CHAPTER 1

INTRODUCTION

1.1 OVERVIEW OF WMNS

Wireless mesh network (WMN) is a powerful technology that has the capacity to provide wireless LAN coverage, Broadband internet access, and network connectivity for network operators and end users at low price. WMNs are communication networks that have increasingly attracted Internet Service Providers (ISPs) recently because of its speedy growing and developing of wireless technologies.

WMN is a promising technology in providing high bandwidth network coverage. WMNs will really help the users to be always on-line anywhere anytime by connecting to wireless mesh routers. Moreover, the mesh routers have the bridge functionality to connect WMNs with various existing wireless networks such as wireless-fidelity (Wi-Fi), wireless sensor, cellular, worldwide interoperability for microwave access (WiMAX) and WiMedia networks.

WMNs will distribute wireless services for a huge variety of applications. Wireless networks can be classified based on the connectivity types of the various network elements, which are either Point to Point (PTP), Point to Multi-Point (PTM) or Multi-Point to Multi-Point (MPM) networks. The complete taxonomy of this classification is shown in Fig. 1.1. PTP networks are reliable. However, they are not scalable and their level of adaptability is low. PTM networks are
moderately scalable, but they have low flexibility and reliability. In order to overcome these limitations, Multi-point to Multi-point (MTM) networks are offering features that provide high reliability, scalability and adaptability to hold a large number of users. As the number of nodes in the network increases, the transmission power needed for each node will be reduced. But, MTM wireless networks use multiple hops to increase coverage without the need for increasing the transmission power. MTM wireless networks are using today’s standard like the IEEE 802.11 family. These types of networks are called mesh networks.

**Advantages of WMNS**

**Self Organizing and Self Configuring**

WMNs are adaptable in network architecture and do not depend on the implementation and the protocols. Self-configuring and self-healing are the WMNs features. This reduces the set-up time and maintenance cost and also it enhances the performance of the network. Due to these features, the network service providers are able to change, expand, and adapt the network as required to meet the request of the end users.

**Low Deployment Cost**

Mesh routers are wireless and they have the capacity to service in multi-hop environments. Thus, using wireless routers in large areas are cheaper compared to single hop routers/access points that they
have wired connections. Typically, due to wired connections that are more expensive to install and maintain, the WMNs deployment with easier plus faster installation and maintenance, leads to a lower operation cost.

**Increased Reliability**

In a WMN there are multiple paths from source to destination nodes. This provides alternate paths in case of failure. Alternate paths may be chosen, in order to minimize the bottlenecks in congested area of the network too. This also allows the traffic loads to be balanced in the network. Load balancing and minimizing the bottleneck via alternate routing can significantly increase network reliability in WMNs.

**Scalability**

In traditional wireless networks, when the number of nodes increases, the network performance will be affected downward. But, in WMNs, increasing the number of nodes will increase transmission capacity for better load balancing and alternate routes. Usually, the local packets (generated in clients of mesh router) run faster compared to packets (generated in two or more hops away) from the neighbors. This is mainly achievable using some WMNs configurations and protocols that manage the communication medium.
**Fig. 1.1 Wireless Mesh Networks Classification**

**Interoperability**

WMN has a hybrid multi-point to multi-point architecture which is compatible with existing standards such as: WiMAX, Cellular, Wi-Fi, Zigbee, Bluetooth, Sensor, MANET, Vehicular, etc. Thus, it is attractive for incremental deployment and reuse of existing infrastructures. All technologies mentioned above are able or will be able soon to configure a WMN and communicate with each other. Most of necessary improvements needed in any type of networks are to enable them communicate with each other and can augment the current standards to maintain interoperability.
**Academic Supporting and Industry Standards**

Many universities have ongoing research projects on various aspects of WMN, including strategic planning, protocols, applications and services. Several communities already use WMN such as: Chaska, Minnesota and Rio Rancho, New Mexico; also many companies including: BelAir Networks, Cisco Systems, Firetide, Mesh Dynamics, Motorola, Nortel Networks, Packet Hop and Strix Systems, etc., have started to provide equipment and technologies for mesh networks.

**Characteristics of WMNs**

**Multihop wireless network:** An objective to develop WMNs is to extend the coverage range of current wireless networks without sacrificing the channel capacity. Another objective is to provide non-line-of-sight (NLOS) connectivity among the users without direct line-of-sight (LOS) links. To meet these requirements, the mesh-style multihopping is indispensable, which achieves higher throughput without sacrificing effective radio range via shorter link distances, less interference between the nodes, and more efficient frequency reuse technology: Support for ad hoc networking, and capability of self-forming, self-healing, and self-organization. WMNs enhance network performance, because of flexible network architecture, easy deployment and configuration, fault tolerance, and mesh connectivity, i.e., multi-point-to-multi-point communications. Due to these features, WMNs have low upfront investment requirement, and the network can grow gradually as needed.
**Mobility dependence on the type of mesh nodes:** Mesh routers usually have minimal mobility, while mesh clients can be stationary or mobile nodes. In WMNs, both backhaul access to the Internet and peer-to-peer (P2P) communications are supported. In addition, the integration of WMNs with other wireless networks and providing services to end-users of these networks can be accomplished through WMNs.

**Dependence of power-consumption constraints on the type of mesh nodes:** Mesh routers usually do not have strict constraints on power consumption. However, mesh clients may require power efficient protocols. As an example, a mesh-capable sensor requires its communication protocols to be power efficient. Thus, the MAC or routing protocols optimized for mesh routers may not be appropriate for mesh clients, such as sensors, because power efficiency is the primary concern for wireless sensor networks.

**Compatibility and interoperability with existing wireless networks:** For example, WMNs built based on IEEE 802.11 technologies must be compatible with IEEE 802.11 standards in the sense of supporting both mesh-capable and conventional Wi-Fi clients. Such WMNs also need to be inter-operable with other wireless networks such as WiMAX, Zig-Bee, and cellular networks. Based on their characteristics, WMNs are generally considered a type of ad-hoc networks due to the lack of wired infrastructure that exists in cellular
or Wi-Fi networks through deployment of base stations (BS) or access points (AP). While ad hoc networking techniques are required by WMNs, the additional capabilities necessitate more sophisticated algorithms and design principles for the realization of WMNs. More specifically, instead of being a type of ad-hoc networking, WMNs aim to diversify the capabilities of ad hoc networks. Consequently, ad hoc networks can actually be considered a subset of WMNs. To illustrate this point, the differences between WMNs and ad hoc networks are outlined below. In this comparison, the hybrid architecture is considered, since it comprises all the advantages of WMNs.

**Wireless infrastructure/backbone:** WMNs consist of a wireless backbone with mesh routers. The wireless backbone provides large coverage, connectivity, and robustness in the wireless domain. However, the connectivity in ad hoc networks depends on the individual contributions of end-users which may not be reliable.

**Integration:** WMNs support conventional clients that use the same radio technologies as a mesh router. This is accomplished through a host-routing function available in mesh routers. WMNs also enable integration of various existing networks such as Wi-Fi, the Internet, cellular and sensor networks through gateway/bridge functionalities in the mesh routers. Consequently, users in one network are provided with services in other networks, through the use of the wireless infrastructure. The integrated wireless network through
WMNs resembles the Internet backbone, since the physical location of network nodes becomes less important than the capacity and network topology.

**Dedicated routing and configuration:** In ad hoc networks, end-user devices also perform routing and configuration functionalities for all other nodes. However, WMNs contain mesh routers for these functionalities. Hence, the load on end-user devices is significantly decreased, which provides lower energy consumption and high-end application capabilities to possibly mobile and energy constrained end-users. Moreover, the end-user requirements are limited which decreases the cost of devices that can be used in WMNs.

**Multiple radios:** The mesh routers can be equipped with multiple radios to perform routing and access functionalities. This enables separation of two main types of traffic in the wireless domain. While routing and configuration are performed between mesh routers, the access to the network by end users can be carried out on a different radio. This significantly improves the capacity of the network. On the other hand, in ad hoc networks, these functionalities are performed in the same channel, and as a result, the performance decreases.

**Mobility:** Since ad hoc networks provide routing using the end-user devices, the network topology and connectivity depend on the
movement of users. This imposes additional challenges on routing protocols as well as on network configuration and deployment.

1.2 WMN ARCHITECTURE

Wireless mesh architecture design is the first step towards providing high-bandwidth Internet access over a specific coverage area. WMNs consist of Mesh Clients (MCs) and Wireless Mesh Routers (WMRs), which relaying each other’s packets in a multi-hop fashion, where mesh routers have minimal mobility and form the Backbone of WMNs (BWMNs). To illustrate more, it is made up of wireless communication nodes, each of which can communicate with other nodes. Mesh architecture breaks the long distance into a series of shorter hops to boost the signal by intermediate nodes. Intermediate nodes not only sustain signal strength, but also forward packages on behalf of other nodes based on their knowledge of the network. Such architecture allows continuous connections and reconfiguration around broken or blocked paths by making forwarding decisions from node to node until the destination is reached. Besides, it provides high-bandwidth Internet access and offers a low cost and flexible deployment.

The infrastructure that supports a WMN is a wireless mesh router network, or Backbone Wireless Mesh Network (BWMN). BWMN provides Internet connectivity to MCs in a multi-hop fashion. MCs can access the Internet via BWMN formed by Wireless Mesh Routers
(WMRs). BWMN consists of some special WMRs, called Internet Gateways (IGWs). IGWs act as communication bridges between the Internet and BWMN, and provide Internet accessibility. A typical WMN is illustrated in Fig. 1.2.

![Wireless Mesh Network Diagram](image)

**Fig. 1.2 Wireless Mesh Networks**

### 1.3 Components of WMNs

There are three types of node in a WMN: WMN client, WMN router, and WMN gateway. WMN clients are the end-user devices such as laptops, PDAs, smart phones, etc, that can access the network for
using applications like email, VoIP, game, location detection, etc. These devices are assumed to be mobile; they have limited power, they may have routing capability, and may or may not be always connected to the network. WMN routers are in the network to route the network traffic. They cannot terminate nor originate the traffic. The routers have limitation in mobility and they have reliable characteristics. Transmission power consumption in mesh routers is low, for multi-hop communications strategy. Additionally, the Medium Access Control (MAC) protocol in a mesh router supports multiple-channels and multiple interfaces to enable scalability in a multi-hop mesh environment. WMN gateways are routers with direct access to the wired infrastructure/Internet. Since the gateways in WMNs have multiple interfaces to connect to both wired and wireless networks, they are expensive. Therefore, there are a few number of WMN gateways in the network. Moreover, their placement has a significant impact on the performance of the network.

1.4 APPLICATIONS OF WMNS

There are some applications cannot be directed and fully supported by other wireless technologies rather than WMNs. It was a motivation to develop WMNs.

**Broadband Wireless Access**

Currently, Broadband access has an important role in information economy. It provides services for real time applications
such as: video telephony, online-gaming, video on demand, and telecommunications. Each new application has a significant impact on quality of life. For example, telecommuting can reduce daily travelling of individuals. It leads to increased productivity for the time saving. It also reduces traffic on the streets; thus it has a positive impact on the environment. In urban and sub-urban areas, wired access (Cable and DSL) is the first choice if the population density be reasonably high. Rural areas have limited coverage using wireless technologies like satellite and cellular networks. Satellite access has two drawbacks: expensive technology and high latency due to the distance between the end client and the satellite.

In the case of cellular networks, the towers are expensive to install and operate. Lack of service providers and the higher cost of the service itself make lower use of broadband access. In order to wider adoption of Internet access, WMNs offer an easy-to-deploy and cost effective alternative in areas where cable TV or DSL lines are not available. WMNs can be deployed quickly without expensive equipment and the service provider can see a quick return on investment. Besides, because of the low cost deployment and operations of WMNs, free broadband access to city residents is also possible. Many such networks already exist, and more are on the way.
**Industrial Applications**

In a building, many devices need to be monitored and controlled like electrical devices including power, light, air conditioner, elevator, etc. Today, the wired networks are taking care of such environment. This is very expensive due to the complexity in deployment and maintenance of a wired network. Currently, Wi-Fi networks are another option to reduce the cost of such networks. But, this solution has not achieved satisfactory performance, yet for expensive wiring of Ethernet which is needed for Wi-Fi Access Points (APs). Replacing APs by mesh routers will solve the problem. The deployment process will be much simpler and also the deployment cost will be significantly reduced.

**Healthcare**

In a hospital or medical center, monitoring and updating patient information like medical history, test results, insurance information, etc., need to be processed and transmitted from room to room. The ability to connect to the network is crucial to ensure data access in every operating room, office, and lab. In many hospitals data transmission is usually broadband due to large amount of data, for instance: high resolution medical images and periodical monitoring information. WMN provides unlimited network access to any fixed medical devices. It does not need to use existing Ethernet connections, so that, it will eliminate dead spots and also cause low system cost and simplicity which cannot be found in traditional wired networks.
Transportation systems

Internet access is limited to stations and stops using IEEE 802.11 and IEEE 802.16. To extend access into buses, plains, ferries, and trains, WMN technology can help. Thus, passengers on-board can access to the net while travelling from one place to another. Other services such as remote monitoring in-vehicle, driver communications and security cameras can be supported too.

Hospitality

In hotels and resorts, one of their services is high-speed Internet connectivity which is free. Wireless mesh networks are easy to set-up, lower in cost, and without having to change the existing structures or disrupt business for both indoor and outdoor.

Warehouses

One way to keep track of stock in warehouses is using handheld scanners. It needs connectivity throughout the area. Wireless mesh networks can ensure connectivity in modern warehouses and shipping logistics with little cost and effort.

Temporary Venues

Construction sites can enjoy the easy set-up and removal of wireless mesh networks. Architects and engineers can stay connected and using camera to communicate and talk to each other on spot. It provides them to see the real picture of the project progresses. Other
temporary venues such as: political rallies, street fairs, and outdoor concerts can set-up and remove wireless mesh networks in minutes.

1.5 PROBLEMS AND ISSUES IN WMNS

Many problems still remain to fully realize the WMN potential while significant advances have been made.

Physical Layer Issues

The most common radio models in use today are single radio single channel, single radio multiple channels, multiple radio multiple channels, and directional antennas. In single radio single channel environment, nodes are half duplex. It means that they cannot transmit and receive a signal simultaneously. Thus, the bandwidth utilization is significantly reduced. Furthermore, when one node transmits, all other nodes have to listen and cannot transmit without causing a collision. In single radio multiple channel, each node can tune its single radio into several non-overlapping channels to reduce contention and increase the capacity. In multiple radio multiple channel model, a node can use multiple non-overlapping channels at a time. Finally, in directional antennas, multiplexing is used to reduce interference.

Medium Access Layer Issues

In WMNs, improvements to the traditional contention based protocols are usually not sufficient to improve allocation efficiently and
fairly. Traditional MAC protocols are limited. Thus, advantages of newer underlying models are limited. Multiple radios and multiple channels bring new problems of channel assignment and medium access for instance. Multiple Input and Multiple Output (MIMO) radios have been proposed to increase the capacity of WMNs to mitigate unfair access and underutilization. However, current MAC protocol cannot take advantage of this underlying technological improvement.

**Transport Layer Issues**

WMNs have some challenges at the transport layer. The transport protocols should efficiently utilize available network resources and allocate them fairly. However, fairness problem in wireless mesh networks is inherently due to the interdependencies among neighboring wireless links.

**Network Layer Issues**

At the network layer, distinct characteristics and traffic flow direction, is highly skewed between the client and the gateway. In order to take the advantage of this, WMNs need the new and improved protocols.

**Topological and Deployment Issues**

The key purpose of a WMN is to equip the end users with high speed Internet access. To achieve this, the design of the network architecture should be addressed carefully. This is a fundamental issue, and providing Quality of Service (QoS) for end users and
determining the network performance is critical for a WMN. Planning a WMN includes determining the number of gateways, optimal placement of gateways, utilizing bandwidth, and minimizing the deployment cost. There are typically two types of deployment: structured deployment and organic deployment. In structured deployment, services will be provided in a new area; thus, it has the flexibility of choosing the topology. This flexibility may translate into improved network performance by capturing the regularity of the deployed mesh network. On the other hand, in organic deployment, the mesh network will be deployed organically over existing infrastructure. Thus, there are limited options of topology for the network architect to choose.

1.6 ADVANCES AND RESEARCH CHALLENGES

The distinct features and critical design factors of WMNs bring many challenging issues to communication protocols, ranging from the physical layer to the application layer. Despite recent advances in research and development in WMNs, many challenging problems still remain: the theoretical network capacity is still unknown, protocols in various layers need to be improved, new schemes are required for network management, and the network still lacks security.

Network Capacity

To date, much research has been carried out to study the capacity of ad hoc networks. Considering the similarities between
WMNs and ad hoc networks, the results from that research can be adopted to study the capacity of WMNs. Lower and upper bounds for ad hoc network capacity are derived in [1], where an important implication is pointed out as the guideline to improve the capacity of ad hoc networks: a node should only communicate with nearby nodes. To implement this idea, two major schemes are suggested in [1]:

- Throughput capacity can be increased by deploying relaying nodes.
- Nodes need to be grouped into clusters.

In other words, communication of a node with another node that is not nearby must be conducted via relaying nodes or clusters. However, considering a distributed system such as ad hoc networks or WMNs, clustering nodes or allocating relaying nodes is a challenging task. The implication given in [1] can also be reflected in [2]. The scheme proposed in [2] increases network capacity of ad hoc networks by utilizing the node mobility. A source node will not send its packets until the destination node gets closer to it. Thus, via the node mobility, a node communicates only with its nearby nodes. This scheme has a limitation: the transmission delay is rather large and the required buffer for a node may become infinite.

The analytical approaches in [1, 2] have significantly driven the research progress in wireless network capacity. One limitation of these approaches is that the networking protocols have not been
appropriately captured. Different medium access control, power control, and routing protocols significantly impact the capacity of a wireless network. However, in the analytical approaches [1, 2], they are only represented by oversimplified models. Another limitation of existing analytical approaches [1] is that the theoretical capacity bounds are derived based on the asymptotic analysis. These results, however, do not reveal the exact capacity of a network with a given number of nodes, in particular when the number is small. The reason is that the assumptions about the network size or node density in the asymptotic analysis do not match the actual scale of any WMNs; neither network size nor node density will go infinite, no matter how a WMN is deployed. Moreover, due to the differences between WMNs and ad hoc networks, the analytical results of ad hoc networks may not be directly applicable to WMNs. Thus, new analytical results need to be derived for WMNs.

**Network Monitoring**

Many functions are performed in a network management protocol. The statistics in the management information base (MIB) of mesh nodes, especially mesh routers, need to be reported to one or several servers in order to continuously monitor network performance. In addition, data processing algorithms in the performance monitoring software on the server analyze these statistical data and determine potential abnormalities. Based on the statistical information collected from the MIB, data processing algorithms can also accomplish many
other functions such as network topology monitoring. Several research issues exist in network monitoring. To reduce overhead, efficient transmission of network monitoring information in a mesh network topology is expected. In addition, in order to accurately detect abnormal operation and quickly derive a multi-hop mesh network topology of WMNs, new data processing algorithms need to be developed.

Security Similar to mobile ad hoc networks, WMNs still lack efficient and scalable security solutions, because their security is more easily compromised due to several factors: their distributed network architecture, the vulnerability of channels and nodes in the shared wireless medium, and the dynamic change of network topology. Attacks in different protocol layers can easily cause the network to fail. Attacks may occur in the routing protocol such as advertising wrong routing updates. The attacker may sneak into the network, impersonate a legitimate node, and not follow the required specifications of a routing protocol. The same types of attacks as in routing protocols may also occur in MAC protocols.

For example, the back-off procedures and network allocation vector (NAV) for virtual carrier sense of IEEE 802.11 MAC may be misused by some attacking nodes, which cause the network to always be congested by these malicious nodes. Attackers may also sneak into the network by misusing the cryptographic primitives. A widely
accepted counter-attack measure is authentication and authorization. For wireless LANs, this is taken care of by authentication, authorization, and accounting (AAA) services directly over the access point or via gateways. However, AAA is performed through a centralized server such as RADIUS (remote authentication dial-in user service). Such a centralized scheme is not applicable in WMNs. Moreover, security key management in WMNs is much more difficult than in wireless LANs, because there is no central authority, trusted third party, or server to manage security keys. Key management in WMNs needs to be performed in a distributed but secure manner. Therefore, a distributed authentication and authorization scheme with secure key management needs to be proposed for WMNs.

**Cross Layer Design**

The methodology of layered protocol design does not necessarily lead to an optimum solution. This is particularly the case in WMNs. The physical channel in WMNs is variable in terms of capacity, BER, etc. Although different coding, modulation, and error control schemes can be used to improve the performance of the physical channel, there is no way to guarantee fixed capacity, zero packet loss rate, or reliable connectivity. In order to provide satisfactory network performance, MAC, routing, and transport layer protocols need to interactively work together with the physical layer. In WMNs, because of their ad hoc feature, network topology constantly changes due to mobility and link failures. Such a dynamic network topology impacts multiple protocol
layers. Thus, in order to improve protocol efficiency, cross-layer design becomes indispensable.

Cross layer design can be performed in two ways. The first approach is to improve the performance of a protocol layer by taking into account parameters in other protocol layers. Typically, parameters in the lower protocol layers are reported to higher layers. For example, the packet loss rate in the MAC layer can be reported to the transport layer so that a TCP protocol is able to differentiate congestion from packet loss. As another example, the physical layer can report link quality to a routing protocol as an additional performance metric for routing algorithms.

The second approach of cross-layer design is to merge several protocols into one component. For example, in ad hoc networks, MAC and routing protocols can be combined into one protocol in order to closely consider their interactions. The first approach keeps the transparency between protocol layers, while the second approach can achieve much better performance through closer interaction between protocols. Certain issues must be considered when carrying out cross-layer protocol design: cross-layer designs have risks due to the loss of protocol-layer abstraction, incompatibility with existing protocols, unforeseen impact on the future design of the network, and difficulty in maintenance and management.
1.7 CROSS LAYER DESIGN IN WMNS

In this thesis the Cross Layer Design research problems are considered and solutions are provided along with implementation and results. A Wireless Mesh Network (WMN) consists of mesh routers and mesh clients forming a multi-hop wireless network [3]. It is usually connected to the Internet to provide users with backhaul access. In many application scenarios, WMNs integrate both ad hoc and infrastructure operation modes and interwork with other wireless networks.

A WMN has many features that are much different from a wireless sensor or a mobile ad hoc network [3]. Furthermore, it is more concerned with scalable end-to-end throughput and satisfactory quality of service (QoS) to deliver heterogeneous traffic. Thus, it is more critical to optimize the overall network performance of WMNs across multiple protocol layers. Whether layered-protocol design or cross-layer design is a better option to optimize protocol performance in WMNs is still an on-going research topic.

The methodology of layered protocol design carries several advantages from a protocol transparency perspective. For example, protocols in one layer can be designed, enhanced, or even replaced without any impact on other protocol layers. However, such a methodology does not provide a mechanism for performance optimization between different protocol layers, which can significantly
compromise network performance. This is particularly true for WMNs because it demands scalable network performance but is exposed to many challenging problems such as heterogeneous QoS constraints, multihop wireless communications, and variable link capacity.

Researchers have proposed to consider new protocol layering by decomposing the overall network-performance optimization [4]. As long as the optimization decomposition is successfully done, each protocol in each layer works as an optimal module to achieve the best network performance; as a consequence, cross-layer optimization has been considered in protocol layering. However, to carry out optimization decomposition, there remain many unresolved issues. A typical example is the lack of a model that can capture the stochastic dynamics in different time scales such as packet, session, connection, and topology levels.

On the other hand, the protocol layering by optimization decomposition does not necessarily match the existing protocol stack that is widely adopted in WMNs. Depending on different representations of the optimization problem, different decomposition structures may be derived, which may result in different architectures for protocol layering. However, the protocol stack in WMNs follows the classical TCP/IP protocol stack. The mismatch between the classical TCP/IP protocol stack protocol and the new protocol layering based on optimization decomposition actually illustrate that cross-layer design
is highly desired if the optimum network performance must be achieved.

Therefore, it is reasonable to believe that cross-layer optimization will continue to be one of the most important tasks in protocol design for WMNs. However, critical issues must be considered for cross-layer design [5], because it has risks due to loss of protocol-layer abstraction, incompatibility with existing protocols, and unforeseen impact on the future design of the network, and difficulty in maintenance and management. Thus, certain guidelines need to be followed when carrying our cross-layer design.

1.8 MOTIVATIONS FOR CROSS LAYER DESIGN

Cross-layer design has been widely used to improve the network performance, particularly in a wireless network [6]. In this section, we illustrate the need for cross-layer design in WMNs from two aspects: theoretical framework and practical factors in protocol design.

1.8.1 Theoretical Framework on Layered Versus Cross Layer Design

Layering as Optimization Decomposition:

Layered protocol architecture is one of the most important factors that has made networking so successful. However, there has been a lack of a systematic approach to analyze whether layering of protocols is optimal or not. The “layering as optimization decomposition” fills a gap between theoretical methods and practical
aspects of protocol design. In this method, various protocol layers are integrated into one single coherent theory, in which asynchronous distributed computation over the network is applied to solve a global optimization problem in the form of generalized network utility maximization (NUM).

The key idea of “layering as optimization decomposition” is to decompose the optimization problem into subproblems, each corresponding to a protocol layer and functions of primal or Lagrange dual variables, coordinating these sub problems correspond to the interfaces between layers [4]. Since different decompositions result in different layering schemes, condition under which layering incur no loss of optimality need to be studied, as well as the sensitivity of a layering scheme. These conditions and sensitivity can help to identify the performance differences between different layering schemes.

The basic NUM is usually formulated for protocol-layer performance optimization, while generalized NUM needs to capture the entire protocol stack. A possible formulation of a generalized NUM is given in [4].

$$\max \text{imize} \sum_s U_s(x_s, P_{e,s}) + \sum_j V_j(w_j)$$

Subject to $Rx \leq c(w, P_e)$

$$X \in C_1(P_e), X \in C_2(F), \text{or } x \in \Pi$$

$R \in R, F \in F, w \in W.$
This NUM tries to maximize the user-utility function $U(\cdot)$ and resources $V_j(\cdot)$ on the network element $j$. $x_s$ and $w_j$ denote the rate for source $s$ and the physical layer resources at network element $j$, respectively. $R$ is a routing matrix, and $x$ denotes the link capacity as a function of physical-layer resource $w$ and the desired error probability $P_e$ after decoding. All physical-layer factors, such as interference, power control, etc., should be captured in function $c$. Thus, the first constraint in the earlier NUM represents the behavior perceived at the routing layer. The coding and error-control mechanisms versus the rate are captured in function $C_1(\cdot)$, while the contention-based MAC or scheduling based MAC is captured in $C_2(\cdot)$ and $\Pi$, respectively, where $F$ is the contention matrix and $\Pi$ is a schedulability constraint set.

Thus, the second line of constraints stands for link-layer behavior that has taken into account the effect of the physical layer. From the earlier generalized NUM, we can see that the network performance is to be optimized at the transport layer subject to the constraints in routing, MAC, and physical layers. The above formulation is based on a deterministic fluid model, which cannot capture the packet-level details and microscopic queuing dynamics. Thus, stochastic NUM is a preferred formulation [4]. Stochastic NUM has been an active research area, in which many challenging issues still remain to be resolved.
Whether it is a deterministic or stochastic generalized NUM, the optimization decomposition is usually carried out by the following three steps:

- The generalized NUM is formulated independent of layering.
- A modularized and distributed solution is developed to perform optimization by following a particular decomposition.
- The space of different decompositions is explored such that a choice of a layered-protocol stack is made.

In the generalized NUM, the objective function is usually comprised of two parts: user- and operator-objective functions. Game theory can also be used to formulate the NUM with both user- and operator-objective functions. The optimization decomposition for the generalized NUM is comprised of both horizontal and vertical decomposition.

**Vertical decomposition**

Here, the entire network functionalities are decoupled into different modules such as congestion control, routing, scheduling, MAC, power control, error control, and so on. Different modules can be classified into different layers in the protocol stack.

**Horizontal decomposition**

This aims at devising a distributed computation solution to individual module. More specifically, this step will work out a specific
distributed mechanism and algorithm for protocols such as congestion control, scheduling, MAC, and so on. As shown in [4], the optimization decomposition lays a theoretical ground for cross-layer design.

Optimization decomposition gives a better insight to existing layered protocols. For example, comparing a decomposition result with the existing protocol stack can tell us which layers need cross-layer optimizations and how to optimize the interactions between layers.

Optimization decomposition provides a systematic approach for the design of optimized protocol architecture. Under this architecture, optimization between layers has already been considered [7], and thus, minimum efforts for cross-layer design are needed. However, such clean-slate protocol architecture usually does not match an existing protocol stack, e.g., the widely accepted TCP/IP protocol stack for WMNs. The architecture mismatch between the optimal decomposition and an existing protocol stack indicates that cross-layer design is necessary for networks based on conventional protocol layering.

Optimization decomposition does not eliminate the need for cross-layer design. For example, vertical decomposition separates functionalities into different modules in different layers. However, the decomposition may still keep coupling between layers or modules. Such coupling actually proves the natural need for cross-layer design in a network.
Multi-hopping is Order-Optimal

Independent from the work of “layering as optimization decomposition,” the scaling laws of transport capacity of wireless multihop networks studied in [5] also suggest that layered design is optimal. Given a planar network in which two nodes are separated with a distance $\rho_{ij}$, if node $i$ transmits a signal level of $X_i(t)$, then it’s received-signal level is

$$Y_i(t) = \sum_{j \in i} \frac{e^{-\gamma_{ij}X_i(t)}}{\rho_{ij}^\delta} + Z_i(t) \quad (1.2)$$

where $Z_i(t)$ is Gaussian noise, constant $\delta$ is the path-loss exponent, and $\gamma$ is the absorption constant. In [5], the following results have been achieved.

scenario of exponential attenuation: Suppose that absorption exists in the medium (i.e., $\gamma > 0$) or the path loss exponent $\rho_{ij}$ is larger than three, then the transport capacity, defined as the distance weighted sum of rates, grows as $\Theta(n)$, i.e., the transport capacity grows on the order of $n$. Furthermore, if the traffic load on each node can be balanced, then the multihop forward-and-decode strategy, treating interference as noise, is order-optimal with respect to the transport capacity.

The scenario of low attenuation: If $\gamma = 0$ or the path-loss exponent is small (e.g., $\delta < 3/2$), then the attenuation is low. In this
scenario, other strategies like coherent multistage relaying with interference subtraction can be order-optimal with respect to the scaling law of transport capacity. This result suggests that new protocol architecture rather than a conventional layered structure is probably needed for information transport. In WMNs, the normal scenario is actually the exponential attenuation. Based on the result of order-optimal multi-hopping, it is stated in [5] that the decode-and-forward strategy can achieve optimal performance, within a constant, with regard to the network capacity.

It is also pointed out in [5] that a natural way of implementing the decode-and-forward strategy is the layered-protocol architecture. Consequently, it is concluded that the cross-layer design can only improve throughput by at most a constant factor and that an unbounded performance improvement cannot be achieved. However, such a statement can be too strong in many scenarios, particularly when we are interested in actual protocol design rather than carrying out an asymptotic analysis.

The theoretical results are only based on simplistic network models and only meaningful asymptotically. For a realistic wireless network, due to reasonable network size (not approaching infinity) and non-ideal network models, the asymptotic scaling law does not really reflect the actual network-capacity bound. Considering cross-layer design versus layered design, their actual network capacity can be
significantly different, even though the asymptotic capacity remains the same.

The decode-and-forward strategy does not actually imply a layered-protocol design. Almost all existing multihop wireless networks are designed based on decode-and-forward strategy, but we still see many examples of cross layer design for improving network performance. For example, the existing protocol stack adopted in 802.11 WMNs is definitely based on a decode-and-forward strategy, but carrying out MAC/physical or MAC/routing cross-layer design is a common technology to improve network performance.

1.8.2 Features Demanding Cross Layer Design

Several characteristics pertaining to WMNs make cross layer design more indispensable for WMNs than that in other multi-hop wireless networks such as mobile ad hoc or wireless sensor networks.

No clean-slate protocol architecture

By optimization decomposition, a new protocol architecture that is quite different from the existing standard protocol stack can also result. The well-known TCP/IP protocol stack has been widely adopted for most applications of WMNs. Thus, how to make the layered-protocol architecture derived from optimization decomposition and the TCP/IP protocol stack match with each other is a technical challenge. It is highly possible that no match can be achieved in several cases. Thus, in order to further improve the network performance without
abandoning the TCP/IP protocol stack, the cross-layer design becomes indispensable.

**Advanced physical-layer technologies**

Many advanced physical-layer technologies have been adopted for WMNs in order to support applications that have high bandwidth demand. These technologies fall into several major categories.

**Multirate-transmission technology**: This is achieved by having multiple options of modulation, coding, and power-control schemes. Different transmission rate usually results in different transmission range and interference range. With multi rate-transmission technology, the same physical layer can support a different transmission rate, depending on the link quality and the environment. In a single-hop wireless network, link-adaptation protocols, which are a type of simple cross-layer design schemes, can satisfy the need for maximizing throughput. In WMNs, however, merely the link adaptation is not enough, since links within multiple hops are related to each other. Thus, in WMNs, link adaptation becomes network wide rather than a one-hop mechanism. Thus, link adaptation is inevitably cross-related to routing and topology control. Such cross-relationship between different protocols reflects the necessity of cross-layer design.

**Advanced antenna technology**: Directional antennas and the advance versions, such as smart antennas, can significantly reduce interference between nodes that are close to each other. Such
techniques certainly increase the network capacity but also require additional algorithms in upper layers to coordinate the antenna direction or beam forming. In a single-hop wireless network, a control algorithm located in the MAC layer, i.e., MAC/physical cross-interaction is enough. However, in WMNs, routing needs to be considered together, since different beam forming or antenna direction impacts the routing path and vice versa. In other words, routing, MAC, and physical layers all need to work together.

A more advanced antenna technology is multiple input and multiple output (MIMO). In a node using MIMO, advanced signaling processing technology is employed to achieve an optimal balance between link reliability and link capacity. MIMO on a point-to-point or point-to-multipoint setup has been well researched. However, taking advantage of MIMO in WMNs usually requires a network wide-scheduling scheme.

**Multichannel or multiradio technology**: Multichannel operation (either single- or multiple-radio) can significantly reduce the interference between nodes in a multi-hop network. To utilize such a technology, an additional algorithm (dynamic channel allocation) must be developed in the MAC layer. This algorithm also needs to be aware of the interference from external networks. Since varying channels in different hops potentially impact the optimal routing path that can be
selected, both MAC and routing protocols must work together to take advantage of the multichannel technology.

It should be noted that the above three classes of physical layer technologies are usually integrated, which further intensify the challenge in protocol design in upper layers. For example, the multi-rate transmission can happen in a physical layer using MIMO and multichannel operation. For a WMN with so many advanced physical-layer features, it is more challenging to re-optimize both MAC and routing protocols.

Imperfect MAC: MAC has always been a critical part in all wireless networks. Many solutions are available. However, none of them is perfect because of the following two major factors:

- The wireless medium is always imperfect in nature, and
- MAC itself has no guaranteed performance.

In the second factor, a typical example is CSMA/CA, which is a best effort protocol and cannot provide any guarantee for delay, collisions, etc. Such unpredictable performance of the MAC can severely limit the performance of a routing protocol. For example, routing messages may not be able to send out in a congested CSMA/CA-based WMN, which in turn impacts the capability of a routing protocol. This issue is even worse in WMNs, because the performance of MAC is not just a matter of single-hop networking but multi-hop. Research can be carried out to constantly improve the MAC
protocols for WMNs. However, as a matter of fact, if routing is not taken into account, optimal performance can only be achieved locally. Consequently, in order to achieve the ultimate goal of perfect MAC, routing must be considered as an integral part of MAC. In this sense, MAC and routing protocols in WMNs are so closely related that they should be put together as two modules in one layer or even just one module in the same protocol layer. A typical example is the upcoming IEEE 802.11s standard for 802.11 WMNs, in which MAC and routing have been put together into the same MAC layer. However, we have also noticed that the optimal interactions between MAC and routing have not been exploited yet in IEEE 802.11s.

Mixed traffic types with heterogeneous QoS: WMNs are expected to support a large variety of services that consist of many traffic types with heterogeneous QoS requirements. In order to deliver such services in WMNs, transport layer, routing, and MAC protocols need to cooperate smoothly; otherwise, either service quality is not ensured or the network resources may be wasted. For example, it is always preferable to use separate transport layer protocols for VoIP, video, and data traffic.

For VoIP and video traffic, finding a reliable routing path is obviously not the goal, since a path does not guarantee the quality of VoIP or video, no matter how reliable the path can be. Thus, finding a routing path must consider bandwidth allocation. This problem has
been researched as a QoS-routing topic. However, when more advanced physical-layer technologies are considered, it becomes more than a QoS-routing problem and has to involve tight routing/MAC cross-layer design. For example, variation of bandwidth demand on a given routing path or change of a routing path can trigger reallocation of time slots, channels, antenna directions, etc., on all links related to the given routing path or vice versa. Based on the above analysis, we know that cross-layer design is imperative for WMNs.

1.9 MULTICHANNEL MULTIRADIO WMNS

Traditional multi-hop wireless networks have almost exclusively comprised of single radio nodes. It is well-known that in such networks, the end-to-end throughput on a route drops as the number of hops increase. A primary reason is due to the fact that a single wireless transceiver operates in half-duplex mode, i.e., it cannot transmit and receive simultaneously. An incoming frame must therefore be received fully before the node can switch from receive mode to transmit mode. Consequently, for a linear chain topology of \( n \) nodes where only one transmission is allowed at a time in the network, the per-node throughput is on the order of \( O(1/n) \) for a CSMA/CA type MAC.

Multiple radios greatly increase the potential for enhanced channel selection and route formation while the mesh allows more fine-grained interference management and power control. There are
several interesting research issues in the context of multi-radio, multi-channel wireless mesh networks (WMN); finding the optimum channel assignment for a given number of radios per node and a given number of orthogonal channels is the objective of this work. It should be noted, however, that use of multiple radios to exploit the availability of multiple non-overlapping channels is not the silver bullet for improving multi-hop throughput in wireless networks. Other approaches which have been researched include use of directional antennas which reduces the interference area around a transmitting node and improved MAC protocols.

It is likely that a suitable combination of these approaches would lead to next generation multi-hop network design. However, outfitting each node with multiple radios is probably the most cost-efficient solution which does not require expensive new hardware or complex modifications to the existing MAC protocols. While mutual interference among the multiple radios (NIC) on a node could limit the degree of actual improvement, it is expected that advanced EMI protection and device integration techniques would mitigate the mutual RF interference considerably.

QoS provisioning in WMNs is very important in order to support real-time communications such as audio and video. However, provisioning of communication QoS over wireless networks is far more challenging than for wired networks because of variability of wireless
links, the lack of any central coordination authority (for QoS and channel assignment), node mobility, limited battery power, multihop communication and contention for accessing the wireless channel.

1.10 ORGANIZATION OF THE THESIS

The thesis is organized as follows: Chapter 1 focuses on introduction to Wireless Mesh Networks and its advantages. Literature survey on cross layer channel assignment, QoS aware routing and load balancing strategies are discussed in Chapter 2. Chapter 3 provides cross layer design principles and metrics. Chapter 4 describes the cross layer based channel assignment schemes in wireless mesh networks. Chapter 5 discusses on efficient cross layer design architecture for routing and channel selection in multi-channel multi-radio wireless mesh networks. Chapter 6 discusses cross layer based multipath routing and load balancing. Chapter 7 presents summary of the research and future work.