WIRELESS MESH NETWORKS

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1. Abstract

Wireless mesh networks (WMN) have attracted increasing attention and deployment as a high performance and low cost solution for mobile communications. Unlike traditional wireless network systems, information in WMN travels through the network by hopping from one node to another to reach its destination. There are many advantages in enabling such connectivity, including cost savings, robustness, scalability and ease of setup.

In this article, a survey of various techniques utilized for WMN deployment is made. Included are a description of various network typologies used, routing protocols, capacity issues and design trade-offs involved with WMN performance optimization. Some of the challenges still remaining for full realization of the potential with WMN will also be discussed.

2. Target Audience

This document provides a survey of various advantages of WMN, while detailing some of the performance metrics and challenges in network deployment. As such, it would be useful for technicians, contractors and wireless management interested in the potential benefits of wireless mesh networking. Although attempts were made to clarify various technical issues as they are discussed in this document, having a full understanding of some sections may require a background in mobile communication architecture and protocols. To guide the reader, the Table 1 can be used to match the target audience with the content presented.

Chapter Number	Target Audience
1 2 3 4	All Readers
5	Most Readers
6 7 8 9 10 11	Technical Readers
12	All Readers

Table 1: Target Audience

3. Introduction

Wireless information technology is experiencing a large increase in systems complexity with the advent of new wireless devices entering the market. A vast array of intelligent devices are being connected to the network, from home health care products to “smart” appliances and devices which facilitate wireless digital living rooms. In wireless “smart” homes, for example, computers, ovens, water sprinklers, door locks, air conditioners, TVs and other electronics will be connected seamlessly. In many cases, these networks will be intelligent, providing feedback and adjusting controls according to pre-defined algorithms. Communications traffic will increase exponentially as these remote devices and sensors become ubiquitous.

This explosion in the use of wireless technology will test the limits of our current network systems. Such networks consist of groups of nodes which communicate with each other wirelessly. These systems may or may not have centralized control, be time-varying (portable) and be capacity limited. Additionally, limitations will exist according to range (depending on receiver sensitivity, output power and type of modulation used), types of connectivity, compatibility, security, numbers of users and data-throughput needs. Added constraints also apply to systems of wireless sensors which have limited transmission ranges and sometimes are organized in an ad hoc fashion. A wireless sensor device may not be able to reach a central access point or another sensor to send needed information.

Outside the home, wireless networks have become essential in the success of the enterprise. Manufacturing facilities rely on wireless for inventory management, temperature and lighting control and real-time yield analysis. In hospitals doctors roam between patient rooms with laptops and smart devices while various electronic sensors and analyzers monitor patient status. The proliferation of “smart grid” technology in the generation and deployment of electrical power also employs numerous types of wireless devices, providing two-way communications between the end user and the utility.

4. Wireless Mesh Networks: A Definition

The development of such connectivity necessitates new technologies capable of meeting this demand. Wireless mesh networking is one technology hoping to fill that void. WMNs are dynamically self-organizing and self-configured. WMNs are comprised of two types of nodes, mesh routers and mesh clients. The foundation of a wireless mesh network is that there is no central device organizing the data transfers. Each wireless station is equipped with transmit and receive capabilities to act as a relay point for other wireless nodes. This allows the network to grow beyond the range and capacity of a central access point by propagating the signal through multiple hops or data transfers. In essence, each node acts as a repeater, enlarging the network based on the availability and geographic distribution of individual nodes. To further improve the flexibility of mesh networking, a router can be equipped with multiple wireless interfaces with either the same or different wireless technologies. Figure 1 below illustrates such a configuration.

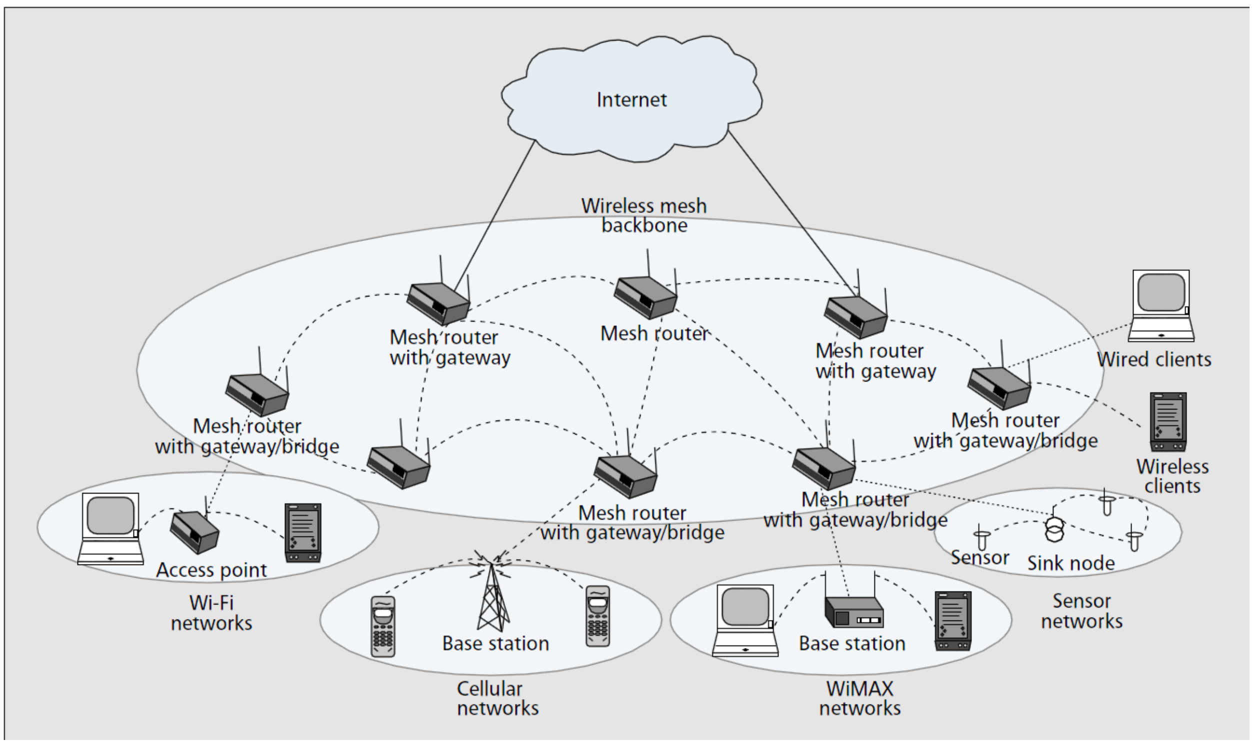


Figure 1: Generic Wireless Mesh Network using Multiple Wireless Interfaces

Source: Akyildiz Ian. "A Survey on Wireless Mesh Networks." 2004.

With sufficient intelligence and smart management configuration, wireless mesh networks can self-organize by adapting to their surrounding environment for optimizing overall data communications. Issues such as quality of service, optimal routing paths and the size and scope of networks can be adjusted real-time according to network needs, usage and capacity.

4.1 Linking the Physical and Virtual Worlds

As we move into the age of information, Information and Communications Technology (ICT) , a term used to reflect the convergence of various communications systems, has focused mainly on deploying mobile and wireless devices which connect many aspects of our daily life locally, regionally and globally. ICT stresses the role of unified communications, addressing various technologies such as telephony, audio/video processing, broadcast media and network control and sensing functions. New opportunities to fundamentally improve public services also exist using collaborative approaches that include end user participation as well as adaptive approaches by service providers to optimize and conserve resources.

As individual communication technologies have proliferated, they have become more linked together into seamless communications networks. Consumers can now program their set-top boxes, monitor home security, reserve tickets to a show and text with their friends from almost anywhere in the world or a variety of different devices. Seamless broadband communications networks are growing exponentially, where the growth is made increasingly possible by meshing together various networks of computers and communications technologies.

5. Wireless Mesh Network Advantages

Where traditional networks rely on a small number of centralized wired access point to connect users; wireless mesh networks employ nodes which “talk” to each other. A wireless mesh network can be seen as a wireless ad-hoc network employing peer to peer communication. Each node is constructed to act as a switch or router. Being programmed on how to interact within the larger network, meshed nodes relay data wirelessly from node A to node B and so forth. This obviates the need for wired access at multiple points for connections to other networks and the internet. In a wireless mesh network, only one node needs a wired physical internet connection. This wired node shares its connections with other nodes in its vicinity. Eventually, entire cities can be seamlessly covered, obviating the need for expensive wired infrastructure such as Ethernet cabling which must be routed throughout office buildings and in public areas. Although the WMN can accommodate multiple technology interfaces, this paper will focus predominately on IEEE 802.11 WLAN mesh networks. The concepts presented here are nevertheless applicable to other technologies. A generic diagram of a wireless mesh network is shown here in Figure 2.

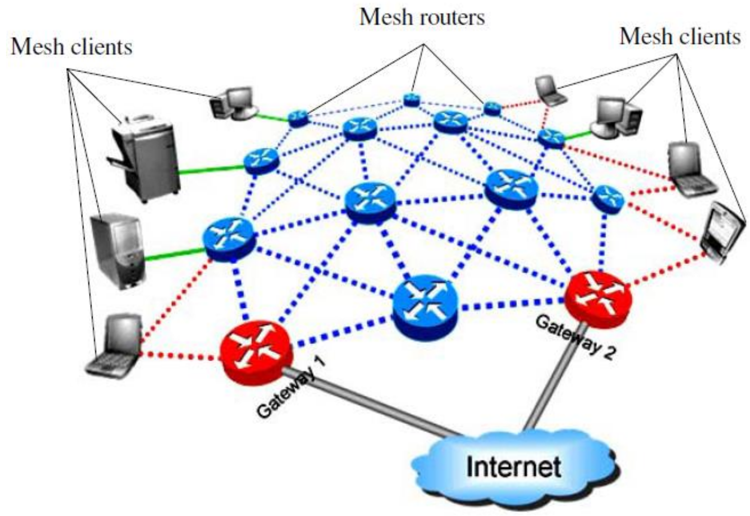


Figure 2: Generic Wireless Mesh Network
Source: Yan, Ye. "Performance Analysis of IEEE 802.11 Wireless Mesh Networks."

Advantages of wireless mesh networking include:

- Self-organizing – mesh networks automatically incorporate new nodes as they appear
- Standards – mesh networks utilize the same technologies (such as WiFi and ZigBee) already in place
- Line of Sight – wireless mesh network do not need line of sight access to other nodes to communicate
- Cost – fewer wires to install means less labor and material expense
- Range – mesh networks, by virtue of their hopping ability, can communicate with nodes far beyond their immediate vicinity
- Technology Support – wireless mesh networks support a variety of wireless radio access technologies, thereby providing the flexibility to integrate different radio access networks such as 802.16 (WiMax), 802.11 (WiFi) and 802.15 (Bluetooth and ZigBee).

- Adaptability – mesh networks can be expanded easily as the need for wireless access grows, ie the subscriber capacity of a mesh actually increases with each additional infrastructure node added
- Robustness – wireless mesh networks are self-healing where signals can be relayed through alternate paths whenever one node becomes inoperable
- Deployment – wireless mesh networks can be deployed quickly in the field for emergency relief and disaster response
- Mobility – high mobility applications involving moving vehicles, trains, etc (the key here is the ability to process inter-node handoffs for rapidly moving clients)

The greatest advantage of WMN is most likely ease of use and cost effectiveness in deployment. The coverage area is scalable with nodes constantly moving into and out of the network. WMNs also provide high redundancy, with nodes having multiple pathways to other nodes. Wireless mesh networks are also able to automatically configure itself as a network and be self-healing.

5.1 Wireless Mesh Application Areas

5.1.1 Home Networking and Digital Living Rooms

Home networking allows communications between various digital devices in the home. This includes computers, printers, mobile computing devices, smart phones and other electronic equipment. A primary initiative now for digital communications is the use of WLAN. Traditional solutions for this communication involved the use of APs. Problems with AP placement and power range have often led to coverage issues. Additionally, smart entertainment electronics such as TVs and video recorders using high-definition video have further taxed the capacity and bandwidth of AP centric networks. In the future, new initiatives such as SocialTV [28], the real time social experience of watching content together and commenting on it to others located down the street or around the world, may become increasing prevalent.

With home mesh networking, access points and routers are replaced with wireless mesh routers. In this case, each electronic device can serve as a communications node.

Information is received and passed along to the next node, enhancing coverage particularly in areas far removed from the wired network connection. Multiple examples or wireless mesh deployments exist by various manufacturers.

5.1.2 Smart Grid

Over the past decade, utilities across the world have been updating their infrastructure to what has become known as the smart grid. The smart grid is a system of two-way communications between the utility and the end user or consumer. Traditional gas and electric meters are being replaced by smart meters, equipped with wireless transceivers that can communicate to both smart devices inside the home as well as to the utility. Smart meters not only provide both the utility and consumer with real time information about energy consumption, but can also adjust energy consumption to make the system more efficient. For example, energy consumption has been known to peak during hot summer months, increasing further yet during those several hottest weeks of the summer. To meet demand, utilities must bring additional power plants on line. These additional power plants may be severely under-utilized, however, during non-peak times. By offering financial incentives to consumers to scale back consumption during peak times, utilities can save money by scaling back power plant development, passing along some of these savings to consumers.

Wireless mesh networks are increasing being used to provide the communications backbone for smart grid. Companies such as Silver Spring, Trilliant and Itron are providing meters and providing infrastructure to service this need. Technologies such as ZigBee, WLAN and others are being deployed throughout the world for smart grid communications. Mesh networking, both inside and outside the home, has been used to provide the foundation for the wireless networking involved.

5.1.3 Enterprise Networking

Enterprise networking operates anywhere from small networks in individual offices to large networks in multi-building office complexes and large university campuses. 802.11 WLAN is mostly used here, with connections being made by wired Ethernet networks. The use of wireless mesh networks eliminates these wired connections while adding robustness to the system. Nortel Wireless Mesh Network system claims to reduce the installation and commissioning costs of deploying wireless by 75 percent [29]. This involves minimizing installation costs while providing auto-configuration capabilities to eliminate the need for specialized installation practices. The self-healing nature of wireless mesh also serves to minimize service outages.

5.1.4 Building Automation

The introduction of wireless sensing devices for building automation has been growing exponentially. The use of sensors in buildings frequently uses ZigBee mesh technology to utilize its low power capabilities [30]. These sensors, equipped with wireless capabilities, monitor the physical or environmental conditions in buildings. Parameters which can be monitored include temperature, sound, vibration, pressure and humidity. Bi-directional communication with these sensors allow many industrial applications such as process monitoring and control, machine health, etc. Networks of sensors can be set up to automatically adjust lighting for the time of day, adjust humidity levels and notify appropriate personnel of security issues.

5.1.5 Neighborhood Networking

Traditional methods of network access involve each individual user obtaining their own connection to the internet (eg DSL, cable, satellite, etc). In this scenario, there is little to no coverage between houses in the neighborhood. Also, access is more expensive given each user must individually provide their own service.

Community based wireless mesh networking can overcome these disadvantages, while providing numerous benefits to the user. Mesh networking is disruptive to the current internet access scenario, which requires individual deployment. Wireless mesh allows a freer flow of information without selective rate controls or other types of restrictions [31]. Everyone in the neighborhood shares the resources which come from one connection. Data transfers will dynamically find a route, hopping from one neighbor's node to another to reach the internet. This method also provides a measure of robustness. In the case of one neighbor's node becoming defective, information traffic can be re-route across other pathways.

To realize this goal, many challenges remain for wireless mesh deployment. These include capacity issues, privacy and security, methods for creating and re-creating routing paths, auto-configuration, quality of service (QoS), etc. These and other challenges are at the forefront of research activities. We will now look into some of these technical issues and hopefully provide the reader with an understanding of the trade-offs and challenges central to the ubiquitous deployment of wireless mesh networks.

6. Wireless Mesh Architecture and Protocols

Wireless mesh networks are multi-hop wireless networks with self-healing and self-configuring capabilities. These networks consist of a set of mesh nodes interconnecting with each other wirelessly to form the backbone of the system. Many of these nodes also serve as access points for mobile users. One or more of these routing nodes function as gateways, with wired nodes connecting to the internet (and to other networks). IEEE 802.11s is a draft IEEE 802.11 amendment for mesh networking, defining how wireless devices interconnect in a WLAN mesh network. A 802.11s mesh network node or device is labeled as a Mesh Station (STA). STAs form mesh links with one another, generating multiple routing paths to other STAs as well as the central portal for the internet or other networks. An example of a generic wireless mesh network is shown here in Figure 3.

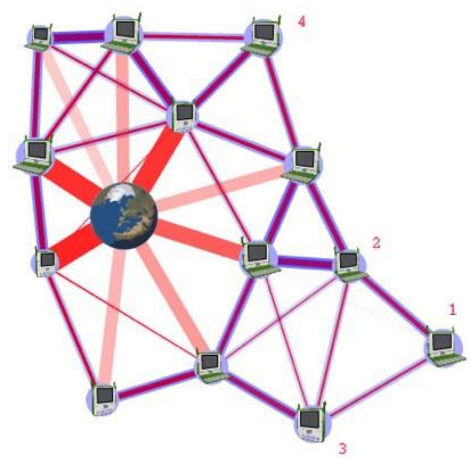


Figure 3: Generic Wireless Mesh Network

Wireless mesh configurations can be either hierarchical, flat or hybrid. A description of each typology is shown below.

6.1 Hierarchical Mesh Configuration

In hierarchical networks, mesh capable devices (typically APs) provide the networking services for other nodes that are not mesh capable. These devices associate with the mesh devices. The fixed APs form the backhaul of the network. Mesh capable devices in hierarchical networks typically have sufficient memory and computing power to control the mesh network. Since the APs are stationary, power consumption is not so much of a concern. Nodes are partitioned into groups called clusters. Clusters contain three types of nodes: cluster-head node (CH), the gateway node (GW) and cluster member (Access Router "AP"). Figure 4 illustrates this configuration.

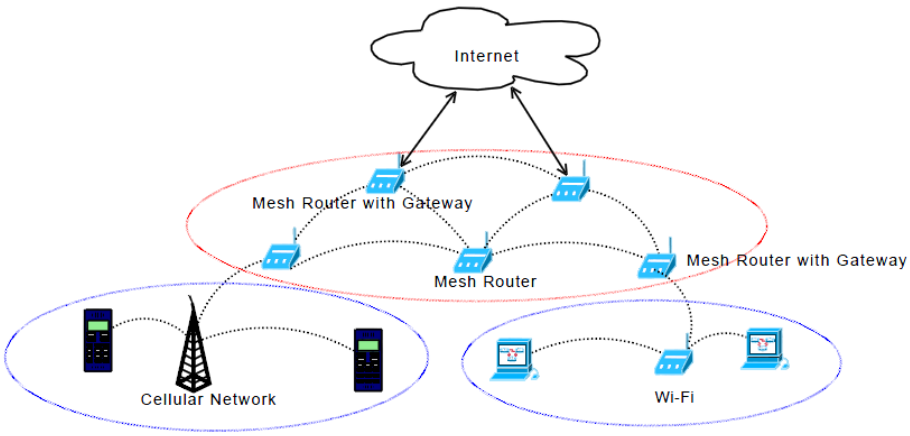


Figure 4: Hierarchical Mesh Cluster Network

Source: Powar, Yogesh. "Multimedia over Wireless and Wireless Mesh Networks." 2007

Cluster Heads have complete knowledge about group membership and their link status in the cluster. Routing schemes are optimized within each cluster as well as between the cluster heads of different networks. Various algorithms can be used in CH election. These may include neighbor connectivity, transmission power and mobility.

Gateway nodes (GW) facilitate communication within the cluster by selecting the frequencies or code used by the cluster. Gateway nodes also act as a bridge between mesh routers and the external network in order to provide services such as broadband. In a clustered system, information is gathered for the gateway that includes hop count to each gateway on the network, load on each gateway and the load on each individual node. Nodes use this information to select appropriate gateways to communicate with the external network.

6.2 *Flat Mesh Configuration*

In flat mesh configurations, all nodes share equal responsibilities. Any wireless device in the network is able to forward frames. In such networks, a device does not solely operate as a sink or source of traffic, but accepts packets not directed to itself for purposes of relaying to other nodes. The devices in such a network require path selection capabilities in order to support multi-hop traffic. In this type of configuration, client nodes constitute the actual network, performing routing and configuration functions. Being highly dynamic, flat networks are generally designed for high mobility multihop environments.

6.3 *Hybrid Mesh Configuration*

This is a combination of both infrastructure (Hierarchical cluster) and client (flat) meshing (see Figure 5). Clients access the network through mesh routers as well as through meshing with other clients. The infrastructure provides the connectivity to other networks.

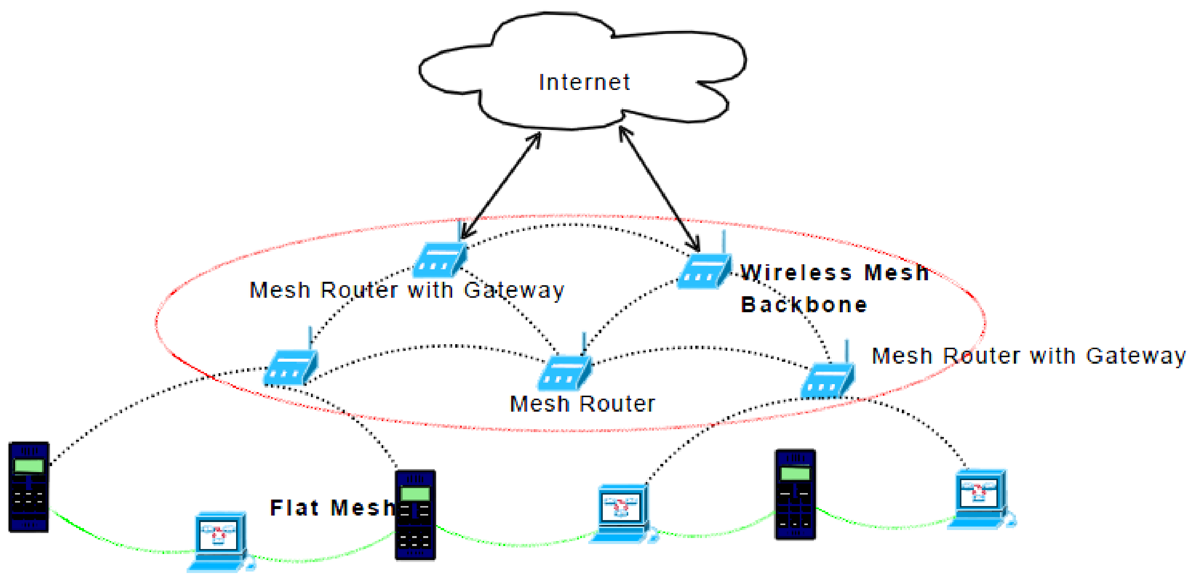


Figure 5: Wireless Mesh Network Hybrid Configuration

Source: Powar, Yogesh. "Multimedia over Wireless and Wireless Mesh Networks." 2007

7. Routing

Traffic routing plays a critical role in determining the performance of a wireless mesh network. Transmission of frames in multi-hop networks increase latencies and reduce the over throughput of data. Roaming devices, physical obstacles and interference caused by multi-path and other noise cause frequent topology changes in wireless mesh networks. Given the constantly changing nature of meshing structures with mobile devices moving into and out of the network, efficient routing algorithms need to be designed to accommodate these challenges. There are basically two ways of enhancing performance of routing protocols in WMNs. One method is by improving the metrics used in path selection. Another way is to modify the routing algorithms by considering new characteristics that may be specific for the WMN. Metrics used by routing algorithms typically utilize measurements such as hot counts, data rates, delays, signal strength, congestion status, availability of relay nodes, etc. Almost all routing protocols try to converge into the shortest path routing when possible. The advantage here is that overall energy efficiency is optimized by minimizing the path lengths or number of hops. However, if this were the only criteria for routing, then certain nodes may become disproportionally loaded. Certain links inevitably become congested. Therefore, other metrics must be utilized to insure that load balancing is achieved (often call system "fairness").

Resource utilization is a well used routing performance metric in order to minimize the use of the most congested links. Various papers exist in the literature simulating traffic congestion and optimization in wireless mesh networks. Some researchers have suggested the use of both traffic estimation and routing optimization in their protocol strategy [18]. By analyzing traffic collected at wireless APs, future traffic demand is predicted based on its historical value. Then, optimal routing strategies take the traffic demand estimations as inputs. Using simulations, it is shown that using both algorithms (congestion analysis and optimization metrics) outperform the shortest path algorithm in approximately 80% of test cases.

Routing algorithms can also be conditioned on the mobility of client nodes in the network [15]. Certain types of algorithms that are efficient in relatively static environments may be problematic in high mobility situations. Table 2 below shows a comparison between three levels of mobility as they relate to mesh networking.

	Static	Low mobility	High mobility
Discovery	Passive/active	Passive/active	Active
Routing	Infrequent updates High steady state performance	Infrequent updates High steady state performance	Frequent updates Low overhead
Security	Infrequent re-authentications, mainly for refresh	Infrequent re-authentications	Frequent re-authentications, mainly due to mobility
QoS	Slow/static mechanisms Long-term reservations	Slow mechanisms	Fast/dynamic mechanisms
Power awareness	Mainly wired connected devices	Mixed devices, wired connected dominant	Many battery-driven devices

Table 2: Mesh Networking Mobility Levels
Source: Faccin, S. "Mesh WLAN Networks: Concept and System Design." 2006

7.1 Routing Protocols: Reactive, Proactive and Hybrid

Most of the routing protocols used in WMN can be classified into reactive, proactive and hybrid routing protocols.

7.1.1. Proactive Approach

The proactive approach involves computing a priori routing information for all network nodes. Routing tables are constructed with all possible pathways in the network, regardless of the link quality. When a packet needs to be forwarded, the route is known beforehand and can be immediately used. Routing tables are maintained by each routing node. Information contained in the tables include destination addresses, next-hop addresses and the hop number to reach the destination node. Using tables, latencies are decreased as pathway information does not need to be acquired before transmission. Proactive routing may be suitable in situations where setup latencies cannot be tolerated.

One problem with proactive routing in WMN is the constantly changing nature of the network. Each node periodically sends updates of its routing table to maintain correct route information for all destinations, resulting is an extensive amount of overhead. Nodes, being mobile, are constantly coming into and out of the network, moving into different positions and changing the nodes with whom they are able to communicate. This creates the need to constantly update routing tables in real time. The routing table becomes quickly out of date and requires extensive overhead to stay relevant. This incurs the need for constant signaling of this new information, consuming power in the process. Additionally, the traffic generated in constantly updating parts of routing tables is wasted where the nodes may never utilize certain paths.

7.1.2 Reactive Approach

Reactive routing analyzes the network on an as-needed basis, eliminating the need for routing tables. When needed, the meshing node sends out queries to the network to discover a route to the destination. The destination node then replies to the source, acknowledging the pathway. Since there can be more than one routing path discovered, the destination may send back more than one path for the routing to take place. The source selects the best route, basis on criteria and metrics for optimization. Since the need for constant routing table updates is obviated in reactive routing, this method is well suited for servicing larger networks where constant updating could eventually become prohibitive. Since reactive routing requires additional time to secure the pathway information in large networks, this method should be used only when higher latencies can be tolerated. Also, stale cache information could result in issues during the route (re-route) construction phase. Reactive performance would also degrade in networks with high mobility of individual nodes.

Examples of reactive routing are Dynamic Source Routing (DSR) and Ad-hoc On-Demand Distance Vector (AODV). With DSR, the node forms a route on-demand by accumulating addresses for each device between source and destination. This information is cached by intermediate nodes along the way. Routed packets contain the addresses of each device along the way, creating high levels of overhead for long pathways. Variations of DSR provide options for packets to be forwarded on a hop-by-hop basis.

In AODV, when a node requires a connection, it broadcasts this request. The connection request is then forwarded, with each intermediate node recording its sender. This creates a system of temporary routing between source and destination. Upon receipt of the request for connection, the destination node sends a message back to the original sender. The sender can then utilize various algorithms to choose the best route available. If a link fails in the process, an error message is returned to the transmitter so that the route creation process can be repeated. With AODV, extraneous traffic overhead is minimized.

7.1.3 Hybrid Routing

A third type of routing combines elements of both proactive and reactive routing. Hybrid routing strives to adapt the type of routing used based on the specific environmental conditions observed. Situations where high latencies cannot be tolerated will employ a table driven system while large networks may use an on demand system. As networks change over time, the routing strategies can adapt accordingly. The type of routing used should be optimized according to the significance of the time duration for the source node to secure route availability. Table 3 below shows a comparison between proactive and reactive routing according to various parameters such as QoS and availability.

Parameters	On-Demand	Table-Driven
Availability of routing Information	Available when needed	Always available regardless of need
Routing philosophy	Flat	Mostly flat except for cluster switch gateway routing (CSGR)
Periodic route mobility	Not required	Yes
Coping with mobility	Using localized route discovery and in ABR and SSR	Inform other nodes to achieve consistent routing table
Signaling traffic generated	Grows with increasing mobility of active routes (as in ABR)	Greater than that of on-demand routing
QoS support	Few can support QoS	Mainly shortest path as QoS metric

Table 3. Comparison of Proactive and Reactive Routing Strategies
Source: Aggelou, George. "Wireless Mesh Networking." 2009

8. Power Conservation

Since the transmit distances for many nodes in the WMN tend to be shorter, less power is needed to communicate. However, increased overheads in routing and messaging could negate some of these power advantages without careful consideration of energy usage. With many nodes in the system operating on battery power, power conservation strategies are important. Observing various power efficiency mechanisms targeted to minimize power consumption and promote fair distribution of traffic are therefore critical in developing a mesh network. Various proposals to conserve battery life are under investigation [17].

8.1 Transmission Power Control

Transmission power influences the bit error rate, data rates and need for re-transmissions. The plot below (Figure 6) shows the probability of error of a WLAN message vs Signal to Noise ratio. The data rate used in the measurement is 11 Mbit/s.

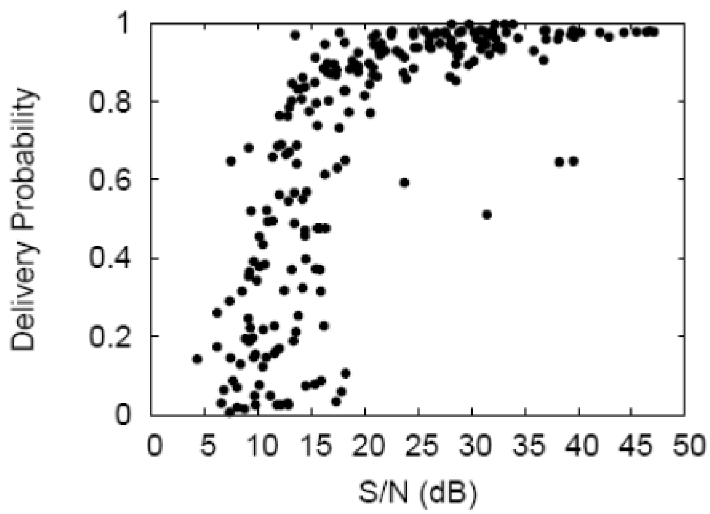


Figure 6: Probability of Error for WLAN Message vs Signal to Noise Ratio
Source: Parissidis, Georgios. "Routing Metrics for Wireless Mesh Networks."

Increasing the output power of a node improves all three parameters mentioned above at the obvious expense of power consumption. In many cases energy related objectives run counter to performance based objectives. When packets are delivered incorrectly or not at all, re-transmissions of those packets are sent at the expense of both delay and added power consumption. Strategies must be developed to optimize power consumption in a way that minimizes distortion in the system. Also, the overuse of certain nodes in the network must be avoided so that its battery power is not prematurely depleted. In such cases, measurements of the use of certain nodes in forwarding packets as well as its battery status can be important parameters in making optimal routing decisions. In error prone or high contention links, algorithms can decide on different routes to minimize power consumption. Various routing metrics have been proposed for WMN that provide algorithms with high flexibility to select best routes, compromising between data throughput, sender to receiver delay and energy consumption. Once such method is shown below.

8.2 *Power-Aware Routing*

Power aware routing has become increasing relevant with the introduction of small battery devices and sensors with limited lifetime. When under a certain threshold or in a defined state of depletion, such nodes can be removed from the network as routing vehicles. Additionally, various systems for multicasting can be developed with an objective of minimizing consumed power. Some network issues relating to power consumption is shown below in Figure 7.

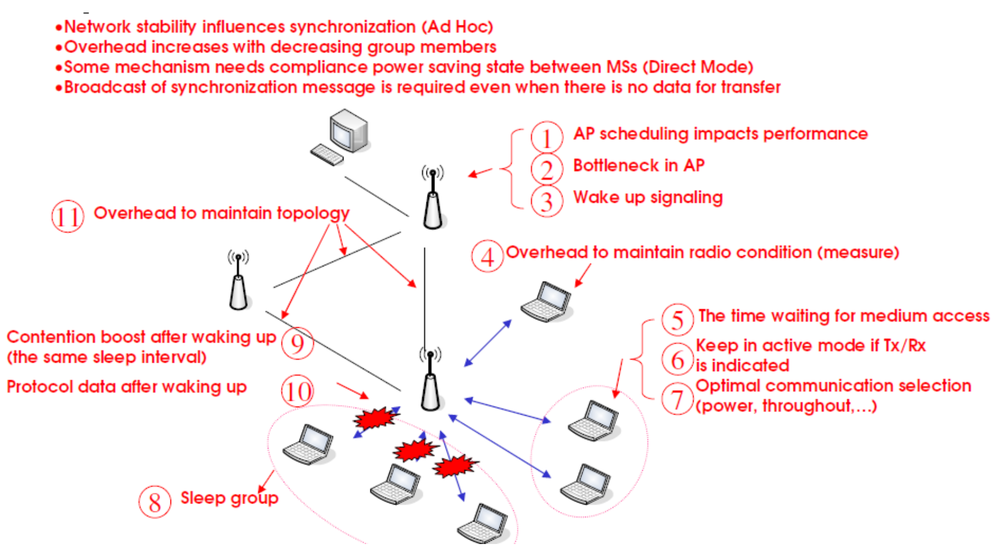


Figure 7: Overview of Power Consumption Considerations for WLAN Network
Source: Lin, Tsu-Ming. "Power Consumption Issues for WLAN Systems."

One such metric in power aware routing is Minimum Battery Cost Routing (MBCR). In this protocol, battery capacity of a node is considered as part of the routing decision. In this scenario, a cost value is assigned to each node based on its residual battery capacity. The total battery lifetime *along a path* is then the sum of the individual battery capacities along the route [32]. Figure 8 illustrates this decision process.

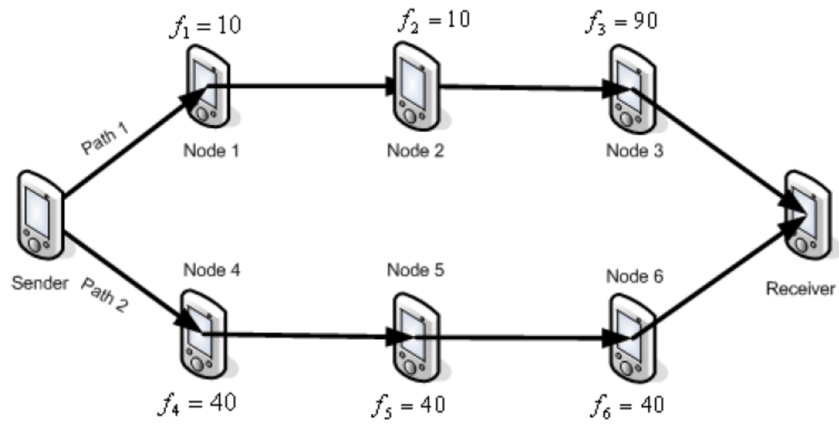


Figure 8: Minimum Battery Cost Routing (MBCR) Illustration
Source: Parissidis, Georgios. "Routing Metrics for Wireless Mesh Networks."

In this case with no further intelligence on battery status, path #1 is selected even though node 3 is almost depleted. Supplemental decision points are added to eliminate paths for consideration with residual battery charge less than 10% (for example). In this case, path #2 could be selected.

It should be noted that there is no "best" solution in power conservation. We have touched here on only a few examples of power strategies that could potentially be incorporated into the routing algorithm. Flexibility is key, ie the ability to employ various strategies given the nature of the network and the objectives that are subsequently prioritized. For example, a strong focus on power consumption (as opposed to high data rates or latency) may be more appropriate for distributed sensor networks where battery power is at a premium.

8.3 Low-Power Modes

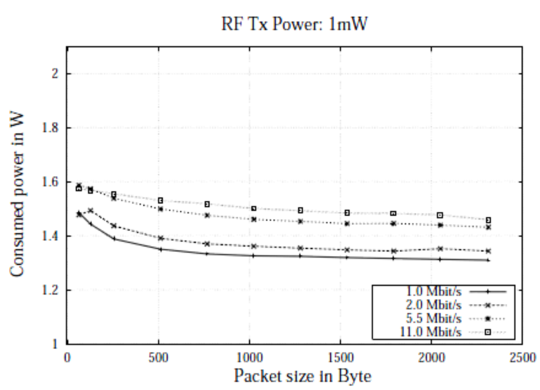
Many wireless devices have the ability to operate either in low power modes or temporarily remove themselves from the network (deep sleep). In low power mode, the node is listening for traffic but is not passing any data to the network. When in deep sleep, the wireless node is basically shut down with the exception of a low power timer that causes a periodic wake-up to transmit information or check for messages. Nodes can also choose to transmit at lower data rates to save power. A comparison of power consumptions for a generic WLAN module is shown in Table 4. We see measured powers in sleep mode, idle state and while transmitting and receiving.

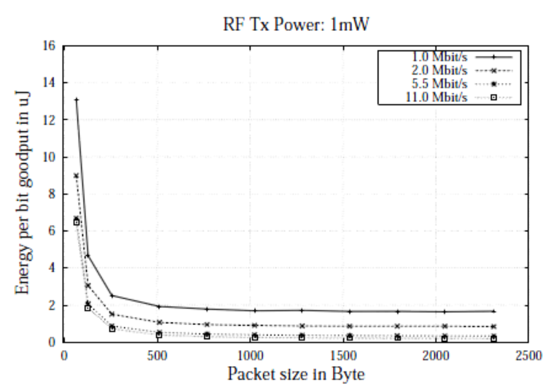
Power Consumption
in mW (V_{dd}=3V or 5V, I_{dd}=max)

IC/Mode	SLEEP	Idle	TX	RX
MAC	5	40	125	125
Baseband	2	23	33	100
IF Modem	10	10	400	500
Dual Freq. Synth.	.075	.075	40	40
RF/IF converter	.05	.05	300	100
Low noise amp.	off	35	of	35
RF power amp.	off	off	1600	off
max. total power	≈ 20	≈ 110	≈ 2500	≈ 900

Table 4: Power Consumption Breakdown for WLAN System
Source: Becker, A: "Measurement and Simulation of the Energy Consumption of an WLAN Interface." 2002

An interesting consideration for optimizing power consumption is the size of the packets being transmitted. Due to the higher overheads in transmitting small packets, one needs to consider an energy per transmitted data bit category. When more information is transferred in a frame, there is less overhead per data bit sent. The graphs below (Figure 9) illustrate this phenomenon at two different transmit power levels and one plot showing power used in receive mode. These measurements are shown as a function of packet size.





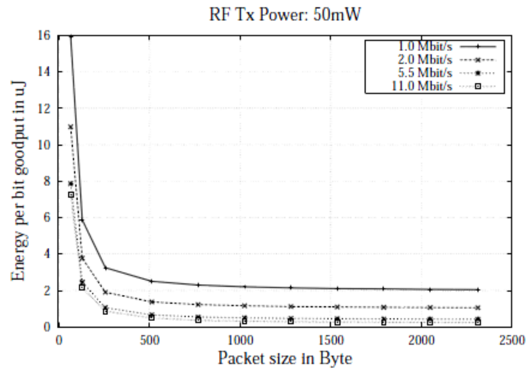


Figure 9: Energy per information bit at different power levels and packet sizes
Source: Becker, A. "Measurement and Simulation of the Energy Consumption of an WLAN Interface." 2002

9. Coverage and Scalability

The scalability of a network is its ability to support the continuous increase of the network without degrading performance. Without support for scalability, network performance degrades significantly as the network size increases. Routing protocols may not be able to find reliable pathways, connections may be lost and throughput congestion could result. Different algorithms have been proposed and various network geometries and channel usages have been considered to optimize coverage and insure scalability.

A frequency proposed approach for increasing capacity is to equip each mesh node with multiple radios which can operate on multiple channels simultaneously. Parallel wireless links between adjacent multi-radio mesh routers can be made during the pathway establishment phase. With proper protocols in place, such changes can result in a significant increase in network capacity. Metrics considered in network capacity include overall hop capacity and per node available throughput [22].

In a mesh architecture, physical changes such as increasing access point density, adding wired connections, and receivers with multiple radios/antennas can also serve to increase network capacity. In physically congested areas, multi-path fading can have a profound effect in degrading the channel. In wireless systems, signals can interact with the environment in complex ways. Interactions such as reflection from physical surfaces can create multipath signals at the receiver. Each of these bounces can introduce phase shifts, times delays, attenuation and distortion. Depending on how various signals combine, loss of signal strength can result. In diversity receive systems, problems with multipath systems are mitigated with the introduction of additional antennas spaced far enough apart so that independent (uncorrelated) signals are detected. One signal may be in a deep fade while another antenna's signal is robust. Based on performance criteria already established, the receiver then makes a decision to select the best signal. The diversity system can be enhanced further with the use of MRC, which combines more than one signal in an appropriate phasing relationship. Rather than choosing the best signal for processing, multiple signals are summed in phase to maximize the overall signal quality (highest SINR).

However, the use of multiple radios and antennas not only adds additional cost to the system, but also results in additional needs for computing power. Care must therefore be taken to use these enhancements to promote overall system performance.

In general, a more efficient network in terms of gateway placements, MAC algorithms, routing intelligence and topology design will ultimately lead to more network traffic capacity. For a truly scalable system, network topology and protocol design will need to be flexible with the ability to optimize various performance parameters as needed.

10. Medium Access Control (MAC)

The medium access control (MAC) protocol is responsible for controlling access to the physical layer while accounting for available resources. A key challenge for WMN is the requirement for developing an effective and adaptive MAC protocol for managing network resources and transferring frames. Existing MAC protocols in IEEE 802.11 networks are not optimized for WMN. MACs for the WMN must be concerned with multi-hop algorithms, distributed networks and self-organization. Additionally, the WMN must be capable of dynamically updating and optimizing routing connections, be scalable and address capacity, throughput, power, latency and coverage concerns.

In traditional IEEE 802.11 networks, a node wishing to send traffic first senses the radio carrier or NAV timer, proceeding to transmit only if the channel is idle. Called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), the system is set up to mitigate collisions from multiple nodes attempting to access the airwaves simultaneously. When sensing a busy channel, the node backs off a random amount of time before attempting another transmission. A diagram of the CSMA/CA protocols is shown here in Figure 10.

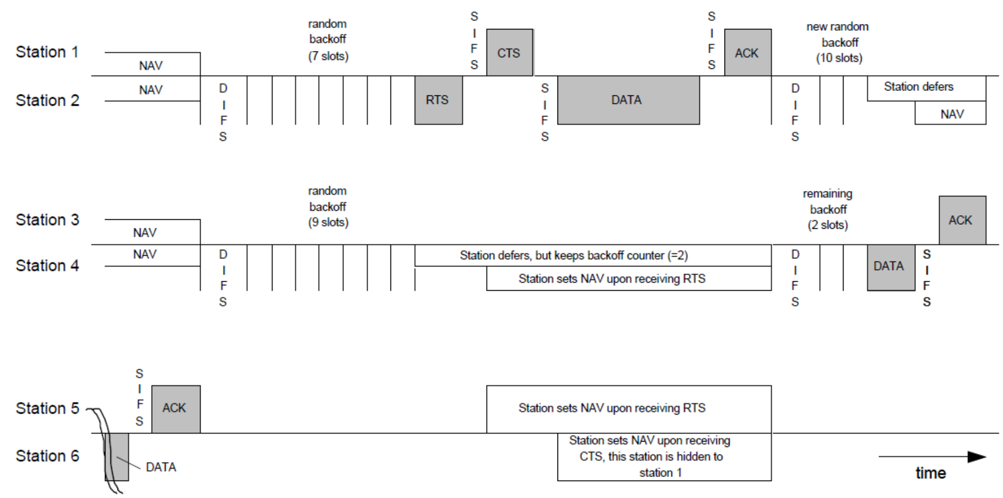


Figure 10: Overview of CSMA/CA Protocol
Source: Ergen, Mustafa. "IEEE 802.11 Tutorial."

In WMN, the distribution of the nodes in the network determines which nodes may be called up to carry more hops. Nodes located at the network's interior, for example, may be called upon to carry more multi-hop traffic than nodes at the periphery of the network. This introduces asymmetries in the traffic amount that some links may carry.

An objective of MAC implementation in WMN is to maximize network capacity. This can be accomplished by controlling the sharing range of network nodes, increasing spatial reuse, intelligently using rate control and optimizing the use of multiple channels. The sharing range is determined at both the PHY/MAC layers. Suggested MAC issues for the WMN are shown here in Figure 11.

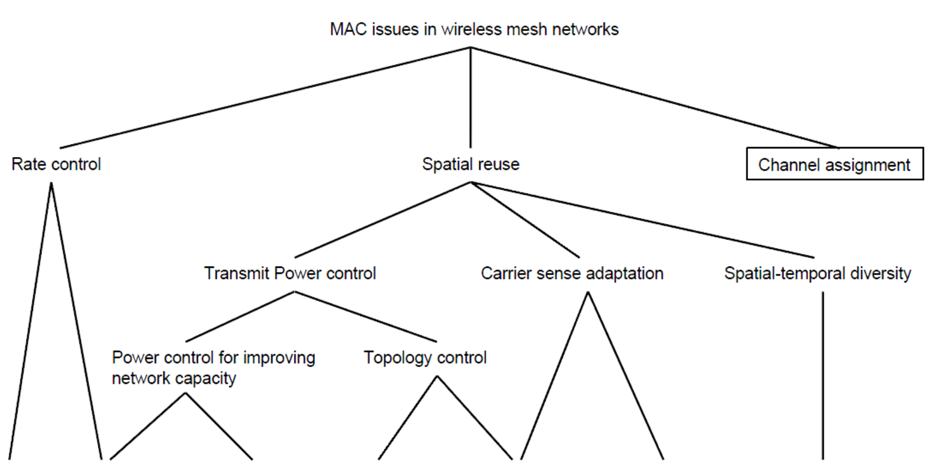


Figure 11: Issues for MAC Control

Source: Hossain, Ekram. "Wireless Mesh Networks – Architectures and Protocols." 2007

Various protocols, not shown in Figure X above, can be adjusted for network optimization. For improvements in spatial reuse, the PHY layer can be modified so nodes transmit at more/less power as conditions dictate. Spatial range can also be set by fixing the carrier sense threshold for each node. This is the level of RF power the node senses in making its decision about whether the channel is free. MATLAB simulations have been done to quantify throughput vs number of nodes with spatial reuse optimization [33]. The improvements using spatial reuse are shown here in Figure 12.

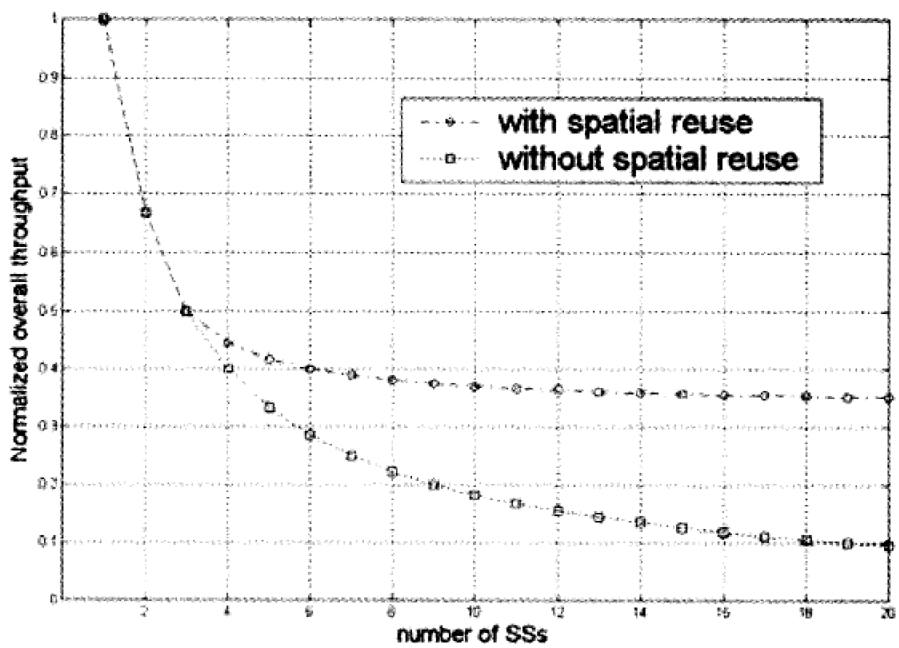


Figure 12: Spatial Reuse Simulation Results

Source: Liqun, Fu. "Spatial Reuse in IEEE 802.16 Based Wireless Mesh Networks." 2005

Specific attention to controlling power output only (PHY layer) for enhancing spatial has also resulted in noteworthy improvements. However, there is a tradeoff to be considered when adjusting output power capabilities of wireless nodes. The control of output power improves spatial reuse because it decreases radio interference between wireless links. At the same time, path length between mesh nodes is increased. Therefore, care must be taken to insure that network connectivity be preserved at some minimum level in order to insure overall performance gains in the system. Various simulations to improve special reuse with power control have been performed, showing a degree of success [8]. Other experiments have been done with the goal of minimizing transmit collisions in the WMN. One such effort involved increasing the output power of the RTS/CTS transmissions, sending these at the highest power levels whereas the data and ACK are sent at lower power levels. The goal here was to enlarge the CTS transmission range of the receiver to defer more potential interferers; however, it was found that now RTS/CTS frames themselves would cause more interference to more neighboring nodes.

Various other algorithms have also been produced for spatial reuse optimization including channel assignments in multi-radio mesh networks, use of directional antennas and exploiting wireless diversity to improve channel or spatial reuse. The use of directional antennas in specific offers some potential for connections to be made with nodes far away, thus minimizing the number of routing hops. Potentially, QoS could also be enhanced in this manner [9].

Rate Control algorithms are another important consideration in optimizing MAC efficiency for the WMN. The wireless medium, being shared and utilized by multiple radios, creates multiple impediments including interference, congestion and noise. In multi-hop systems, traffic can become congested when "optimal" pathways are over-used "Fairness" needs to be maintained such that one node is not used in such a way that bandwidth becomes restricted. Once the bandwidth of each node in the network is known, these values can be utilized as part of the route calculation decision process. Various rate control methods have been proposed to achieve network layer fairness in channel/node utilization.

One such rate control method addresses the role of distant interferers, ie nodes which may not transmit enough power to contend for a channel, but which are strong enough to contribute noise to the system. These effects degrade the SNIR (Signal to Noise and Interference Ratio) levels of the network. The problem is compounded in ISM bands where shared use can flood the system with noise. The amount that a given SNIR degrades a system is conditioned on the different data rates and modulation types used. Therefore, a node seeing a given SINR on a channel can elect to modify its data rate according to these and other considerations to optimize system effectiveness. Conversely, MAC algorithms can elect to determine forwarding pathways using nodes on channels with optimal SINR.

Congestion aware MAC protocols have been proposed which establish diverse routing pathways though the least congested areas of a WMN. An important advantage here is the ability to discover optimal routing in a distributed manner. One proposal has been made for a congestion awareness route selection method to optimize the packet delivery ratio

(ratio between packets successfully received to packets sent), routing packet overhead (ratio of control packets overhead to successfully received packets) and average latency [12]. Starting with a standard routing protocol (AODV-MR) which uses hop counts as a routing metric, congestion awareness was included (AODV-CA). By implementing algorithms accounting for congestions, simulations show improved results as shown in Figure 13.

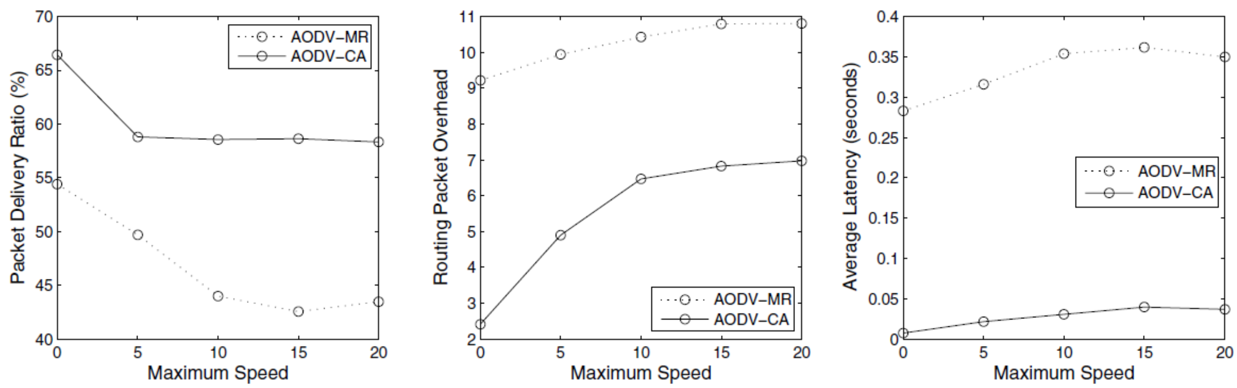


Figure 13: Congestion Aware Routing Simulation Results
Source: Asad, P. "Congestion Aware Routing in Hybrid Wireless Mesh Networks." 2007

11. Security

Security is a key issue in the design of wireless mesh networks. For each node in the network, it is essential that they be assured of end-to-end security. Security measures should be taken to avoid threats and to make the system reliable. Encryption and integrity protection mechanisms must be in place to prevent eavesdropping and modifications of the data being transmitted. For IEEE 802.1X, the Extensible Authentication Protocol (EAP) transmits authentication information to the network backbone. In a flat type of mesh network (ad hoc peer to peer system), individual nodes can authenticate other nodes in a distributed system.

In WMN, nodes can potentially be compromised due to the lack of physical protection. Attacks can come here from both inside and outside the network. Given the dynamic nature of the mesh network, frequent changes in both typology and membership occur. The trust relationship can therefore be strained between nodes as continual changes take place. Additionally, individual nodes have memory, energy and computational power constraints. This restricts the options each node has in providing security to the network. Various encryption methods must be developed to insure network integrity, accounting for the different that the WMN presents. Various security issues in the network include the following:

- Signal Jamming – at the PHY layer, attacks occurs due to jamming with interfering signals
- Resource Consumption Attack – flood network with extraneous requests
- Routing Table Overflow – attack on node routing table
- Battery Exhaustion – attacks which cause ‘sleep deprivation’ on nodes
- Impersonation Attach – use of other sender’s identity in sending traffic
- Integrity – attack which modifies the transmission in some way
- Route Maintenance Attack – attacker creates routes to nonexistent nodes
- Denial of Service – the network is flooded with requests, making the system so overwhelmed that normal traffic cannot be processed

Encryption Procedures - Hop-by-hop encryption can be used. A source node encrypts traffic at the MAC level using the encryption key it shares with an AP. The AP then decrypts the traffic and re-encrypts it using the group key, forwarding the information to the next node. When traffic reaches the destination, the information is decrypted. In this scenario, intermediate nodes are not required to decrypt/encrypt traffic which is forwarded.

In a flat (peer to peer) system, it would be optimal if individual nodes could produce digital signatures and have the capacity to check them. One node can verify the other node’s signature using public key cryptography. However, many WMN nodes may have insufficient computational complexity or power capacity to implement such as system. New types of cryptography (such as Ellliptic Curve Cryptography ECC) provides more computational and energy efficient techniques and may be suitable for some nodes [4]. Additional security methods include the Diffie-Hellman (D-H) key exchange [34]. This allows two nodes having no previous communication or knowledge of each other to jointly established shared keys.

In providing network security for WMN, it is also important that protocols be in place for misbehaving client detection. One such algorithm involves identifying the communications history between two nodes. For example, previous traffic between two clients may have moved between a common set of routers. Based on this history, an algorithm can be developed to correlate the relationship between clients to determine where a given communication falls outside the normal distribution [23]. Another proposal quantifies the interactions between network performance parameters and the potential of a security threat [35]. In this scenario, the *effects* of the attack show discrepancies between expected and actual behavior, a behavior that can be monitored.

Denial of service attacks and intrusions in wireless mesh networks can cause extensive damage to the deployed network. Although there exists many security schemes for technologies such as WLAN, most of these security solutions may not be practical or show poor performance when used in mesh networks, which lack a centralized authority to distribute public keys. New security schemes must be considered to detect intrusions and to authenticate clients

12. Summary

According to Bell Labs, by 2015 there is predicted to be 18x more smartphone devices available, 32x greater smartphone usage per urban kilometer and 30x more wireless data traffic overall. If only a fraction of this projected increase is realized, it is clear that the proliferation of wireless traffic demands more efficient approaches to accommodate this growth. An increasing popular initiative to meet these current and future needs is the development of wireless mesh networking. The promises of scalability, robustness, ability to self-organize, easy of deployment and low cost offer a great incentive for wireless providers to develop WMN. The volume of WMN research conducted so far additionally speaks to the interest and potential of this new technology.

In this paper, it is hoped that the reader has been given not only a high level overview of wireless mesh networking, but also some detail on some of the important current research issues currently being addressed. It seems clear that there may be no one method or approach for deploying WMN that would be suitable for all environments and network configurations. While there are many challenges still facing the engineering community in maximizing the WMN's potential, it seems likely that WMN has a good future in addressing our society's communication needs.

Appendix A

13. Acronyms

ACK: Acknowledge

AODV: Ad-Hoc On-Demand Distance Vector

AODV-MR: Ad-Hoc On-Demand Distance Vector, Routing Metric

AODV-CR: Ad-Hoc On-Demand Distance Vector, Congestion Awareness

AP: Access Point

CH: Cluster Head

CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

CTS: Clear to Send

D-H: Diffie-Hellman Key Exchange

DSL: Digital Subscriber Line

DSR: Dynamic Source Routing

EAP: Extensible Authentication Protocol

ECC: Elliptic Curve Cryptography

GW: Gateway Node

ICT: Information and Communications Technology

IEEE: Institute for Electrical and Electronic Engineers

MAC: Medium Access Control

MBCR: Minimum Battery Cost Routing

MRC: Maximum Ratio Combining

PHY: Physical Layer

QoS: Quality of Service

RTS: Request to Send

SINR: Signal to Noise and Interference Ratio

STA: Mesh Station

TDMA: Time Domain Multiple Access

WiFi: Wireless Fidelity (IEEE 802.11)

WMN: Wireless Mesh Network

WiMax: Worldwide Interoperability for Microwave Access (IEEE 802.16)

WLAN: Wireless Local Area Network (IEEE 802.11)

ZigBee: IEEE 802.15.4

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