Wireless Mesh Networks (WMNs)

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Abstract

Wireless Mesh Networks (WMNs) have been expected to be the ultimate solution for the next decade wireless networking. The attractions of WMNs include easy set-up on the fly, off-the-shelf cost, flexible interoperability with other networks, and highly reliable connectivity. Because of these advantages over other wireless networks, WMNs are undergoing rapid development. However, research problems still exist. This paper provides a comprehensive survey of current on-going research, academic and industrial activities for WMNs, such as cutting-edge technologies used in deploying WMNs, algorithms designed to improve the performance of WMNs. WMNs protocols and products are also presented to offer readers a broad view of WMNs.

Keywords: Wireless Mesh Network, WMNs, WiMAX, mesh architecture, metro-scale mesh wireless network, mesh test-bed, mesh product, BWA, IEEE 802.11s, IEEE 802.15.3a, IEEE 802.15.4, IEEE 802.15.5, IEEE 802.16a, IEEE 802.20.

Table of Contents

1.0 Introduction

Wireless Mesh Networks (WMNs) are comprised of two types of nodes, mesh routers and mesh clients. Mesh routers form the infrastructure backbone for clients. WMNs are multi-hop Ad-Hoc wireless networks. Compared to conventional Ad-Hoc wireless networks, WMNs contain wireless nodes, which can be either mobile or fixed. Communication in WMNs between two nodes in WMNs mostly relies on infrastructure. The majority of the traffic is user-to-gateway oriented, whereas in conventional Ad-Hoc networks, traffic is mostly user-to-user oriented. Through multi-hop communication, the same coverage area is achieved by mesh routers but with lower transmission power.

The communication between devices in WMNs is Non-Line-of-Sight (NLOS). Therefore, it is anticipated to provide a wide range of coverage. The distinctive characteristics of WMNs is the dynamic topology, which enables WMNs to be dynamically self-configuring and self-healing. In the case when one path fails, a new path will take over to maintain the network connectivity. Therefore WMNs are highly reliable. Nodes (mesh routers and mesh clients) inside the topology will be able to connect and communicate with each other. Moreover, the gateway/bridge functionalities of mesh routers makes it possible for WMNs to be able to interoperate with current existing networks, such as Wi-Fi, WiMax, Cellular Networks, and Wireless Sensor Networks (WSNs). All of these features give WMNs many irresistible attractions, such as automatic network maintenance, low establishment cost, robust and reliable service coverage.

WMNs will provide services in many areas, such as enterprise, campus, hospital, public surveillance, etc. Numerous applications can be developed using WMN technology. Many companies have already put mesh products on the market. Many WMN deployments are under construction in several cities. For example, a metro-scale Wi-Fi mesh network using Tropos Networks' MetroMesh architecture is being deployed in the City of Chaska, Minnesota. WMNs are expected to be one of the key technologies for wireless networking in the next generation.

WMNs are expected to solve the current networks' limitations and improve the performance of Wi-Fi, WPANs, WiMax, WSNs. WMNs have been undergoing wide range research and rapid development. However many problems still remain unsolved. For instance, the protocols at MAC and routing layers are not scalable; security is still a major issue in WMNs. Researchers are proposing modifications to existing protocols or designing completely new protocols. Working groups, such as IEEE 802.11, IEEE 802.15, IEEE 802.16 and IEEE 802.20 are working actively on inventing new protocols for WMNs.

The aim of this paper is to provide a survey of the state-of-the-art of WMNs as a promising future networking solution. This paper first presents the Advantageous aspects of WMNs. Then three types of system architecture are illustrated, followed by examples of real-world applications. Research work that has been done to realize or enhance the performance of WMNs are investigated, such as cutting-edge radio technology on the PHY layer, novel scheduling and routing algorithms on MAC/IP layer. And some research problems are also mentioned. Avid activities on IEEE 802.16 WiMAX are explored. Current state-of-the-art of WMNs protocols is then presented. Lastly, some academic WMN test-beds and industrial products are briefly introduced.

Back to Table of Contents

2.0 WMNs Architecture

WMNs are different from other wireless networks. Usually WMNs consist of two kinds of nodes. Based on the composition of the WMN, the WMN architecture will be classified into three types.

2.1 Types of nodes in WMNs

There are two types of nodes in WMNs [Akyildiz05], namely mesh routers and mesh clients.

Examples of mesh routers based on embedded system include PowerPC, or Advanced Risc Machine (ARM). These routers are very compact. Mesh routers can also be built upon usual computers such as laptop or home desk PC. Besides the common functionality that a wired router possesses, mesh router has its own special routing functions to support mesh networking. Mesh routers have multiple wireless interfaces, which can be built on either the same or different wireless access technologies. With the built-in gateway/bridge functionalities, mesh routers can incorporate with other types of networks.

Examples of mesh clients include laptop, Radio Frequency Identification (RFID) reader. Mesh clients have two roles: being an end client and being a router in the network. However mesh clients can only take on the minimum routing functions. For instance, gateway/bridge functions are not applicable on mesh clients. Consequently, mesh clients only have one wireless interface.

2.2 WMNs architecture

The architecture of WMNs can be grouped into three categories [Akyildiz04]: Client Architecture, Infrastructure/Backbone Architecture, and Hybrid Architecture.

Client Architecture only contains client nodes, as shown in Fig. 1. These client nodes play double roles of network routers and network end-users. No mesh routers are used in this type of networks. Client mesh architecture provides peer-to-peer communications among all the nodes in the network. This type of network is more like a conventional Ad-Hoc network since only one radio technology is usually involved. Special requirements such as software/hardware installation are needed for client nodes in WMNs, since these nodes have to perform the routing functions.

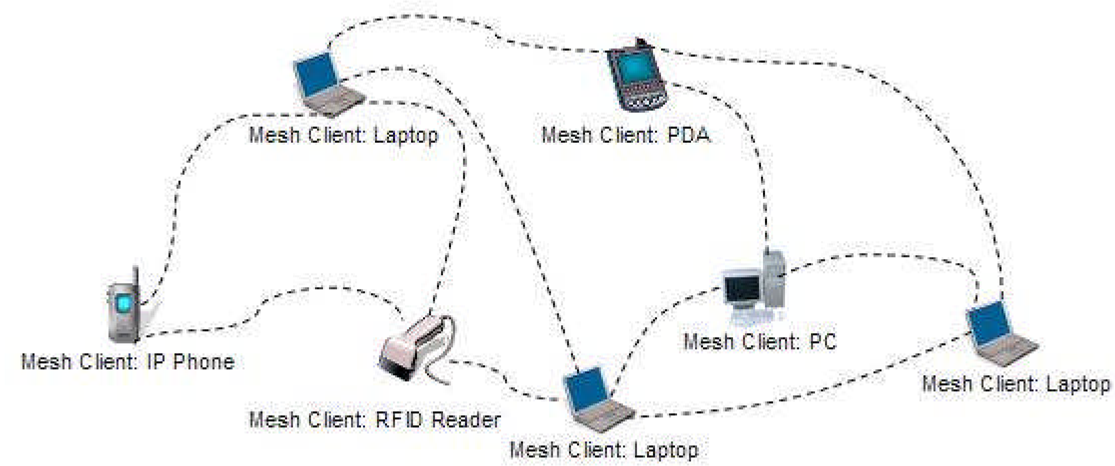

Fig. 1: Client Architecture

Infrastructure/Backbone Architecture contains both mesh routers and mesh clients nodes, as shown in Fig. 2. Mesh routers form the infrastructure backbone for clients and bring connectivity to them. Mesh routers perform functions such as routing, as well as self-configuring and self-healing. Moreover, various radio technologies, such as IEEE 802.11, IEEE 802.16, can be used with this type of meshing architecture. Hence, with the built-in gateway/bridge functionality of mesh routers, infrastructure meshing architecture provides an interface for integrating existing wireless networks. Multiple wireless interfaces are enabled in an infrastructure/Backbone architecture. Conventional clients that have Ethernet interface can be connected to mesh routers through the Ethernet interface. If the conventional client uses the same radio, then it can directly communicate with mesh routers. Otherwise, the conventional client has to communicate with its Base Station (BS) that is connected to mesh routers via Ethernet interface.

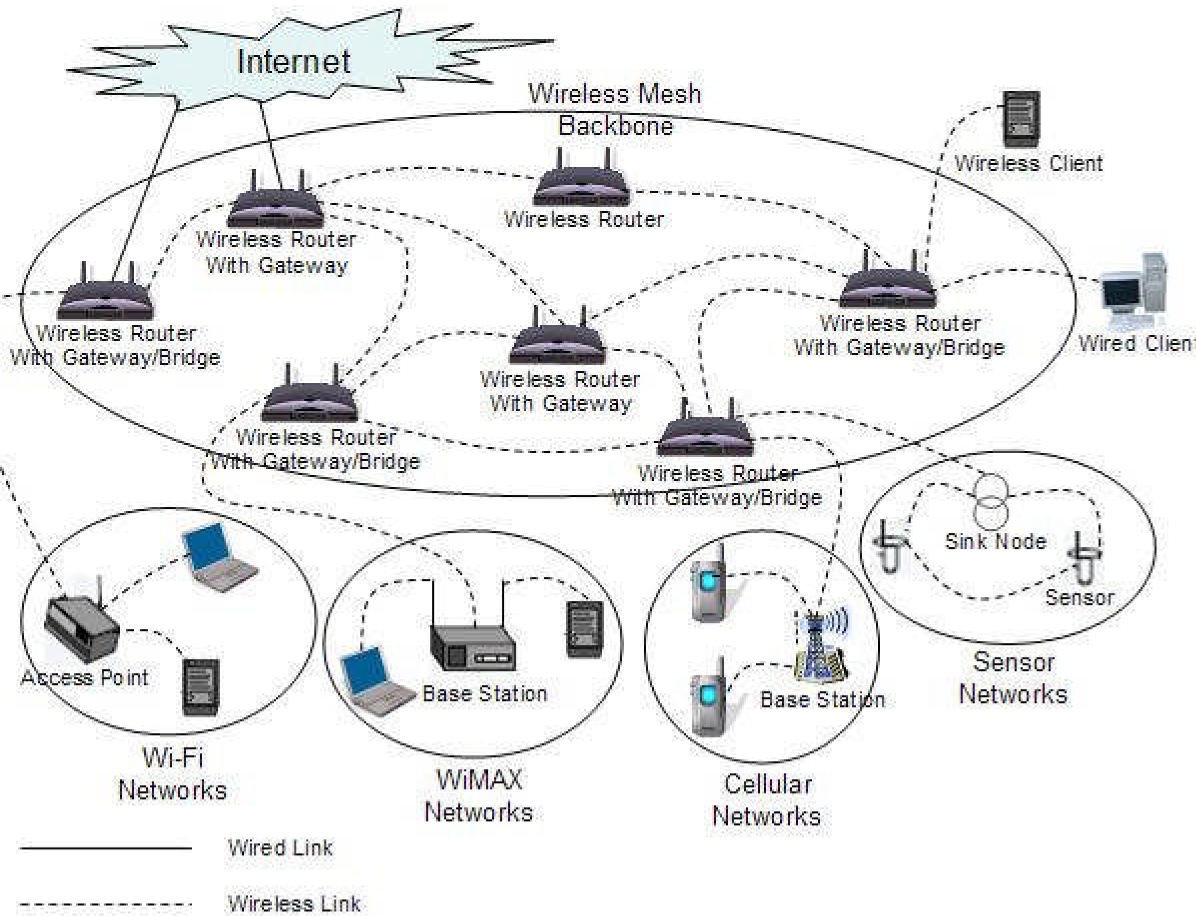

Fig. 2: Infrastructure/Backbone Architecture

Hybrid Architecture, as the name suggested, combines the above two types of meshing architecture, as shown in Fig. 3. In this type of architecture, client nodes communicate with each other via mesh routers, or via peer-to-peer among clients themselves. At the same time, the infrastructure backbone makes the connectivity possible to other existing wireless networks, such as Wi-Fi, WiMax, WPAN and WSNs. This architecture is the model for the future generation networking.

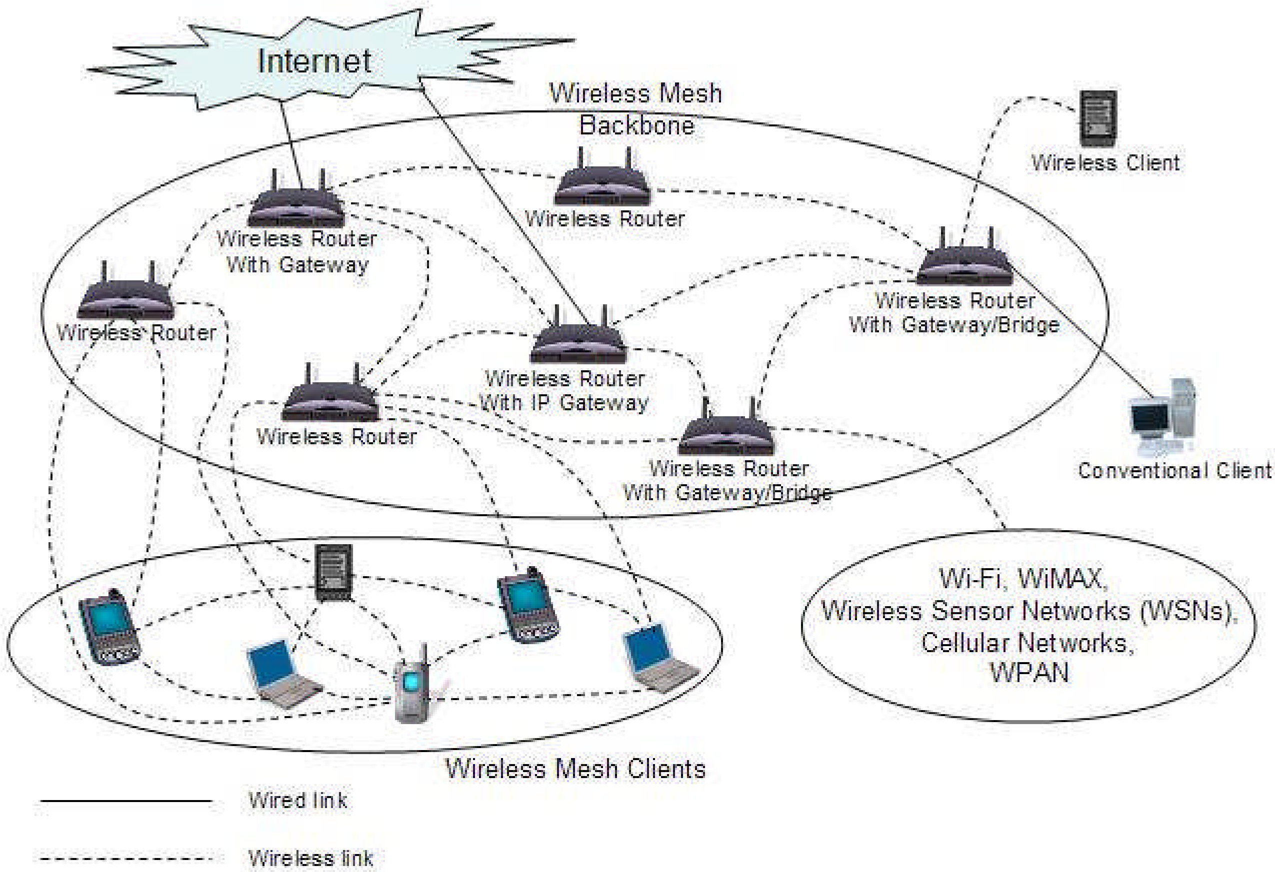

Fig. 3: Hybrid Architecture

Back to Table of Contents

3.0 Real-world WMNs applications

A variety of applications based on WMNs are emerging and some are being deployed.

One of them is broadband home networking. Current broadband home networking is implemented through IEEE 802.11 WLANs. The difficulties include dead zone without coverage and expensive multiple APs installation. Moreover, two nodes from different access points (APs) cannot communicate with each other directly, communication between them has to be done by tracing back all the way to each other's hub. With WMNs, these issues can be solved by replacing APs with wireless mesh routers and deploying more of these routers in the dead zone.

WMNs can be used to provide services for metropolitan area. There are several advantages for metropolitan area networking. First of all, the transmission rate at PHY layer is much higher than any other current cellular networks. It can be a big competition with 2.5G and 3G systems. Secondly, it is cheaper to use WMNs for broadband WiMan, comparing to wired networks of cable or optical. Lastly, larger service area can be provisioned by WMNs through NLOS and multiple hops among the nodes.

WMNs can also be used to solve the public safety issues. To-date, several WMNs are used to provide public safety applications. For example, the San Matteo Police Department in the San Francisco Bay

Area equipped all patrol cars with laptops and patrol motorcycles with PDAs, using IEEE 802.11b/g wireless cards as means for communications. The outdoor communications are realized by Tropos networks. Over 30 Tropos Wi-Fi APs are deployed throughout downtown to achieve the absolutely wide range coverage.

WMNs are ideal for building control applications. In a building, electronics devices like power, lights, elevators, air conditioner, etc., are currently controlled by wired networks. Wired networks are expensive in deployment and maintenance. With WMN technology, deployment becomes easier to handle because of the mesh connectivity among mesh routers. And the cost will be much lower too.

Other applications include transportation system, health and medical systems, and public Internet access. It is clear that WMNs are able to provide its advantageous service over other networks on many aspects.

Back to Table of Contents

4.0 Activities on WMNs

Much work has been done to realize and enhance WMNs over the past a few years. Many advances have been achieved. However critical issues of WMNs still exist. Researchers are working hard in order to overcome these difficulties. Such topics include capacity and scalability issues in mesh networks, homogeneous/heterogeneous mesh network architectures, network auto-configuration and planning solutions, inter-working between mesh networks, cross-layer design, MAC schemes, error control mechanisms, routing at IP layer, QoS support, security issues, use of advanced antenna, and broadcasting and multicasting. In order to solve these challenging issues, researchers have been making a great deal of effort to propose and design new algorithms at different layers.

4.1 Radio Technologies

Radios from current wireless networks can be used in WMNs. In recently years, many cutting edge approaches have been proposed and put into use. These wireless radio technologies combine different modulation and coding rates to support multiple transmission rates, such as Time Division Duplex (TDD), Frequency Division Duplex (FDD) or Quadrature Phase Shift Keying (QPSK). 2.5G Enhanced Data Rates for GSM Evolution (EDGE) system uses Gaussian Minimum Shift Keying (GMSK) modulation providing 3bits/Hz.

Various enhanced radio technologies have been invented. For instance, Orthogonal Frequency Division Multiple Access (OFDM) has greatly increased the speed. IEEE 802.16a has adopted this technology to provide Broadband Wireless Access (BWA) service. According to Nyquist Theorem, higher frequency increases the channel capacity. Ultra Wide Band (UWB), used in Wireless Personal Area Network (WPAN), can reach even higher data rate. But it is only for limited range of 1-10m. Further data rate enhancement can also be achieved with the aids of antennas. Popular technologies include smart antennas, directional or omni-directional antennas, multiple input multiple output (MIMO) systems and space-time coding (STC).

Newly emerging radio technologies are frequency agile/cognitive radios, reconfigurable radios, and software radios (programmable radios). A high performance network design will involve all the layers from PHY to Application. Protocols from each layer should cooperate with each to deliver the specified Qos of the network. So these will be the future PHY technology for wireless networks because they can be dynamically manipulated by higher layer protocols. However, protocols at all layers will have to be changed in order to handle these new radios.

4.2 Scheduling

Protocols at WMNs MAC layer should be modified due to the special characteristics of WMNS. There are three differences for protocols at MAC between WMNs and other wireless networks. First, WMN MAC protocol should handle communications of multiple hops. Second, due to the mesh topology, MAC protocols of WMNs is distributed. Last, WMN balancing is needed between the neighboring nodes and nodes in multi-hop distances.

Research at MAC layer is focusing on designing new strategy channel management and assignment. In WMNs, a single frequency channel or multiple channels can be used.

Most WMNs use multi-channel and multi-radio to further enhance network capacity and to improve network performance. New proposals and algorithms have been developed and tested recent a few years. [Acharya04] proposed a Request To Send/Clear To Send (RTS/CTS) based MAC protocol, named MACA-P that enables simultaneous transmission and can be used in current PHY without modifications. However, there is a performance drawback due to MACA-P's attempts at parallel transmissions. [Adya04] proposed a new protocol for IEEE 802.11. It is called Multi-radio Unification Protocol (MUP). Local spectrum usage is optimized via intelligent channel selection. MUP works with IEEE 802.11 hardware and does not require changes to applications layers. MUP also supports dynamic traffic patterns. It achieves 70% increase in throughput and 50% decrease in delay.

Besides proposing new protocols, novel channel assignment algorithms have been explored. [Tasaki04] has designed a channel assignment strategy subject to the degree of co-channel interference. [Das05] proposed an interference-concerned channel assignment scheme with the goal of maximizing the number of simultaneously active bidirectional links. However, since the experiment is designed in static WMN, it is restricted to finding a fixed channel assignment rather than a dynamic assignment. Their experiment shows that throughput can be improved by designing cross-layer protocols, such as taking into account both channel assigning and routing [Alicherry05].

In the case of single frequency channel, changes can be made by modifying existing MAC protocols, such as adjusting contention window size. Another approach is to propose new MAC protocols. [Zhao05] proposed a protocol named Wireless Channel-oriented Ad-hoc Multi-hop Broadband (W-CHAMB). It is based on Time Division Medium Access/Time Division Duplex (TDMA/TDD) in a fully distributed manner on a single frequency channel. W-CHAMB is a candidate link layer solution for IEEE 802.11.

Research has shown that new protocols or algorithms can somewhat improve the WMN performance. Yet, problems are still await to be solved, such as MAC scalability, MAC/PHY cross-layer design and interoperability with other networks at MAC layer.

4.3 Routing

WMNs routing, like other networks, relies on routing metrics. Existing routing protocols use minimum hop counts as a performance metric when selecting routing path. Given the difference between WMNs and conventional Ad-Hoc networks, modification to the existing routing protocols or invention of completely new routing protocols are imperative.

[Draves04] proposed a new metric called Weighed Cumulative Expected Transmission Time (WCETT), which aims at high-throughput path between a source and destination. WCETT is a path metric that is constructed by combining individual link metrics. WCETT takes into account both link quality and minimum hop counts. It is incorporated into a Multi-Radio Link-Quality Source Routing (MR-LQS) protocol. Significant benefits have already been shown, but they are limited on longer path, or heavily-loaded networks.

In the search for the optimal route that simultaneously satisfies more than one QoS parameters in WMNs, heuristics like random search are commonly used, but they are not effective. [Liu05] proposed a novel multi-constrained routing method named Mean Field Annealing (MFA-RS). Results show MFA-RS is comparable but faster than conventional simulated annealing methods.

Mesh routers play double roles of forming network backbone as well as forwarding packets. Routing layer should be aware of the local issues of the underlying layers. Thus cross-layer metrics approaches are explored by researchers. [Iannone04] proposed a new metric which takes three primitive physical layer parameters: Interference, Packet Success Rate, and Data Rate. The Routing algorithm aims at finding the path with low levels of generated interference, reliability in terms of Packet Success Rate, and highest possible transmission rate.

Another cross-layer protocol, Bandwidth-Aware Routing (BAR) is proposed by [Tang05]. BAR problem is formulated over dynamic traffic in the conjunction of the minimum Interference Survivable Topology Control (INSTC). Given a network topology, BAR seeks routes for QoS connection requests with bandwidth requirements. INSTC seeks a channel assignment for the given network such that the induced network topology is interference-minimum among all K-connected topologies. Comparing to the simple common channel assignment and shortest path routing approach, their results show improvement by 57% on average in terms of connection blocking ratio.

Some novel approaches, such as cooperative IP header compression technique for parallel channels [Fitzek05] is invented. It is reported to have achieved both robustness and efficiency for a wide range of errors.

Much work has been done, yet more work needs to be done in WMNs routing protocols to solve the persistent problems, especially scalability, and optimal performance metrics.

4.4 WMNs over WiMAX

IEEE 802.16 standard (WiMAX) is designed intentionally for BWA at very low cost while providing high speed, easy installation and large coverage. It is ideal for metropolitan or rural urban area. The amended IEEE 802.16a defines WMN specification, which explains the control mechanism and management messages to set up connections in WMN. In IEEE 802.16a mesh (multipoint-to-multipoint) mode, traffic can be routed through other Subscriber Stations (SSs) and can occur directly between SSs, whereas in the early version IEEE 802.16, MAC layer only supports point-to-multipoint (PMP) topology, on which traffic only occurs between BSs and SSs. IEEE 802.16a supports two types of data transmission scheduling schemes: centralized and distributed scheduling. Distributed scheduling is more suitable for the mesh mode.

The first research work ever done that theoretically investigates IEEE 802.16 mesh mode scheduling performance is carried out by [Cao05], where the simulation is not treated as PMP topology. In their experiment, a distributed scheduler at MAC layer is used. Results show that a good reservation scheme is needed to guarantee the bandwidth allocation fairness and to improve the channel utilization. A combination scheduler of both centralized and distributed manners alongside with a bandwidth allocation is used to achieve high traffic throughput [Chen05]. Results show higher concurrence rate, and reduction in nearly 50% centralized time slots than FIFO serving mode.

In order to increase the utilization of WiMAX, cross-layer protocols at MAC/IP are being studied. [Wei05] proposed an interference-aware cross-layer design to increase the throughput of the WMN, where routing is a tree-based framework, along with an interference-aware scheduler. Results show significant increase in the throughput. Another approach takes into account the degree of spatial reuse in WMN [Fu05], where a cross-layer algorithm of scheduling and routing is adopted. The maximum spatial reuse is achieved since the scheduler is aware of interference in the network. Researchers have been looking into providing end-to-end QoS over IEEE 802.16. [Shetiya05] considers providing end-to-end QoS to different flows in the network. Routing is first handled by reducing it to a tree, then a scalable centralized scheduling algorithm is used to provide per flow QoS.

Metro-scale WMNs deployment can be realized with IEEE 802.11 manners as well. For instance, WMNs in several urban environments are simulated [Sridahara05] using IEEE 802.11, Performance such as coverage, bit-rate, music streaming are evaluated. And it was found that infrastructure densitities will provide adequate coverage to outdoor nodes, while indoor nodes need much higher infrastructure densitities to get covered. Unfortunately, it was also found that infrastructure densitities proposed for urban mesh networks will not provide acceptable performance.

For years, the wildly successful WiFi wireless LAN technology has been used in BWA applications along with some proprietary based solutions. As far as capacity is concerned in terms of bandwidth and subscribers, range and a host of other issues, then WLAN approach is a great fit for indoor but probably not a great fit for outdoor BWA.

4.5 Topology and architecture

The three system architectures of WMNs enable nodes in the network to self-configure, self-organize and self-heal. Research has been done to investigate how well WMNs can perform in terms of throughput, QoS, etc. There are two approaches to design and construct a WMN. One is to carefully pre-select the layout for the network, such as where to place APs or antennas. The other is called unplanned network, which is more spontaneous, in the sense that APs are loosely connected without extensive planning or central management. Yet both of these approaches have the same of goal of providing wide service coverage and as good as possible QoS. More research has been conducted on planned WMNs since they are the common approach in practice.

Implementation in [Navda05] is an infrastructure-mode WMN. A test-bed called iMesh uses IEEE 802.11b based Access Points (APs), which also act as mesh routers to provide the wireless access routing service. iMesh is designed and evaluated with its goal of providing seamless networking service to the mobiles both for last mile access and peer-to-peer access. i.e. Clients are unaware of handoffs between layer-2 and layer-3. The involved routing issues are solved in the mesh network backbone. Two different types of routing are applied, one is a mobile IP like solution called Transparent Mobile IP and the other is a "flat"routing scheme. Results show the latter one outperforms the first one. The total latency for both layers is less than 50-100ms depending on what technique layer 2 uses.

APs layout design is examined in an infrastructure-based network by of Hisao [Hsiao05]. The problem is how to position APs in a multiple simultaneously operable WMN environment, where radio interference is inevitable. One common way is to divide the available radio into sub-channel for each network. In [Hsiao05], the whole spectrum is shared by all networks with the aid of directional antennas and by carefully arranging APs throughout the network. Results show the diagonal placement layout is optimal under the constraint that each WMN is identical 2-dimensional W|H mesh of squares with the edges of each square being of unit length.

MIT Computer Science and Artificial Intelligence (CSAI) laboratory has designed and evaluated an unplanned 802.11b WMN with a case study of the Roofnet. To carry out the experiment, unplanned nodes are placed in the network; omni-directional antennas instead of directional antennas are used; multi-hop routing, rather than single-hop BSs or APs are deployed to improve coverage and performance. The network has grown to 37 nodes during the testing, with little administrative or installation effort from researchers. And it achieved average throughput of 627 kbps between nodes. This is a realistic and powerful model in the sense that users usually can spontaneously add nodes as needed. However, the network scalability is not investigated in the experiment. [Bicket05]

A ring-based WMN using multi-channel is designed and evaluated by [Huang05]. This design is intended for outdoor applications. A distance-based rate adaptation scheme and a PHY/MAC cross-layer performance model based on CSMA with RTS/CTS are established to achieve the scalability. The best number of rings in a mesh and the optimal radius for each ring can be calculated by mixed-integer non-linear programming.

A hybrid WMN architecture for rural communication, Meghadoot [Balaji05] is designed. Impact on multi-hop relaying and constrained devices on end-to-end throughput are studied. It shows that Meghadoot performs better sometimes comparing to single-hop last mile networks.

4.6 Capacity and Performance

WMNs have drawn lots of attention since it is a rising new broadband internet access technology. Currently, WMN performance evaluation is done via simulating WMN of a particular architecture possibly with only one network technology such as IEEE 802.11.

Researches show that cross-layer design and optimization can improve the performance. Traffic balancing can also affect network performance [Wei05]. Experiments reveal that performance can be improved dramatically by traffic balancing with correct placement of APs [Tao05]. [Seo05] simulated different scenarios with varying number of gateways, different sizes of the group of users, and different transmission and carrier sensing ranges over IEEE 802.11. It is shown that network scalability is the major issue. Throughput for WMNs of each node decreases as O(1/n) [Jun03], where n is the total number of nodes in the network. Also constrained nodes will drastically bring down the performance [Balaji05].

However, these simulations could be over simplified. Innovative analytical engineering schemes need to be invented to better evaluate the capacity and performance of a WMN.

Back to Table of Contents

5.0 WMNs standards

WMNs are expected to integrate different types of wireless networks, such as Wi-Fi, WiMAX, WPAN, WSN. In order to do so, WMNs have to be able to work with different network technologies. Therefore protocols of WMNs are proposed and added to IEEE 802.11s for Wi-Fi, IEEE 802.15.1 for WPAN Bluetooth, IEEE 802.15.4 for WPAN ZigBee, IEEE 802.15.5 for all other WPANs, IEEE 802.16a for WiMAX, and IEEE 802.20 for Mobile Broadband Wireless Access (MBWA).

5.1 IEEE 802.11s

Working group IEEE 802.11s is to extend current IEEE 802.11 architecture to an extended service set (ESS) mesh, a network that will be able to self organize, and configure network topology and automatically search path. To do so, current IEEE 802.11 MAC layer needs to be extended to a wireless distribution system that supports both broadcast/multicast and unicast delivery via radio-aware metrics over self-configuring multi-hop topologies.

Currently, several different standards for IEEE 802.11s are engaging a great competition. Two major competitors are Wi-Mesh Alliance (WiMA) and SEEMesh. WiMAX is led by Nortel along with Accton Technology, ComNets, InterDigital Communications, NextHop Technologies, Philips, Extreme Networks, MITRE, Naval Research Laboratory, Swisscom Innovations and Thomson. WiMAX proposed to design WMNs to work for all three major applications of mesh technology - consumer and small business, metropolitan, and military. SEEMesh is backed by Intel, Nokia, Motorola, Texas Instruments, and NTT DoCoMo. Mesh Portals were introduced by SEEMesh group. Mesh portals offer interoperability to WMNs by allowing older or newer wireless standard technology to be recognized and incorporated into the network. However, the debate focuses on different-sized network conception, therefore it is thought to be easier to reconcile.

The ultimate goal of standardization is to form a highly interoperable IEEE 802.11 based standard to provide high speed data communication, QoS support, faster and smooth handovers. IEEE 802.11s task group is developing a new mesh standard, due for completion in 2007 [Molta05].

5.2 IEEE 802.15

Lately groups have been looking into WPAN to incorporate WMNs. IEEE 802.15 are therefore modified and amended for WMNs.

5.2.1 IEEE 802.15.3a

Two groups, MultiBand OFDM Alliance (MBOA) and Direct Sequence-UWB (DS-UWB) have competed on IEEE 802.15.3a, a protocol for high throughput for PAN with UWB. Main applications of UWB are for home networking with wireless USB extension eventually. UWB networks have many advantages such as high speed, low power consumption and affordable cost. The only shortcoming is its limited service coverage. Therefore, MBOA has proposed and added a new MAC extension protocol to IEEE 802.15.3a to adopt WMNs. Piconet structure and decentralized resource handling are used in MBOA MAC to provide service in a wider range with high speed.

5.2.2 IEEE 802.15.4

IEEE 802.15.4 is for WPAN ZigBee networks. ZigBee is designed for industrial monitoring and application control that require small amount of data and turned off most of the time. These requirements can be met by using ultra-low power and low data rate. ZigBee operates on three bands: 16 channels at 250 kbps in ISM 2.4 GHz, 10 channels at 40 kbps in ISM 915 MHz, and 1 channel at 20 kbps in European 868 MHz. ZigBee supports many topologies such as star, tree and mesh.

Research has been done to investigate wireless mesh ZigBee. [Maleysson05] simulated a WMN with its nodes in ultra low power and long range, where network configuration, power management, and performance are examined. ZigBee Alliance is working on higher level protocols that will run over PHY and MAC layers that use license-exempt bands. In a mesh ZigBee, a special node, called coordinator is needed to initiate the network setups. Due to this character, mesh ZigBee is perhaps more suitable for WSNs.

5.2.3 IEEE 802.15.5

Recently a new working group IEEE 802.15.5, the Mesh PAN Alliance (MPA) is developing protocols that will operate on short range wireless networks of mobile or fixed devices such as cell phones, laptops or PDAs. Standardization aims at protocols at PHY and MAC layers to support meshing. IEEE 802.15.5 project is to provide easier network configuration, better power management, extension communication coverage with the same low transmission power, higher throughput and fewer retransmission, and enhanced network reliability via alternative paths. Challenges remain on how to implement a lightweight meshing technology considering WPAN is a smaller wireless network with limited resources. Another issue is how to incorporate IEEE 802.15.1 Bluetooth since communication in Bluetooth is through a piconet topology.

5.3 IEEE 802.16a

IEEE 802.16a is designed to suit broadband wireless access in metropolitan area (also called last mile). It is added in 2003 to cover frequency bands in the range between 2 GHz and 11 GHz, specifying a metropolitan area networking protocol that will enable a wireless alternative for cable, DSL and T1 level services for last mile broadband access, as well as providing backhaul for 802.11 hotspots. Both PHY and MAC layer protocols are modified for WiMAX. OFDM (to support multi-path outdoors with LOS and NLOS), TDD, FDD, adaptive modulation (to maximize data rate), dynamic frequency selection (to minimize interference), advanced antenna systems, and space time coding are used in PHY layer to support BWA operation. At MAC layer, TDMA with intelligent scheduling is adopted. Interested readers may refer to WiMAX white paper for details.

IEEE 802.16a requires NLOS, which enables WMNs to be included in this standard. In mesh topology, end-users can be directly connected with each other. Communications in these direct connections could be done by either centralized scheduling or distributed scheduling. How to use TDMA based MAC protocol in a mesh network is a question. It is quite certain that some modification has to be made to accommodate that.

Commercial products compliant with IEEE 802.16a are just emerging from the market. Many products currently used in deploying metro-scale wireless networks are actually IEEE 802.11 based, for instance, Tropos MetroMesh. WiMAX forum is formed to promote and facilitate the development of BWA based wireless network [Bruno05].

5.4 IEEE 802.20

IEEE 802.20 group, established in 2002, has focus on Mobile Broadband Wireless Access. It operates on licensed band below 3.5 GHz, and aims at delivering data rate over 1 Mbps. It strives for optimization of IP data transport, and therefore it is a competitor with IEEE 802.16e. The 802.20 project also intends to support WMNs in both indoor and outdoor environment. A draft 802.20 specification was balloted and approved on January 18th, 2006.

Back to Table of Contents

6.0 Academic WMNs test-beds

Many academic research test-beds have been established and actively tested to further the development of WMNs.

6.1 MIT Roofnet

Roofnet is an experimental multi-hop IEEE 802.11b/g mesh test-bed providing broadband internet access to Cambridge, MA. There are about 20 active nodes in the network. The major feature of Roofnet is that it is non-configuration and unplanned. The on-going research includes link-level measurements of 802.11, finding high-throughput routes in the face of lossy links, adaptive bit-rate selection, and developing new protocols which take advantage of radio's unique properties.

6.2 Georgia Institute of Technology BWN-Mesh

BWN-Mesh is a mesh test-bed at Broadband and Wireless Network (BWN) Lab at Georgia Institute of Technology. BWN-Mesh consists of 15 IEEE 802.11 b/g mesh routers, some of which are connected via gateway/bridge to other future generation test-beds, e.g. wireless sensor networks (WSNs). Other nodes residing in BWN-Mesh are laptops and desktops. They are exploring factors such as router distance, backhaul placement, and topology with mobility. They are developing and evaluating adaptive protocols at MAC, IP and transport layers. Another goal of BWN-Mesh is to integrate with other networks, such as Wi-Fi, WiMAX, Cellular networks, and WSNs. BWN-Mesh is working towards the next generation network architecture: heterogeneous network that combines different types of wireless networks with different protocols.

6.3 State University of New York: Hyacinth

Hyacinth is a test-bed at Experimental Computer Systems Lab (ECSL) Lab at State University of New York. In Hyacinth, each node uses multiple IEEE 802.11 radios. So Hyacinth is a multi-channel WMN. Experiments focus on the design of interface channel assignment and packet routing. The idea is that during the communication between two nodes, a common channel will be used; when more nodes get involved in, using the same channel will cause great interference within the range therefore different channel should be assigned accordingly. An intelligent channel assignment employing both centralized and distributed algorithm is proposed and tested to assign channels dynamically and to route packets. Hyacinth is intended to be readily built using IEEE 802.11 a/b/g, and 802.16a technology.

Another test-bed example is CalRadio 1 and CalRadio 2 at California Institute for Telecommunications and Information Technology with its goal of developing and providing wireless development platforms. There are many other academic test-beds being designed and developed, with the same goal of solving difficulties and enhancing performance for current WMNs.

Back to Table of Contents

7.0 Industrial WMNs products

Many companies throughout the world have explored WMNs and have put products into real-world deployment.

7.1 U.S. Companies

- MeshNetworks, bought by Motorola, is devoted on mobile broadband internet access, which provides high speed access to mobile users. MeshNetworks provides progressive solutions, such as Quad-Division Multiple Access (QDMA) radio technology, adaptive transmission protocol, etc.
- SkyPilot Networks provides broadband internet access using WMNs. Features include eight directional antennas, high power radios, dynamic bandwidth scheduling, etc.
- Tropos Networks has been a leader in metro-scale Wi-Fi mesh networking. They strive to bring high speed, affordable broadband data communication via their trademark MetroMesh architecture and MetroMesh router. They provide services such as VOIP, metro-scale network, with emphasis on throughput, mobility and security. Many cities, such as San Francisco, Chaska in Minnesota, have adopted Tropos solutions.
- Hawaii and California Silicon Valley based Firetide provides applications on indoors and outdoors Layer 2 connectivity. It offers products with 2.4GHz and 5GHz radio technologies, with Advanced Encryption Standard (AES), Wired Equivalent Privacy (WEP) security measures, and network management software.
- Intel has been conducting research on WMNs since 2002. Their Berkeley Research Lab has been focused on issues such low power and traffic balancing.
- California based Kiyon make WMNs equipment for indoor networks using IEEE 802.11. Features include network management software and enhanced custom routing algorithms.
- California based Mesh Dynamics provides variety of products for indoor, outdoor, metro, VOIP, and video. They use multiple RFs, and dynamic channel assignment is employed.
- Microsoft has been focusing on community WMNs. Their software, called Mesh Connectivity Layer (MCL) aims at routing and link quality. Modifications are transparent to other layers.

Other companies, like Nortel, B&B Electronics Manufacturing Company,Packet Hop, Ricochet Networks, Strix Systems, and SkyPilot Networks also offer exciting products with cutting-edge technologies.

7.2 UK Companies

- LamTech, formally known as Radiant Networks, focuses on broadband internet access. Their trademark product, MESHWORK uses Asynchronous Transfer Mode (ATM) switching in wireless routing, four directional mobile antennas therefore making links directional. The speed could be up to 90Mbps, offering Qos of Constant Bit Rate (CBR), Variable Bit Rate (VBR).
- NOW.co.uk, a division of the NOW Wireless group, offers two mesh product lines: Mesh Enabled Architecture (MEA) and MeshLAN. The former one uses MeshNetworks' proprietary QDMA radio protocol to provide Mobile Broadband solution. The latter one is Multi-Hopping 802.11b networking solution that uses an industry standard 802.11b radio protocol. Both of them use Direct Sequence Spread Spectrum (DSSS) over ISM II 2.4GHz band.
- Locust World focuses on community networking, featuring MeshAP hardware.

Back to Table of Contents

Summary

Wireless mesh networking is still a fairly new technology. Its special mesh topology makes it outstanding from other existing wireless networks. WMNs consist of nodes of both mesh routers and mesh clients. The three fundamental networking architectures make it possible for WMNs to be self-organizing, self-configuring and self-healing.

WMNs extends conventional Ad-Hoc multi-hop wireless network to a new concept. While nodes inside WMN can communicate with each other among either mesh router or mesh clients, nodes can also communicate with other nodes in other wireless networks of different types. This is done via mesh routers with built-in gateway/bridge functionalities. Advantages of WMNs include low cost, highly reliable coverage, automatic network maintenance, robustness, and flexibility. WMN technology inspires many applications, such as broadband home networking, community networking, metropolitan networking, public safety, and inter-vehicular communication.

Much work has been carried out to fulfill the expectation and enhance the performance. However, research problems still remain. Among them, scalability and security are of most significant importance. It is no doubt more and more research will be devoted to solving these problems. Numerous companies throughout the world provide extraordinary meshing products. These impressive products make it possible for many undergoing WMNs deployments. Different standards for WMNs are proposed and drafted to target different network environment. These standardizations are still on the way. And there will be some time before these standardizations to be finalized.

All in one, WMNs will provide flexibility to integrate a variety of wireless radio and access technologies such Wi-Fi, WiMAX, WPAN, and Cellular networks, into one unified environment. WMN is a key enabling technology for the next generation networking.

Back to Table of Contents

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Back to Table of Contents

List of Acronyms

AES	Advanced Encryption Standard
ATM	Asynchronous Transfer Mode
APs	Access Points
ATM	Advanced Encryption Standard
BWA	Broadband Wireless Access
BWN	Broadband and Wireless Network
CBR	Constant Bit Rate
DSSS	Direct Sequence Spread Spectrum
DS-UWB	Direct Sequence-Ultra Wide Band
EDGE	Enhanced Data Rates for GSM Evolution
FDD	Frequency Division Duplex
FIFO	First In First Out
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile Communication
LOS	Line of Sight
MAC	Media Access Control layer
MCL	Mesh Connectivity Layer
MIMO	Multiple Input Multiple Output
MBWA	Mobile Broadband Wireless Access
MBOA	MultiBand OFDM Alliance
NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Multiple Access
PHY	Physical layer

PMP	Point to Multiple Point
QDMA	Quad-Division Multiple Access
Qos	Quality of service
QPSK	Quadrature Phase Shift Keying
RFID	Radio Frequency Identification
RTS/CTS	Request To Send/Clear To Send
STC	Space-Time Coding
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UWB	Ultra Wide Band
VBR	Variable Bit Rate
VOIP	Void Over IP
WEP	Wired Equivalent Privacy
WMN	Wireless Mesh Network
WSN	Wireless Sensor Networks

Back to Table of Contents

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