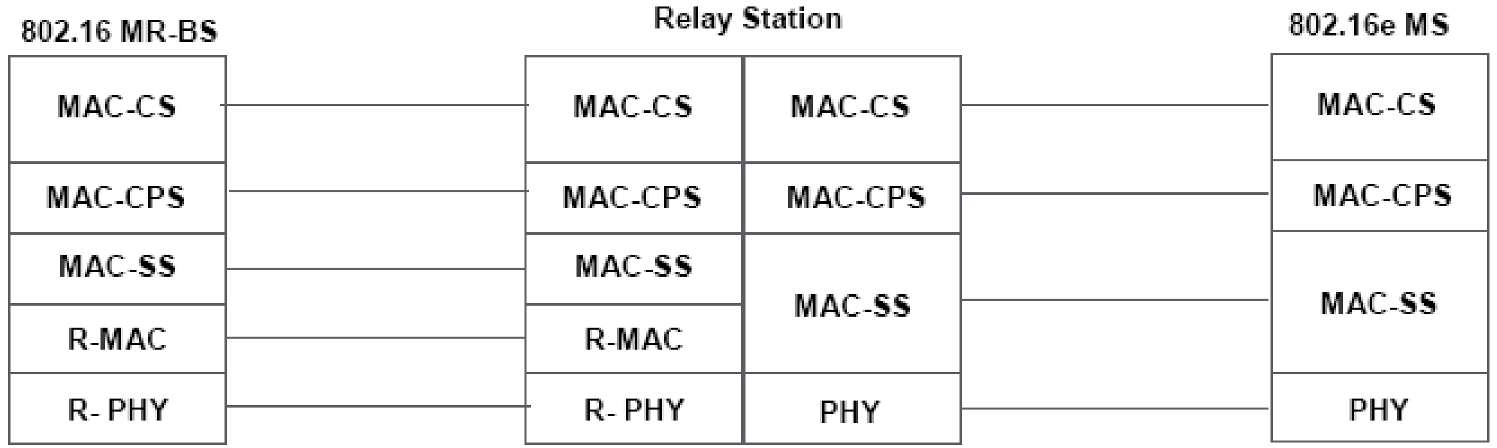


Figure 2b—Example MR Data Protocol stack for moving RS in moving BS mode (MS traffic relaying)

6. Medium Access Control

- **Open research issues on MAC layer**
- The WMN scalability issue has not been fully solved yet
  - Most of existing CSMA/CA MAC protocols solve partial problems but raise others
  - A distributed TDMA MAC overlaying CSMA/CA has been proposed as a possible solution to this problem.
    - *X. Wang, et.al., A high performance single-channel IEEE 802.11 MAC with distributed TDMA, Technical Report of Kiyon, Inc. (patent application), October 2004.*
  - Other techniques than CSMA/CA are TDMA and CDMA but a distributed scheme is needed to locally eliminate the difficulties of implementing TDMA or CDMA in an ad hoc network.
- Novel MAC is needed When MIMO and cognitive radios are used

- A scalable MAC protocol for ad hoc networks may not be effective to WMNs. In WMNs, mesh routers and mesh clients have different characteristics (mobility, power constraints, etc.) Same distributed solution may not work for both mesh routers and clients.
  - WMNs MAC must consider both scalability and heterogeneity between different network nodes.

6. Medium Access Control

- **Open research issues on MAC layer**

- Some mesh routers in WMNs are responsible for integration of various wireless technologies.
  - Advanced MAC bridging is needed to interconnect IEEE 802.11, 802.16, 802.15, etc.: Reconfigurable/software radios and the related RRM schemes may be the ultimate solution to these bridging functions

- Multi-channel MAC protocols for radios with multiple transceivers are still in development
  - As the cost goes down, a multi-channel multi-transceiver MAC will be a promising solution.

- To really achieve spectrum efficiency, a multi-channel MAC protocol must include the single-channel
- solution that can fundamentally resolve the scalability issue of WMNs
  - How to apply the innovative single-channel solution to a multi-radio or multi-channel system is another research problem.

- Much research work exists in MAC , on capacity, throughput, and fairness.

- Additionally the development of MAC protocols with multiple QoS metrics is an important topic for WMNs, to support rt applications.

6. Medium Access Control

- **Open research issues on MAC layer**

- Implementation is an open issue (software and firmware may be involved when a MAC protocol is to be modified)
  - Example :IEEE 802.11 MAC chips
  - many timing critical functions still remain in the firmware.
    - This provides little flexibility in modifying MAC protocols
  - To avoid modifying firmware, one approach is to design a MAC without coupling with firmware.
  - Example, the virtual MAC protocols do not require any modification in firmware or hardware
    - However, some critical rt key functions remain in the firmware
  - Changing the firmware is a doable but not a viable solution (cost and complexity).
    - A solution is to choose a more flexible MAC protocol architecture.
  - There are several IEEE 802.11 chipset manufacturers that have eliminated firmware in their MAC implementation architecture. With such an architecture, a true soft MAC or even a programmable MAC can be implemented.
  - When software radios become mature enough for commercial use, more flexible and powerful MAC protocols can be easily developed.

CONTENTS

7. Network and Transport layers

- Routing protocols requirements
  - Flexibility: Work with/without gateways, different topologies
  - Low latency for route discovery and rediscovery: Essential for reliability
  - Low control traffic overhead
  - Scalability: W.r.t. mobility and network dimension
  - Mobile user support: Seamless and efficient handover
  - QoS Support: Consider routes satisfying specified QoS criteria
  - Multicast: Important for some applications (e.g., emergency response)
  - Multiple paths- desirable

- **Route optimisation criteria (potential list)**
  - Minimum no. of Hops
    - Interference
    - Delays (RTT)
    - Error Rates
    - Power Consumption
  - Maximum
    - Data Rates
    - Route Stability
  - Use of multiple routes to the same gateway
  - Use of multiple gateways

  - **Combinations of the above**

7. Network and Transport layers

- **Proactive routing protocols**
  - Classical routes determination principle
    - periodical exchange of topological and/or distance information between nodes
    - each node knows (partially or totally) the shortest path to each node in the network
  - More useful in small networks (low routing overhead, low memory requirement, thus minimizing the delay due to routing table lookups)
  - Sample examples
    - *Destination Sequenced Distance Vector (DSDV)*
    - *Optimized Link State Routing (OLSR)*
    - *Topology Dissemination Based on Reverse-Path Forwarding (TBRPF)*
    - *Open Shortest Path First – MANET (OSPF-MANET)*
    - *Fisheye State Routing (FSR)*

- **Reactive (on demand) routing protocols**
  - Routes are established on-demand
  - Preferable
    - when the network size (no need to store all routes)
    - in high mobility networks
  - As the routes are created on demand, reactive algorithms are also traditionally preferred for mobile scenarios
  - Examples of common used protocols
    - *Dynamic Source Routing (DSR)*
    - *Ad Hoc On-Demand Vector (AODV) and some other extensions derived from it*

7. Network and Transport layers

- **Hybrid routing protocols**
  - May be more efficient in WMNs
  - Could be used proactively towards Mesh Points (MPs) in the neighborhood and reactive towards MPs far away
  - Alternatively, multiple algorithms can be used simultaneously, if WMN is segmented into clusters
    - Within each cluster a proactive algorithm is used, whereas between clusters a reactive algorithm is used. Examples: *Hybrid Wireless Mesh Protocol (HWMP)*
  - **Alternative of a hybrid approach**
    - adaptive routing protocol: its behavior is modified dynamically by monitoring the change in the network (e.g., size, dynamicity, mobility, etc.)
      - uses proactive algorithms for small network and low mobility
      - reactive algorithms in larger network and/or high mobility
    - moreover, the protocol modifies its behavior in real time as the network changes its topology

7. Network and Transport layers

- **MAC-Layer Routing vs. IP Layer Routing ?**
  - *Some authors claim that L2 is more appropriate*

  - MANET : when a node wants to send data to a destination D
    - it refers to an existing route in its routing table
      - and forwards the packet to the next hop for delivery to the destination
    - If a route towards D exists
      - the protocol entity finds the IP address of the next hop, and gets the MAC address of the next hop (ARP)
      - the node then sends a MAC data frame to the next hop and so on

    - Critics:L3 routing mechanisms work well when all the intermediate nodes are stations and have L3 capabilities
      - But WMN nodes can be both MSTAs and MAPs.
      - APs are traditionally purely L2 devices; adding L3 functionality to an AP is more costly
      - Therefore, the L3 routing techniques proposed by MANET cannot be directly applied to all mesh networks
      - the routing metric (hop count) defined in MANET *is not sufficient* in WMNs (bandwidth, interference, latency, security, power efficiency, link condition awareness – new issues that appear)

7. Network and Transport layers

- **MAC-Layer Routing vs. IP Layer Routing (cont'd)**
- Solutions:
  - making these parameters available to L3 routing protocols for use in the path metrics; but this involves tight integration (cross layer optimisation) L2-L3- not easy and non-standardizable (cross-layer optimisation is not in the scope of IETF, IEEE 802.11)
  - *layer 2 routing* based on MAC addresses –another solution considered for 802.11 WMN (it borrows concepts from MANET routing)

- L2 Routing Protocols for WMNs
  - The source STA has the destination IP address
    - obtains the MAC address (via ARP) of the destination through ARP
    - and looks up the MAC layer routing table to verify
      - if a route exists
      - or needs to be created.
    - then data frames are forwarded towards the next hop.

7. Network and Transport layers

- Routing protocols examples:
- ***Single Radio Single Channel***
  - DSR-based : DSR (Dynamic Source Routing), DSR-based: LQSR Link Quality Source Routing)
  - Cooperative diversity–based: ExOR (Extremely Opportunistic Routing)
- ***Single Radio Multi Channels***
  - AD hoc on Demand Distance Vector (AODV)-based: AODV, MCRP (Multi Channel Routing Protocol)
- ***Multi Radio Multi Channels***
  - DSR-based: MCR (Multi Channel Routing), MR-LQSR (Multi Radio LQSR)
  - Graph-based : Hyacinth, RCL (Joint channel and routing)

7. Network and Transport layers

- **MAC-Layer Routing vs. IP Layer Routing**
- **WMN can be very dynamic**
  - MPs are being added/removed frequently
  - Variation in size and mobility level.
  - using of any single routing protocol, either proactive or reactive, would not be efficient.
- A *hybrid protocol* can be beter
  - it would be proactive towards MPs in the neighborhood
  - and reactive towards MPs far away
- Alternative solutions:
  - Solution 1:
    - multiple algorithms can be used simultaneously, where the mesh network is segmented into clusters.
    - within each cluster a proactive algorithm is used, whereas between clusters a reactive algorithm is used.
  - Solution 2:
    - WMN runs *adaptive routing protocols*, whose behavior is modified dynamically by monitoring the change in the network parameters (e.g., size, dynamicity, mobility, etc.)
- **Conclusion on algorithm "good" usage :**
  - proactive - in small and low mobility networks
  - reactive - for large scale and high mobility networks
  - Moreover, the protocol modifies its behavior in real time as the network changes its topology

7. Network and Transport layers

- **Metrics for Wireless Mesh Networks Routing**
  - Metric: an essential component of the routing solution in order to support routing with different QoS, bandwidth, latency, and security requirements
  - In WMNs they are partially inspired from ad hoc networks
  - but WMN can benefit from more stationary topology and use quality-aware routing metrics.
  - *Multidimensional metric* capable to capture various link conditions is useful
  - The routing algorithm may/should use a multidimensional metric including , e.g: QoS parameters (for rt applications), power efficiency, security of wireless links and intermediate nodes, reliability, etc.- depending on application requirements

7. Network and Transport layers

- **Metrics (cont'd)**
- **Desirable characteristics of a good WMN routing metric**
- **1. Isotonicity:** the order of weights of two paths is preserved if they are appended or prefixed by a common third path (this is necessary and sufficient condition of a routing metric for the existence of efficient algorithms to find minimal weight paths, such as Bellman-Ford or Dijkstra

- **2. Interference** awareness
  - ***Intra-flow I****:* the radios of two or more links of a single path or flow operate on the same channel and can be reduced by increasing channel diversity. Interference range of a node is typically bigger than a single hop

  - ***Inter-Flow I:*** caused by other flows that are operating on the same channels and are competing for the medium

7. Network and Transport layers

- **Metrics (cont'd)**
- Desirable characteristics of a good WMN routing metric (cont'd)
  - **3. Locality of Information**: information such as channels used on previous hops of a path, or other metrics observed on other nodes of the networks, (e.g. packet delivery rate, noise level).This non-local information can be part of routing metric and can be used to make more optimal routing decisions.
  - **4. Load Balancing**: The ability of a metric to balance load and provide fairer usage of the network's distributed resources (important for concentration of traffic at he Internet Gateways in mesh networks.
  - **5. Agility:** ability to respond quickly and efficiently to changes in the network in terms of topology or load
  - **6. Throughput:** In general, a metric should be able to select routes with greater throughput consistently

7. Network and Transport layers

- **Metrics (cont'd)**
- **Examples**
  - **Hop Count:**
    - Traditional, simple, aditive, isotonic metric used in most IP routing protocols. In MANET/WMN: AODV, DSR,DSDV use hop count
  - *Advantages:*
    - In scenarios of high mobility, it can outperform (it is agile) other load dependent metrics.
    - high stability, isotonic
  - *Drawbacks:*
    - All links in the network are seen alike.
    - No info on link load, capacity, channel diversity and interference
    - It can often find paths having
      - high loss ratio and poor performance.
      - low throughput and poor medium utilization, (note that slower links need more Tx time)

7. Network and Transport layers

- **Metrics(cont'd)**
- **Per-hop Round Trip Time (RTT)**
  - Aditive metric, based on measuring the RTT *seen by unicast probes* between neighboring nodes
    - Dialogue : time-stamped packets - *probe/probe-ack*, done between two neighbours at each Tsec (e.g 0.5 sec)
    - The node keeps an exponentially weighted moving average of the RTT samples to each of its neighbors.
  - RTT will be higher if
    - either the node/neighbor is busy
    - other nodes in the vicinity are busy (channel contention)
    - a loss appears on the link, then 802.11 ARQ will retransmit
    - despite the ARQ mechanism, a probe or a probe-ack packet is lost
  - *Advantages:*
    - Aditive, isotonic, it avoid highly loaded or high loss links
  - *Drawbacks*
    - Being load-dependent metric, it can lead to route instability (well-known problem in wired networks).
    - It does not consider the actual throughput if the probes dimensions are small in comparison to real data packets.

7. Network and Transport layers

- **Metrics (cont'd)**
- **Expected Transmission Count (ETX)**
  - ETX [4] [22] is the expected number of transmissions (including retransmissions) a node requires to successfully unicast transmit a packet across a link.
  - The ETX of a path is the sum of ETX of each link along the path.
  - The derivation of ETX
    - measurements of the packet loss probability in both the forward and reverse directions; (P*f* and P*r)*
    - Let *p* denote the probability that the packet transmission from x to y is not successful Then:
    - p = 1− (1 − Pf) ∗ (1 − Pr), **ETX = = 1/(1-p)** (1)
    - ETX is measured in link of a real network by ETX = 1/(Df*Dr)
      - where Df is the forward delivery ratio (1 - Pf), Dr is the reverse delivery ratio (1 - Pr)
    - Df and Dr are measured by broadcasting dedicated link probe packets of a fixed size every average period (typically at 1 second) from each node to its neighbors.

7. Network and Transport layers

- **Metrics : ETX (cont'd)**
- **Advantages:**
  - It considers the link loss ratios and asymmetry in the loss ratio in both directions of each link
  - It favors paths with higher throughput and lower number of hops as longer paths have lower throughput due to intra-flow interference
  - It deals with inter-flow interference but only indirectly (the links with a high level of interference will have a higher ETX value)
  - ETX is isotonic: it allows effcient calculation of minimum weight and loop-free paths
  - By minimizing transmission counts, ETX tends to minimize spectrum use, which should maximize overall system capacity

7. Network and Transport layers

- **Metrics : ETX (cont'd)**
- **Drawbacks:**
  - It is a routing metric for single-channel
  - It does not consider
    - neither link bandwidth nor packet size
    - in an explicit way, the interference experienced by the links
    - differences in transmission rates
    - actual load of the link, so it may select heavily loaded routes
  - It does not accurately reflect loss rate of actual traffic (Tx rate of probe packets is typically low)
  - No information on the effective link share.
  - It does not discriminate between same channel paths and channel-diverse paths. So, it makes no attempt to minimize intra flow interference.
  - In highly mobile single radio environments, ETX shows poor agility due to long time window over which it is obtained

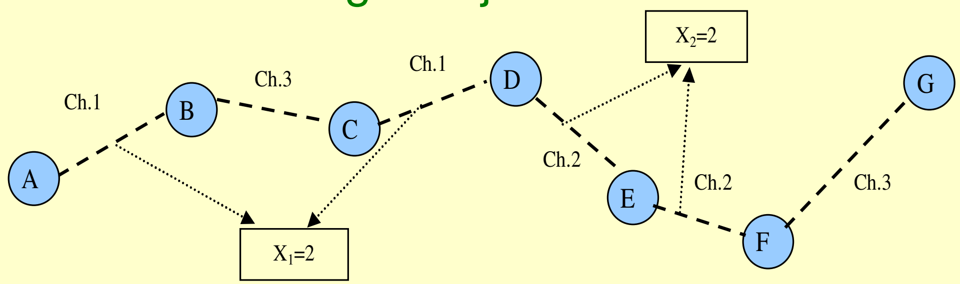
7. Network and Transport layers

- **Metrics (cont'd)**
- **Expected Transmission Time (ETT)**
  - Extension of the ETX
  - ETT is expected time to successfully transmit a packet at the MAC layer and is defined for a single link as
  - **ETT = ETX × S/B** (2)
    - S = data-packet size
    - B = estimated link bandwidth. The B value can be retrieved from the firmware, or estimated by measurements.
  - ETT is aditive; the path metric is the sum of the links' ETT
  - *Advantages:*
    - It can increase the throughput of path by measuring the link capacities and would increase the overall performance of the network
    - isotonicity
  - *Drawbacks:*
    - It inherits the main disadvantages of ETX.
    - ETT does not consider link load explicitly due to which it cannot avoid routing traffic through already heavily loaded nodes and links.
    - ETT is not designed for multiradio networks so it does not minimize intra-flow interference.

7. Network and Transport layers

- **Metrics (cont'd)**
- **Weighted Cumulative ETT (WCETT)**
  - Extension of ETT
  - *Multiple channels mode* (on a single radio or multiple radios per node) can improve throughput by using, at the same time, the *available non-overlapping channels* defined by IEEE 802.11
  - WCETT [14], consider *intra-flow interference*
  - This metric is a sum of E2E delay and channel diversity parameter
    - A tunable parameter is used to combine both components or prioritize one of them
- Consider an n-hop path, using a total of k channels.
  - Define Xj (computed for channel j) as the sum of transmission times of hops on channel j. The total path throughput will be dominated by the bottleneck channel, which has the largest Xj.

$$X_j = \sum_{\text{Hop } i \text{ is on channel } j} ETT_i \quad 1 \leq j \leq k$$



Per channel Xj computation

7. Network and Transport layers

- **Metrics (cont'd)**
- **WCETT (cont'd)**
  - One can combine, the desirable properties of the two metrics : sum of ETTi and max (Xj) taking their weighted/balanced average (α is a parameter , $0 \leq \alpha \leq 1$)
  - The WCETT metric of a path p is:

$$WCETT_p = (1-\alpha) * \sum_{i \epsilon p} ETT + \alpha * max_{i \leq j \leq k} X_j$$

- Example of a routing protocol using WCETT metric
  - (MR-LQSR) is proposed in [20], [21] , for multi-radio WMNs
  - WCETT takes into account both link quality metric (losses, bandwidth,.) and the minimum hop-count
  - It can achieve good tradeoff between delay and throughput because it considers channels with good quality and channel diversity in the same routing protocol

7. Network and Transport layers

- **Metrics (con't)**
- **WCETT**
- **Advantages:**
  - WCETT considers the intra-flow interference and selects channel diversified paths all the advantages of ETT except isotonicity.
  - Better perf. of multi-radio, multi-rate wireless networks when compared to hop count, ETX, ETT,
  - The two weighted components of WCETT attempt to strike a balance between throughput and delay
- **Drawbacks:**
  - WCETT considers the no. of links operating on the same channel and their respective ET but not the relative location of these links. It assumes all links of a path operating on same channel interfere which can lead to selection of non-optimal paths
  - Because of the second term, WCETT is not isotonic
  - WCETT does not explicitly consider the effect of inter-flow interference. Due to this, it may establish routes having high levels of interference.
  - WCETT has the same limitations as ETX/ETT by not estimating the effective link share.

- **Metrics(cont'd)**

- **Metric of Interference and Channel-switching (MIC)**

  - LS-based routing protocols require minimum - cost routes to be loop-free.
  - WCETT does not avoid inter-flow interference may lead to choose routes in congested areas.The MIC tries to solve these problems [7].

  - First, each node takes into account the number of interfering nodes in the neighborhood to estimate inter-flow interference.

  - In addition, MIC uses virtual nodes to guarantee the minimum-cost routes computation. MIC also calculates its value based on the ETT metric.

  - MIC improves WCETT by solving its problems of non-isotonicity and the inability to capture inter-flow interference.
  - Let:
    - N is the total number of nodes in the network
    - min(ETT) is the smallest ETT in the network, which can be estimated based on the lowest transmission rate of the wireless cards
    - **MIC for a path p is given below as MIC(p)**
    - MIC has two components :
      - IRU (*Interference-aware Resource Usage*)
      - and CSC (*Channel Switching Cost*)

7. Network and Transport layers

- **Metrics (cont'd)**
- **MIC (cont'd)**

$$MIC(p) = \frac{1}{N \times \min(ETT)} \sum_{\text{link } l \in p} IRU_l + \sum_{\text{node } i \in p} CSC_i$$

$$IRU_l = ETT_l \times N_l,$$
$$CSC_i = \begin{cases} w_1 & \text{if } CH(prev(i)) \neq CH(i) \\ w_2 & \text{if } CH(prev(i)) = CH(i), \end{cases}$$
$$0 \leq w_1 < w_2,$$

- *Meaning of components:*
  - IRUl: aggregated channel time of neighboring nodes that transmissions on link l consumes.
    - It captures the inter-flow interference since it favors a path that consumes less channel times at its neighboring nodes.
  - CSC : intra-flow interference
    - it gives higher weights to the paths with consecutive links using the same channel than paths that alternate their channel assignments
    - it favors paths with more diversified channel assignments

7. Network and Transport layers

- **Metrics (cont'd)**
- **MIC (cont'd)**
- Advantages:
  - MIC takes both inter and intra-flow interferences and it can be made isotonic if it is decomposed into virtual nodes while applying minimum weight path finding algorithms such as Dijkstra's algorithm
- Drawbacks:
  - The overhead required to maintain update information of the ETT for each link can lower the performance depending on traffic loads.
  - It assumes that all links located in the collision domain of a particular link contributes to same level of interference and counts the amount of interference on a link only by the position of interfering nodes no matter whether they are involved in any transmission simultaneously with that link or not.
  - The second component CSC captures intra-flow interference only in two consecutive links.

7. Network and Transport layers

- **Metrics (cont'd)**
- **ILA - Interference Load Aware**
  - (ILA)[12] metric is built over MIC metric.
  - Components: Metric of channel interference (MTI) and channel switching cost (CSC is the same as in MIC metric).
  - The path weight function is as follows

$$ILA(p) = \alpha * \sum_{link_i \epsilon p} MTI_i + \sum_{node_i \epsilon p} CSC_i$$

- MTI metric is :
  - MTIi(C) = ETTij(C) * AILij(C); if NI(C) <> 0
  - MTIi(C) = ETTij(C); if NI(C) = 0
- NI(C) = Set of interfering nodes of neighbors i and j
- AILij=Average load of neighbors that may interfere with transmission between nodes i and j on channel C.
- *Advantages*
  - It addresses the limitations of metrics such as hop count, ETX, ETT, WCETT, MIC
  - It finds paths with less congestion, low level of interference, low packet drop ratio and high data rate.
  - ILA calculates inter-flow interf. by considering the amount of traffic generated by interfering neighbors which is drawback of MIC.
- *Drawbacks*
  - The second component CSC captures intra-flow interference only in two consecutive links.

7. Network and Transport layers

- **Metrics (cont'd)**
- **LAETT - A load dependent metric for balancing Internet traffic in WMN**

  - **LAETT is an adaptation of the ETT**
  - **It provide a path which**
    - **satisfies the bandwidth request of the flow**
    - **and creates possibility for future requests by balancing the load**
    - **LAETT combines wireless access characteristics and load estimates.**

    - **ETTij = ETXij * S/Bij**

    - ETXij =Expected transmission count on link(i,j), S =Packet size
    - Bij =Effective bit rate, Bij = Bi/Qij, Bi =Transmission rate of node i
    - Qij=Link quality factor
    - Qij >= 1 ; when the link quality degrades, Qij increases and Bij decreases

  - To consider load balancing the Bij has an expression which takes into account the used bandwidth

  - *Advantages:*
    - It is load aware isotonic routing metric that uses weighted shortest path routing to balance the load across the network.
    - It captures link quality and traffic load.
  - *Drawbacks:*
  - It does not consider intra-flow interference and does not explicitly consider inter-flow interference.

7. Network and Transport layers

- **Metrics (cont'd)**
- **Exclusive Expected Transmission Time (EETT)**
  - It is a novel interference aware routing metric based on ETT
  - It selects multi-channel routes with least interference
  - It gives better evaluation of a multichannel path
  - For any given l, Interference set (IS) is defined as the set of links that interfere with it(the set includes the link itself)
  - The link l's EETT is

$$EETT_l = \sum_{link i \epsilon IS(l)} ETT_i$$

- IS(l)= Interference set of link l. The path weight is de_ned as the sum of EETT's of all links on the path.
- ***Advantages***
  - **All the advantages of ETT; isotonic.**
  - ***It considers intra-flow interference and indirectly considers inter-flow interference***
- ***Drawbacks:***
  - **EETT of link l represents the busy degree of the channel used by link l. It is the worst case estimation of transmission time for passing link l.**

7. Network and Transport layers

- **Metrics (cont'd)**
- **Interference Aware Metric (iAWARE) [ ]**
  - iAWARE[13] consider both inter-flow and intra-flow interference
  - The iAWARE metric is:

$$iAWARE(p) = (1-\alpha) * \sum_{i=1}^{n} iAWARE_i + \alpha * max_{1 \leq j \leq k} X_j$$

- Xj is same as in WCETT
- The iAWARE value of a link j is: iAWAREj = ETTj / IRj
- IRj =Interference ratio for a link j (between two nodes u and v):
- IRj = min(IRj(u); IRj(v));
- Interference ratio(IR) value for a node u and link i :
- IRi(u) = SINRi(u) / SNRi(U)
- SINRi(u) is the signal to interference noise ratio and SNRi(u) is the signal to noise ratio at node u for link i.

7. Network and Transport layers

- **Metrics (cont'd)**
- **Interference Aware Metric (iAWARE)**
  - *Advantages*
  - It considers variation in link loss ratio, differences in transmission rate and both types of interference
  - It keeps the main WCETT characteristics , but it directly measures the average interference generated by neighboring nodes
  - Using SINR for inter-flow interference gives possibility of cross layer optimisation (if compared with ETX based metric like MIC, ETX, WCETT etc.
  - *Drawbacks*
  - Non-isotonic
  - If a link has higher IRj that ETTj , the iAWAREj metric will have a lower value. This will result in choosing a path with lower ETT but higher interference
  - It gives more weight to ETT compared to degree of interference of the link.

7. Network and Transport layers

- **Metrics (cont'd)**
- Mod-iAWARE:
- Recent proposed new metric [ ] based on : iAWARE, LAETT and EETT
- The path metric of Mod-iAWARE is

$$Mod-iAWARE(P) = \sum_{link(i,j)=1}^{n} Mod-iAWARE_{ij}$$

$$Mod-iAWARE_{ij} = \frac{EETT_{ij}}{IR_{ij}}$$

$$EETT_{ij} = \sum\nolimits_{link(i,j)\epsilon IS(i,j)} LAETT_{ij},$$

- EETTij =Exclusive expected transmission time of a link ij, IRij =Interference Ratio
- LAETTij = Load aware expected transmission time
- IS(i,j) = Interference set of link(i,j) (mentioned in EETT section)
- Advantages:
  - Isotonic.
  - iAWAREij may choose a path with lower ETT but higher interference. The Mod-iAWARE selects path with less interference.
  - It considers load balancing as it uses LAETT
  - It has all advantages of iAWARE, EETT and LAETT
- Drawbacks:
  - Overhead to calculate the link metric; it needs knowledge of interference set.
  - Inter flow interference is calculated twice, both in EETTij and IRij.
  - It does not consider the cost of channel switching delay

7. Network and Transport layers

- **Metrics (cont'd)**
- Mod-ILA
  - New modified version of ILA with inputs from metrics such as LAETT and EETT
  - It addresses the limitations of ETT, ETX, WCETT, MIC
  - It finds paths with less congestion, low interference, low packewt drop ratio, high data rate

$$Mod - ILA(p) = \sum_{link_{ij} \epsilon p} MTI_{ij}$$

$$MTI_{ij}(C) = EETT_{ij}(C) * AIL_{ij}(C), N_l(C) \neq 0$$

$$MTI_{ij}(C) = EETT_{ij}(C), N_l(C) = 0$$

- where MTIij =Metric of interference on link ij
- AILij(C) is the average load of the neighbors that may interfere with the transmission between nodes i and j over channel C
- *Advantages:*
- Isotonic.
  - In ILA metric, the second component CSC captures intra flow interference only in two consecutive links. But Mod-ILA overcomes this drawback.
  - Mod-ILA considers load balancing as it uses LAETT
  - It has all the advantages of ILA, ETT and LAETT routing metrics.
- *Drawbacks:*
  - Overhead to calculate the link metric, it needs the knowledge of interference set (IS) etc.
  - It considers inter flow interference twice (redundant computation)
  - This metric also does not consider channel switching delay.

7. Network and Transport layers

- **Metrics(cont'd)**
- Routing metrics comparison;
  - Source: Addagada, B.K, et.al, A Survey: Routing Metrics for Wireless Mesh Networks, May 5, 2009, http://www.public.iastate.edu/~vkisara/Survey%20On%20Routing%20Metrics%20in%20WMN.pdf

	Hop	ETX	ETT	WCETT	MIC	ILA	iAWARE	EETT	LAETT	Mod-ILA	Mod-iAWARE
Intra	X	X	X	√	√	√	√	√	X	√	√
Inter	X	√ *	√*	√*	√#	√	√	√*	X	√	√
External	X	X	X	X	√	√	√	√	X	√	√
Load bal	X	X	X	X	X	X	X	X	√	√	√
Agility	√	X	X	X	X	X	X	X	X	X	X
Isotonic	√	√	√	X	√$	X	X	√	√	√	√

* - Indirectly , #- Not Accurate, $ -Complex,

7. Network and Transport layers

- **Metrics(cont'd)**
- **Conclusions**
  - A lot of metrics have been proposed
    - From the most simple (hop count)
    - To very complex ones, considering
      - Link quality (including its variation)
      - Intra and interflow interference
      - Load balancing, load awareness, etc.
  - The complex metric involves less agility and more computation overhead
  - Some of them are not isotonic
  - **More quantitative studies are necessary to evaluate the increase in performance versus cost of implementation**
    - **Based on simulation**
    - **Based on real life testbeds**

7. Network and Transport layers

- **Routing protocol examples**
- **Proactive Routing Protocols**
- **Destination-Sequenced Distance-Vector Routing (DSDV)**
  - table-driven DV routing scheme for MANET, based on the Bellman-Ford algorithm
  - It solved the routing loop problem
    - Each entry in the routing table contains a (seq_no) to measure the freshness of a route
    - The number is generated by the destination, and the emitter has to send out the next update with this number
    - Routing info is distributed between nodes by sending full dumps infrequently and smaller incremental updates more frequently.
    - If a router receives new information, then it uses the latest seq_no.
  - Old routes are deleted automatically.

7. Network and Transport layers

- ***Routing protocol examples***
- **Proactive Routing Protocols**
- **Destination-Sequenced Distance-Vector Routing (DSDV) (cont'd)**
- **Advantages**
  - suitable for small number of nodes
  - **other protocols have borrowed similar techniques (e.g AODV).**

- **Drawbacks**
  - No formal specification, no significant commercial implementation
  - But many improved forms of this algorithm have been suggested and used
  - Need regular update of its routing tables, (battery power problem)
  - network topology changes -> a new *seq_no* is necessary before the network re-converges
  - not suitable for highly dynamic networks

7. Network and Transport layers

- **Proactive Routing Protocols**
- **Optimized Link State Routing (OLSR) RFC 3626**
- protocol optimized for MANET but can also be used in WMNs
- Key concepts
  - *Multipoint relays (MPRs)* : selected nodes to forward (only them) broadcast LS info during the flooding process
  - The objective is to reduce the message overhead as compared to a classical flooding mechanism.
  - A MPR node may chose to report only links between itself and its MPR selectors
    - Hence, partial LS information is distributed in the network
    - Metric: number of hops
  - OLSR - suitable for large and dense networks
    - because the technique of MPRs works well in this context

7. Network and Transport layers

- **Proactive Routing Protocols**
- **Optimized Link State Routing (OLSR) cont'd**
  - **Advantages**
    - Proactive -> no route discovery delay associated with finding a new route
    - routing overhead is greater than that of a reactive protocol, but does not increase with the number of routes being used.
    - Default and network routes can be injected into the system
    - Timeout values and validity information are used

  - **Drawbacks**
  - OLSR assumes that a link is up if a no. of hello packets have been received recently
  - It sees the links either working or failed, (not always true in WMNs)
  - Extensions for link quality features
    - E.g. OLSRd (commonly used on Linux-based mesh routers) have been extended called Radio-Aware \OLSR
      - included in the 802.11s draft standard. It was influenced by the HSLS protocol.

7. Network and Transport layers

- **Proactive Routing Protocols**
- **Optimized Link State Routing (OLSR) cont'd**
  - **Drawbacks (cont'd)**
    - As OLSR unreliably floods the link state DB; so it may cause transient loops if the LS database becomes inconsistent due to packet loss
    - OLSR propagates data about possibly unused routes. -> unsuitable for sensor networks
    - Requires sufficient CPU power to compute optimal paths in the network
    - In the typical networks where OLSR is used (a few dozens of nodes), this is acceptable
  - **Some solutions**
  - The OLSR-NG project- evolutionary approach
    - tried to address some of the above drawbacks
    - The original OLSR : Dijkstra , O(n*n)
    - OLSR-NG : Dijkstra , O(n*log(n))

7. Network and Transport layers

- **On Demand Protocols**
- **Ad Hoc on Demand Distance Vector Routing Protocol AODV**
- RFC 3561/2003
- **Main features**
  - The AODV algorithm enables *dynamic, self-starting, multihop routing between mobile nodes* in an ad hoc network.
  - Obtain routes on demand and does not require nodes to maintain routes to inactive destinations
  - Nodes can respond to link breakages and topology changes in a timely manner
  - Is loop-free, and by avoiding the Bellman-Ford "counting to infinity" problem (by using *destination sequence numbers* (*dst_seq_no)* on route updates); offers quick convergence when the network topology changes (e.g. node move)
  - If links break, AODV causes the affected set of nodes to be notified so that they are able to invalidate the routes using the lost link
  - AODV message types are : *Route Requests (RREQs; Route Replies (RREPs); Route Errors (RERRs)*

7. Network and Transport layers

- **On Demand Protocols**
- **AODV (cont'd)**

- When a route to a new destination D, is needed
  - The node wanting it broadcasts a RREQ message
  - A route can be determined
    - when the RREQ reaches either the D itself
    - or an intermediate node with a 'fresh enough' route to D (i.e. a valid route entry for the D, whose associated *dst_seq_no* is at least as great as that contained in the RREQ)

    - The route is made available by unicasting a RREP back to the origination of the RREQ

    - Each node receiving the request *caches a route back to the originator of the request*, so that the RREP can be unicast from D along a path to that originator, or likewise from any intermediate node that is able to satisfy the request
    - The requesting node selects among answers received the route with minimum number of hops.
    - Unused entries in the routing tables are recycled after a time. When a link fails, a routing error is returned to a transmitting node, and the process repeats.

7. Network and Transport layers

- **On Demand Protocols**
- **Dynamic Source Routing (DSR) RFC 4728/2007**

  - Simple and efficient routing protocol designed specifically for use in multi-hop wireless ad hoc networks of mobile nodes

  - DSR allows the network to be completely self-organizing and self-configuring, without the need for any existing network infrastructure or administration

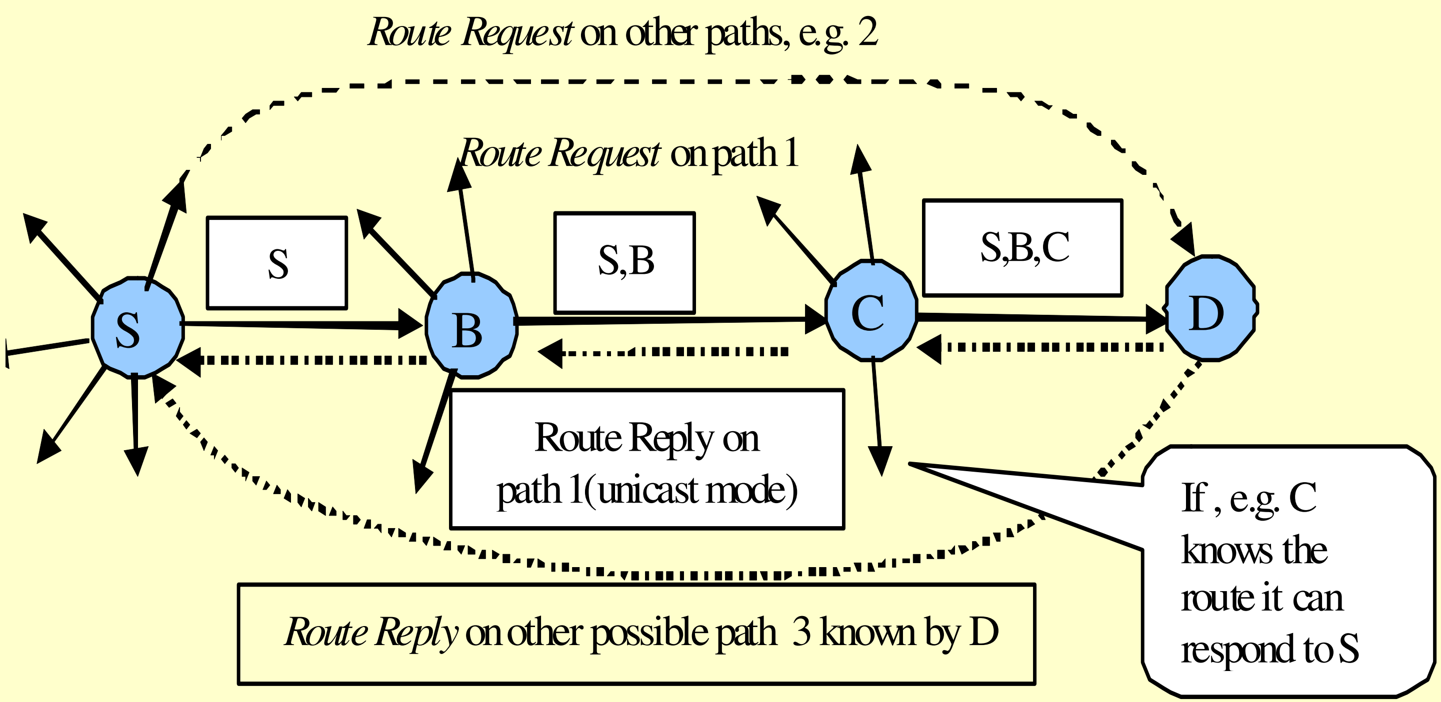
  - Two main mechanisms
    - *Route Discovery* and *Route Maintenance*, which work together to allow nodes to discover and maintain routes to arbitrary destinations in the network.

  - On demand operation : the routing packet overhead of DSR scales automatically to only what is needed to react to changes in the routes currently in use

  - The protocol allows multiple routes to any destination (D)
    - It allows each sender (S) to select and control the routes used in routing its packets,e.g for load balancing

7. Network and Transport layers

- **On Demand Protocols**
- **Dynamic Source Routing (DSR) (cont'd)**
  - DSR Route Request and Route Reply
    - Each node uses a single IP address to be known in the network
    - This in necessary in order to assign a unique ID to a node



7. Network and Transport layers

- **On Demand Protocols**
- **Dynamic Source Routing (DSR) (cont'd)**
  - Other advantages
    - Avoids the need for up-to-date route information in intermediate nodes
    - Nodes that are forwarding or overhearing cache routing information for future use (promiscuous mode, supported by 802.11 cards)
    - Reduced control overhead, by
      - eliminating the periodic table-update messages
      - Taking adavantage on existing knowledge on topology. Each node caches the information learned from other nodes.
  - **Drawbacks/limitations**
    - The route maintenance mechanism does not locally repair a broken link
    - Stale route cache information could also result in inconsistencies during the route reconstruction phase
    - The connection setup delay is higher than in table-driven protocols
    - DSR performs well in static and low-mobility environments, but the performance degrades rapidly with increasing mobility
    - Routing overhead (proportional to the path length) is involved due to the SR mechanism employed in DSR

7. Network and Transport layers

- **Hybrid proactive/On Demand Routing Protocols**
- **Link Quality Source Routing (LQSR)**
-
  - Protocol derived from DSR
  - Combines link-state proactive routing with the reactive strategy from ad hoc networks
  - As a LS routing protocol, LQSR uses a complete view of the network topology to compute shortest paths
  - Nevertheless, LQSR uses a route discovery procedure as in reactive protocols to reduce routing overhead, which may become high because of medium instability and user mobility
  - During route discovery, LQSR obtains up-to-date link state information of the traversed links, reducing the periodicity of regular link-state advertisements.

7. Network and Transport layers

- **Hybrid proactive/On Demand Routing Protocols**
- **Hazy-Sighted Link State (HSLS)**
  - Tries to optimally balance the features of proactive, reactive, and suboptimal routing approaches
  - developed by the BBN Technologies and CUWiN Foundation ???
  - Its network overhead is theoretically optimal, utilizing both proactive and reactive link-state routing to limit network updates in space and time
  - **HSLS was made to scale well to networks of over a thousand nodes**
    - carefully designed balance of update frequency, and update extent in order to propagate link state information optimally
    - HSLS does not flood the network with link-state (LS) information to attempt to cope with moving nodes that change connections with the rest of the network.
    - HSLS does not require each node to have the same view of the network.

7. Network and Transport layers

- **Hybrid proactive/On Demand Routing Protocols**
- **Hazy-Sighted Link State (HSLS) (cont'd)**
  - Advantages
    - The HSLS strategies are blended by limiting LS updates in time and space
      - By limiting the time to live of the LS updates, the amount of transmission capacity is reduced
      - By limiting the times when a proactive routing update is transmitted, several updates can be collected and transmitted at once, also saving transmission capacity
  - Drawbacks
    - Need capable nodes with large amounts of memory to maintain routing tables.
    - It sends distant updates infrequently, so, nodes do not have recent information about whether a distant node is still present

7. Network and Transport layers

- **Hybrid Wireless Mesh Protocol (HWMP)- IEEE 802.11s draft**
- **Main characteristics :**
  - 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 nets
    - The 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

7. Network and Transport layers

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- **Hybrid Wireless Mesh Protocol (HWMP)- IEEE 802.11s draft (cont'd)**
  - **Pro-active routing**
    - is based on tree based routing: If a Root portal 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

- **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 to the originator and confirms the reverse route
  - *Route Error* (broadcast): tells receiving MPs that the originator no longer supports certain routes

7. Network and Transport layers

- **Hybrid Wireless Mesh Protocol (HWMP)- IEEE 802.11s draft (cont'd)**
- **On-demand Routing in HWMP– Key Features**
  - It 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
  - 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.

7. Network and Transport layers

- **Hybrid Wireless Mesh Protocol (HWMP)- IEEE 802.11s draft (cont'd)**
- **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"
    - MPs may respond by a unicast RREQ to the Root (answered by RREP)
    - MPs select next hop to Root based on best path metric
    - Best path propagates down from the Root
    - "Registration" of subtrees by MPs facilitates outward message routing

7. Network and Transport layers

- **Hybrid Wireless Mesh Protocol (HWMP)- IEEE 802.11s draft (cont'd)**
- **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 causes RRER to sent down. This allows nodes to decide/select own back-up paths. It signals route holders that some route is broken

- **IEEE 802.11s option:**
  - Optional Path Selection Protocol Radio Aware OLSR (RA-OLSR) which has the main characteristics :
  - Proactively maintains link-state for routing
  - Changes in link state are communicated to "neighborhood" nodes
  - Extensible routing scheme based on the two link-state routing protocols:
    - OLSR (RFC 3626)
    - (Optional) Fisheye State Routing (FSR)
  - Extended with:
    - Use of a radio aware metric in MPR selection and routing path selection
    - Efficient association discovery and dissemination protocol to support 802.11 stations

7. Network and Transport layers

- **Multi-channels and Multi-radio Routing Protocols**
- **MR-LQSR Protocol (1/3)**
  - *(R. Draves, J. Padhye, and B. Zill, "Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks," ACM MobiCom, Sept. 2004)*

  - Combination of the LQSR protocol with the metric WCETT (Weighted Cumulative Expected Transmission Time- see section about metrics)
  - Developed by Microsoft for static community wireless networks

  - Works in conjunction with the Mesh Connectivity Layer (MCL). The MCL permits higher layer applications to connect to the WMN using Wi-Fi or WiMAX. The MCL implements a L2.5 layer

  - It essentially consists of a loadable driver, acting as a virtual network adapter with the ability to multiplex several physical adapters.

  - Components:
    - 1- discovering the neighbors of a node
    - 2- assigning weights to the links a node has with its neighbors
    - 3- propagating this information to other nodes
    - 4- using the link weights to find a good path for a given destination

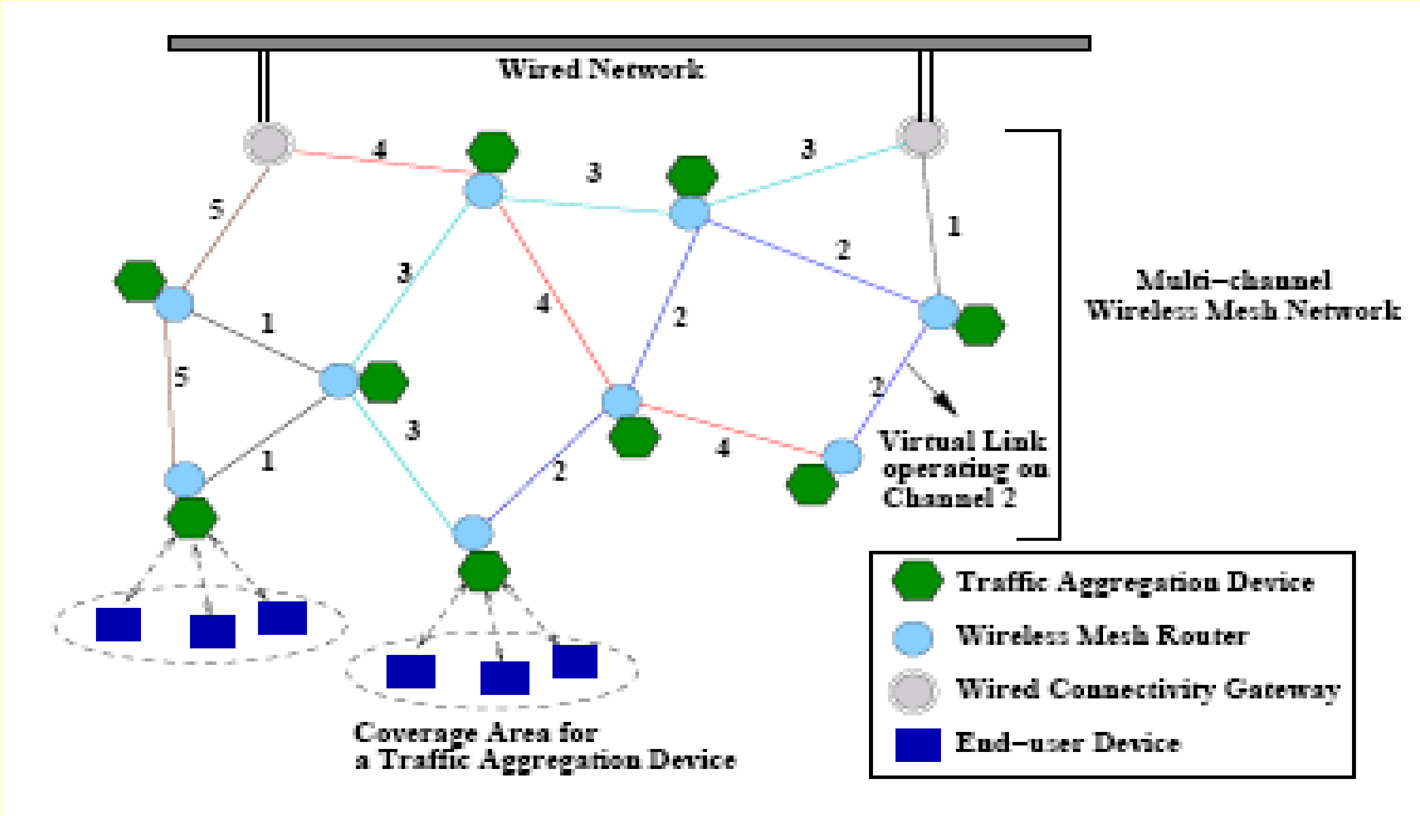
7. Network and Transport layers

Multi-channels and Multi-radio Routing Protocols

Hyacinth Protocol (1/4)

- *(A. Raniwala, et. Al., Architecture and Algorithms for an IEEE 802.11-based Multi-Channel WMN, Proc. of the 24th Annual Joint Conference of the IEEE Computer and Comm. Societies (INFOCOM)', Vol. 3, IEEE Press)*
- Multi-channel static multiple radios WMN protocol supporting a distributed channel assignment (ChA) algorithm, which can dynamically adapt to varying traffic loads
- It uses a spanning-tree (ST) based routing algorithm to load balance the network or to solve route failures
- The mesh routers (MRt) connected to the wired network are considered as the root nodes of the ST.
- The ChA algorithm breaks a single-channel collision domain into multiple collision domains, each operating on a different frequency
- It operates in two phases: *Neighbour-Interface Binding* and *Interface-ChA*

7. Network and Transport layers

- **Multi-channels and Multi-radio Routing Protocols**
- **Hyacinth Protocol (cont'd)**
  - **Raniwala A., Tzi-cker Chiueh, Architecting a High-Capacity Last-Mile Wireless Mesh Network**
  - 

7. Network and Transport layers

- **Multi-channels and Multi-radio Routing Protocol**
- **Multi-Channel Routing Protocol (MCR)**
  - Designed for dynamic WMNs, where nodes have multiple wireless interfaces, each supporting multiple channels. The protocol uses an interface switching mechanism to assign interfaces to channels.
  - Two types of interfaces: fixed and switcheable
    - In fixed interfaces, K number of interfaces, out of a total M, operate on K fixed channels
    - M-K interfaces are dynamically assigned to any of the remaining channels
    - Switching is carried out depending upon the maximum number of data packets queued for a single channel. Multiple queues are maintained for all switchable interfaces.
    - Each node maintains
      - a neighbour table (information regarding the fixed channels used by the node's neighbours)
      - and a channel usage list (the count of nodes that are using each channel as their fixed channel).

7. Network and Transport layers

- **Multi-channels and Multi-radio Routing Protocol**
- **Multi-Channel Routing Protocol (MCR)**
  - Each node periodically transmits a HELLO packet on all channels, containing the node's fixed channel number
  - Each node receiving the HELLO packet updates its neighbour table and channel usage list
  - The information from the table and list is used to control the channel and interface switching mechanism. The switching mechanism assists the MCR protocol in finding routes over multiple channels
  - MCR uses a new routing metric, which is computed as a function of
    - Channel diversity, interface switching cost and hop-counts
    - A route with a larger number of distinct channels in a route is considered to be having a lower diversity cost
    - The switching cost is used to minimize the frequent switching of wireless interfaces
  - The route discovery mechanism of MCR is similar to that of DSR

7. Network and Transport layers

- **Multi-channels and Multi-radio Routing Protocol**
- **Comparison of some recent protocols**
- Source: A.A.Pirzada, et.al., Hybrid Mesh Ad-hoc On-demand Distance Vector Routing Protocol, Queensland Research Laboratory, National ICT Australia Limited, 2007

Protocols	Research Group	Year	Type	Mobility	Derivative	Routing Metric	Remarks
Hyacinth	Stony Brook University	2005	Multi-Radio	No	Spanning Tree	Hop Count, link/path loads	Independent channel switching protocol required.
MCRP	University of Illinois, Urbana-Champaign	2004	Single-Radio	Yes	AODV	Hop Count	High speed interface switching required. Complex to handle multiple flows.
MR-LQSR	Microsoft Research	2004	Multi-Radio	No	DSR	WCETT	Proprietary Mesh Connectivity Layer. Bandwidth computed using packet probes. Requires propagation of intermediary node ETT's to source node.
MCR	University of Illinois, Urbana-Champaign	2006	Multi-Radio	Yes	DSR	Channel diversity and switching cost	Hybrid of fixed and switchable channels. Periodic distribution of channel usage lists.

7. Network and Transport layers

- **Open research issues on Network layer**
- Scalability is the most critical question in WMNs.
  - Hierarchical routing protocols can only partially solve this (complexity and difficulty of management)
  - Geographic routing need GPS or similar – high cost and complexity
    - The inquiry of destination position produces additional traffic load, thus we need new scalable routing protocols.
- Existing performance metrics incorporated into routing protocols need to be expanded.
  - Integration of multiple performance metrics into a routing protocol to increase performance
- Routing for multicast applications (many new applications need it)
- Cross-layer design between routing and MAC protocols
- Previously, routing protocol research was focused on layer-3 functionality only
  - However, performance of a routing protocol may not be satisfactory in this case
  - Adopting multiple performance metrics from layer-2 into routing protocols is an example. Interaction MAC/ routing is so close that merging certain functions of MAC and routing could be necessary

7. Network and Transport layers

- **Open research issues on Network layer (cont'd)**

- New routing protocols are needed for multi-radio or multi-channel case
  - The routing protocol not only needs to select a path in-between different nodes, it also needs to select the most appropriate channel or radio on the path
- Cross-layer design becomes a necessity because change of a routing path involves the channel or radio switching in a mesh node

- Most existing routing protocols treat all network nodes in the same way
- such solutions may not be efficient for WMNs, because the mesh routers in WMNs backbone and mesh clients have significant differences in power constraint and mobility.
  - More efficient routing protocols that take into account these differences are desired for WMNs

7. Network and Transport layers

- **Transport layer issues**
  - No generally agreed and relevant transport protocol (TP) exists to work on top WMNs (proposals exist)
  - A large number of reliable TP have been proposed for ad hoc networks:
    - TCP variants as enhanced TCP versions
    - and entirely new TP designed from a fresh start, to avoid basic TCP problems.
- **TCP variants**
  - Problem: The classical TCP performance on ad hoc and WMN degrades significantly.
  - Main reason: TCPs do not differentiate congestion and non-congestion losses
    - As a result, when non-congestion losses occur, the network throughput rapidly drops
    - After wireless channels are back to the normal operation, the TCP cannot recover quickly
  - **Proposals:**
    - Enhancing TCP through a feedback mechanism to differentiate between losses caused by congestion or wireless channels. This concept can be adopted to WMNs.
  - However, how to design a loss differentiation approach and accordingly modify the TCP for WMNs accordingly – still subject to study.

7. Network and Transport layers

- **Transport layer issues (cont'd)**
- **Link failure** degrades the TCP performance.
  - Link failures are frequent in ad hoc mobile nets
  - Less in WMNs – due to mesh infrastructure
  - To enhance TCP performance, congestion losses and link failure also need to be differentiated. Schemes similar to ECN can perform such differentiations.
- **Asymmetry issues**
  - TCP is critically dependent on ACK, so its performance is impacted by network/pathsasymmetry (TCP data and TCP ACK packets may take different paths with different loss rate, latency, or bandwidth)
  - Even if the same path, asymmetry in time can happen (the varying channel condition and bandwidth)
  - Result: TCP has poor performance for wireless multihop ad hoc networks.
  - Solving the network asymmetry:
    - Schemes such as ACK filtering, ACK congestion control, etc., have been proposed.
    - Or different network architectures – but the effectiveness of these schemes in WMNs needs investigation.
- **WMNs are rather dynamic** (especially the hybrid ones)
  - Large variations in RTT can happen -this will degrade the TCP performance (because it is based on RTT measurements)
  - Enhance a TCP to accommodate large RTT variations – open issue

7. Network and Transport layers

- **Transport open research issues**

- **Cross-layer optimization**, since
  - TCP performance degradation are mainly related to protocols in the lower layers
  - Cross layer optimization is a challenging but effective solution

- **To avoid asymmetry**
  - it is desired for a routing protocol to select an optimal path for both data and ACK packets but without increasing overhead
  - L2 performance directly impacts packet loss ratio and network asymmetry.
  - MAC layer may need to treat TCP data and ACK packets differently

- **Error control schemes** may need to be enhanced in the MAC layer
  - Restriction: enhanced TCP to have minimal impact on existing TCP (interworking needed)

- **E2E issues**
  - A network node can communicate with nodes outside of WMN.
  - In the E2E paths a mixture of wireless and wired links may exist
  - Need that enhanced TCP in WMNs work together with classical TCPs
  - Example the intermediate-layer concept of ATCP can be a solution

7. Network and Transport layers

- **Transport open research issues**
- **Integration of WMNs with various wireless networks** (802.11/16/15)
  - The characteristics of these networks may be heterogeneous due to different network capacity and L2, L3 and control behaviors protocols.
  - Such heterogeneity makes the same TCP ineffective for all networks. Applying different
  - TCPs in these networks will make the integration be complicated and costly.
  - As a consequence, proposing an adaptive TCP is the most promising solution for WMNs

  - Adaptive transport protocol is proposed for an integrated network of wireless LANs, cellular networks, Internet backbone, and satellite networks.
    - *O.B. Akan, I.F. Akyildiz, ATL: an adaptive transport layer suite for next-generation wireless internet, IEEE JSAC 22 (5) (2004) 802–817*
    - However, due to the hybrid ad hoc and infrastructure architecture, an integrated WMN is much different from the integrated network proosed above.
    - New adaptive transport protocols need to be proposed for an integrated WMN.

7. Network and Transport layers

- **Transport open research issues**
- **Integration of WMNs with various wireless networks** (802.11/16/15)

- **Real-time delivery:** no existing solution from ad hoc networks can be adopted and tailored for the use of WMNs.
  - Thus, new solutions for rate control are to be developed for WMNs
  - New loss differentiation schemes must be developed to work together with RCPs.
  - Since WMNs will be integrated with various wireless networks and the Internet, adaptive rate control protocols will be useful

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8. Cross layer optimisations

- **WMNs :**
  - variable PHY channel (capacity, bit error rate, unreliable, etc.)
  - dynamic network topology, distributed network architecture,
  - actual PHY layers are very flexible and intelligent (see 802.16e PHY), capable to change the mode and deliver to MAC a lot of useful parameters
- Classical MAC does not consider the flexible PHY capabilities
  - Result: Poor performance
- **Solution: cross-layer design/optimisation L1-L2- L3 and even towards higher layer**
  - **Cross-layer alternatives:**
  - ***1. Protocol layer L_n improve its performance by considering parameters in L_{n-1} or even other protocol layers.***
    - Example:
      - PHY bandwidth, error rate, link quality, etc. may be reported to MAC in order to incluence the modulation, coding, etc.
      - Channel assignment at MAC layer can influence the routing and vice-versa
    - This solution still keep the protocol stack essentially unaltered
  - ***2. Merge several protocols into one component***
    - e.g., L2 + L3, L1+ L2
    - more powerful solution in terms of performance, but can lead to
      - increased complexity
      - more difficult design, development, maintenance, upgrade
      - breaks the classic protocol stack principles

8. Cross layer optimisations

- **Cross-layer examples**
- Routing – Physical layers
  - Link quality feedback may help 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 smart antennas case is possible.
- Routing – MAC layers
  - 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 – Transport layers
  - 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
  - Less used : e.g. with respect of satisfying QoS constraints

8. Cross layer optimisations

- **EXAMPLE:**
- **Hybrid Mesh Ad-hoc On-demand Distance Vector Routing**
  Source: A.A.Pirzada, et.al., Hybrid Mesh Ad-hoc On-demand Distance Vector Routing Protocol Queensland Research Laboratory, National ICT Australia Limited, 2007 Protocol (AODV-HM)

  - Main ideas:
    - Make distinction between MRts and MCIs
    - Mximize the channel diversity

  - Objectives
    - 1. In a hybrid WMN AODV-HM gives preference to paths crossing mainly high capacity MRts whenever possible
      - This increases the overall throughput and reduces latency
      - Conserve the battery power of client devices
    - 2. It tries to maximize per-path channel diversity (e.g. it aims to prevent the use of the same channel on neighbouring links of an E2E path)

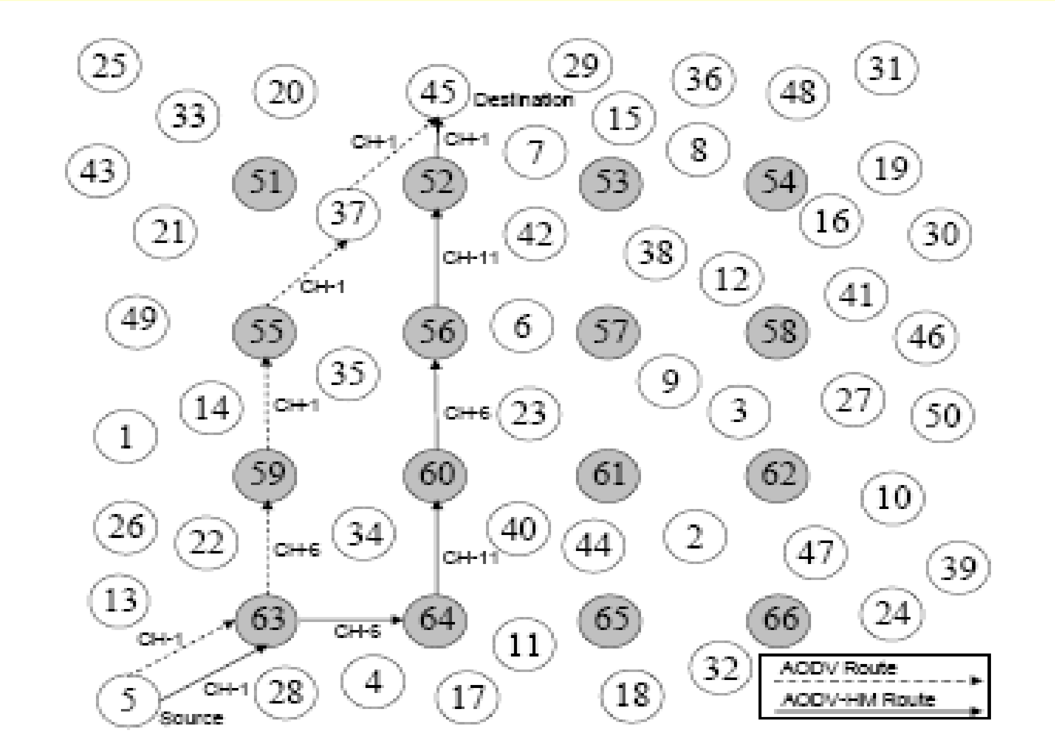
8. Cross layer optimisations

- **Example**
- **Hybrid Mesh Ad-hoc On-demand Distance Vector Routing Protocol (AODV-HM)**

- AODV-HM modifies AODV's route discovery mechanism to allow selection of paths which maximize the use of MRts and minimize the involvement of MCIs
  - These routes are more stable and provide lower latency, improved packet delivery rates and a lower control packet overhead.
  - AODV-HM integrates a channel selection scheme into AODV's route discovery mechanism which increases channel diversity of end-to-end paths.
    - This reduces interference and contention and further increases the packet delivery rate and reduces latency.

9. Cross layer optimisations

- **Cross-layer examples: AODV-HM**
  - **AODV – gives preference to routes:**
    - Having more mesh routers on paths
    - Offering more channel diversity

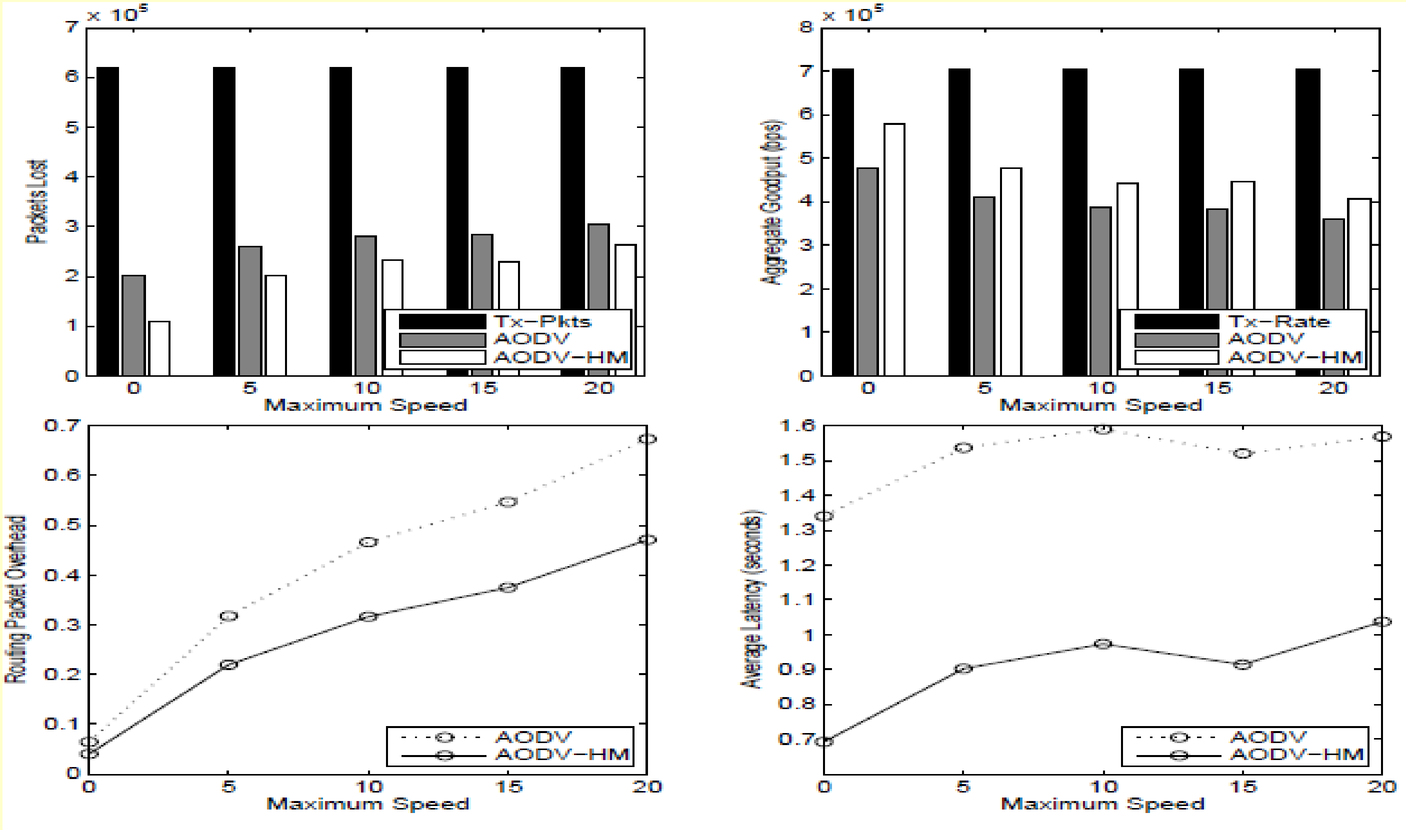


Route Development in AODV-HM

Source: A.A.Pirzada, et.al., Hybrid Mesh Ad-hoc On-demand Distance Vector Routing Protocol Queensland Research Laboratory, National ICT Australia Limited, 2007 Protocol (AODV-HM)

9. Cross layer optimisations

- **Multi-channels and Multi-radio Routing Protocols**
- **Hybrid Mesh Ad-hoc On-demand Distance Vector Routing Protocol (AODV-HM)**
  - Comparison AODV/AODV-HM (simulation, [ ])



CONTENTS

9. Mobility management

- **General issues**
- Two important tasks:
  - location management: location registration and call delivery
  - handoff management: initiation, new connection generation, and data flow control for call handoff
- The mobility management (MM) schemes developed for cellular or mobile IP could be useful for WMNs
- Problems for <u>MNs:</u>
  - the centralized scheme is generally not applicable on WMNs which are based on distributed and ad hoc architecture
  - distributed mobility management is a preferred solution for WMNs

9. Mobility management

- **General issues**
- MM schemes of ad hoc networks are of two types: *distributed and hierarchical*
  - They may not perform well for WMNs ; the backbone of WMNs does not have high mobility but connections between all MRts are wireless
  - Mesh clients may constantly roam across different mesh routers
  - These features also render the mobility management schemes for cellular networks ineffective for WMNs
  - As a result, new mobility management schemes need to be developed for WMNs

9. Mobility management

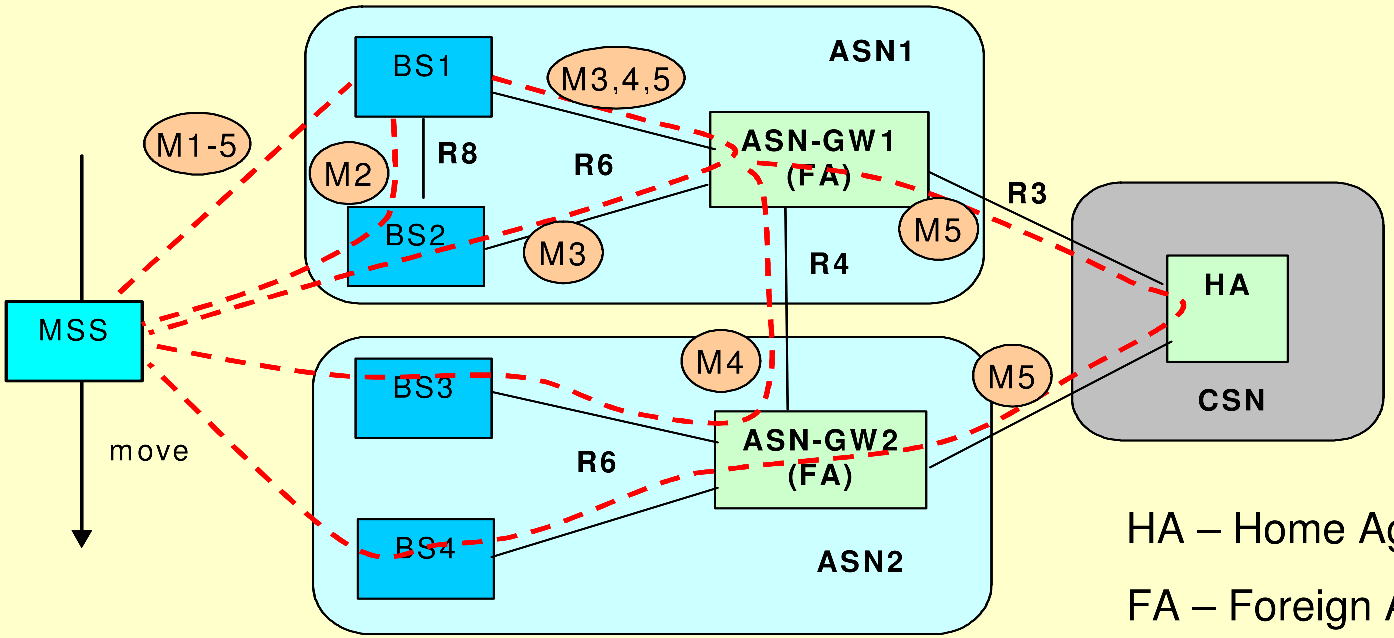
- **General issues**
- Note: For 802.16j networks (they can be considered as special cases of WMNs) the mobility is solved in the standard

- Location service is a desired feature in WMNs.
  - Location information can enhance the performance of MAC and routing protocols
  - It can help to develop promising location-related applications
  - Proposing efficient algorithms for location service is still an open research topic
  - Mobility management is closely related to multiple layers of network protocols
  - The development of multi-layer mobility management schemes is a possible approach

9. Micro and Macro-mobility

Possible 802.16/MIP mobility cases:

- M1 – intra BS – this is a micro-mobility solved "behind" a given instance of BS
- M2 – inter-BS, intra-ASN – via R8 I/F
- M3 – inter-BS, intra-ASN via R6 and ASN-GW
- M4 - inter-BS, inter-ASN via R6 , ASN-GW1, R4, ASN-GW2, R6..
- M5 – inter-BS inter-ASN plus **IP mobility (MIP v4/6)**



HA – Home Agent

FA – Foreign Agent

9. Media Independent Handover

- **Current situation on Wireless technologies evolution**
  - Multiple Wireless Technologies exist
  - More capable terminals
  - Evolving Usage Models
  - Multi-radio
- **Problems related to HO**
  - best network selection is difficult - by the mobile terminal (MT) alone - based on signal strength criteria only
  - Increasing number of interfaces on devices
    - Problem – how to leverage multiple interfaces
    - Needed – handover across different technologies
- Various fast HO mechanisms are defined in IETF and should be supported better by the L2 layers
    - MIPv4, FMIPv6
- IETF anticipated L2 constructs in standardized form
    - Triggers, events, hints etc, but former 802 docs did not provide a standard framework to use them in a media independent form

9. Media Independent Handover

- **Handover Types**
  - **Horizontal/Homogeneous**
    - Within Single Network (Localized Mobility)
      - 802.11r, 802.16e, 3GPP, 3GPP2
    - Limited opportunities
  - **Vertical/Heterogeneous**
    - Across Different Networks (plus possible Macro/Global Mobility)
    - More Opportunistic

- **Solution MIH – IEEE 802.21 (standard draft)** www.ieee802.org/21

- **Initial MIH objectives**
  - Define media independent information to enable MTs to detect and select networks effectively Develop common standard across 802 media
  - Define L2 Triggers to make Fast MIP work well
  - Define a way to transport this information and these triggers over all 802 media
- **MIH is basically targeting vertical handover but it can be used also in horizontal case**

9. Media Independent Handover

- **Initial MIH targets**
  - Define media independent information to enable MTs to detect and select networks effectively Develop common standard across 802 media
  - Define L2 Triggers to make Fast MIP work well
  - Define a way to transport this information and these triggers over all 802 media
  - 802.21 is designed for existing and evolving Networks

- **P802.21 Draft D5.2 Issue- approved in June 2007**

- **MIH benefits**
  - MIH is basically targeting vertical handover but it can be used also in horizontal case
  - IEEE 802.21 enables Co-operative Handover Decision Making
  - Facilitates:
    - optimum network selection
    - seamless roaming to maintain connections (make-before break – approach)
    - lower power operation for multi-radio devices

9. Media Independent Handover

- **MIH scope**

802.21 Scope

Handover Initiation → **Handover Preparation** → **Handover Execution**

Search New Link	Setup New Link	Transfer Connection
Network Discovery Network Selection Handover Negotiation	Layer 2 Connectivity IP Connectivity	Handover Signaling Context Transfer Packet Reception

IEEE 802.21 facilitates:
Handover Initiation,
Network Selection
Interface Activation

9. Media Independent Handover

MIH Architecture

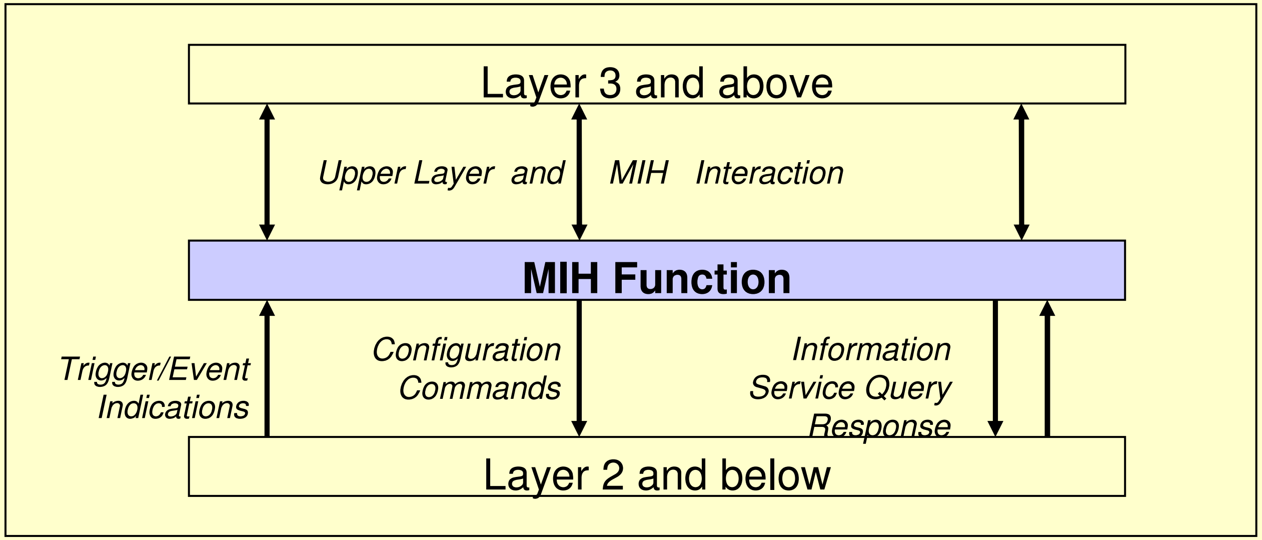
The HO is achieved through

- **MIH protocol**
  - Instantiated in MTs and network, supporting ‘hard’ or ‘soft’ HO
- **Service Access Points** (SAPs): provide the exchange of service primitives between MIH layer and adjacent layers
- **MIH function**:
  - **Media Independent Event Service**
    - provides a set of events and triggers from local and remote interfaces
  - **Media Independent Information Service**
    - collects information from different ANs and provides the MIH users with the home network directives in order to make effective handover
  - **Media Independent Command Service**
    - enables MIH user to control local link behavior related to handover
- ecision engine in MT: identifies the best available access technology for current connectivity

9. Media Independent Handover

MIH reference model

- MIH layer is placed between L2 and L3 layersMAC and PHY (IEEE interfaces) or RRC and LAC (3GPP or 3GPP2)



- MIH Function (MIHF) help Layer 3 Mobility Protocols
  - To maintain service continuity between heterogeneous interfaces
  - adaptation to QoS
  - link selection and network discovery

CONTENTS

10. Conclusions

- WMNs characteristics make them an attractive solution:
  - self-organization, flexibility
  - reduces the complexity of network deployment and maintenance, minimal investment.
  - The backbone of WMNs attractive solution for BWA and community networks
  - It enhance the reliability of the mobile ad hoc network of mesh clients.
  - Enable the integration of multiple wireless networks.
  - WMNs can be built up based on existing technologies.

10. Conclusions

- WMNs characteristics make them attractive solution:
  - Companies already have products
  - Deployments exist for various application scenarios
- Many open research issues need to be further developed:
  - Scalability, capacity
  - Self-organization and self-configuration.
  - Security
  - Network integration in E2E architectures
  - Performance, QoS for rt and multimedia applications

Thank you
Questions?

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