DYNAMIC ASSOCIATION IN WIRELESS MESH NETWORKS

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Contents

Summary

Nowadays, network communications with end devices are increasingly wireless. IEEE 802.11 based wireless local area networks (WLANs) and cellular network based mobile phones are widely used in our everyday life. With increasing demand for multimedia transmission and unrestrained roam, all the existing wireless networks should be updated. Hence, many standards for wireless networking are now taking the next step to support mesh architectures in which data is commonly forwarded on paths consisting of multiple wireless hops. Wireless mesh networks (WMNs) are one of these new technologies which support higher link capacity and wider wireless network coverage.

As a promising next generation wireless networking technology, WMNs have been attracting considerable research and industrial focus, and they are undergoing rapid progress and inspiring numerous applications. All unique characteristics and advantages of WMNs owe to the multi-hop wireless mesh backbone, which is formed through the self-organization of mesh routers. Mesh end stations (STAs) should associate with mesh access points (MAPs) to obtain network access and be part of the network. STAs can roam freely over the wireless network coverage area by handoff among MAPs nearby. Furthermore, WMNs can be integrated with other types of networks, such as Internet, Wi-Fi, WiMax, cellular networks and so on, with gateway functionalities in some of the MAPs. This unique architecture brings in many advantages to WMNs. Thanks to the multi-hop wireless backbone, WMNs enable rapid deployment with lower cost backhaul, self-healing, resilience and good scalability. Also, WMNs support widespread wireless network coverage due to multi-hop forwarding, higher bandwidth due to shorter hops, better battery life in end devices (e.g., STAs) due to lower power transmission.

In order to enable these unique characteristics and advantages of WMNs, many issues and challenges should be solved. Many conventional management mechanisms which have significant effect on network performance should also be reconsidered. Such a mechanism is the association of STAs with MAPs of the wireless backbone. Previous standards and literatures have already devised many association mechanisms in wireless networks. IEEE 802.11 specifications define a simple Received Signal Strength Indication (RSSI) based association mechanism, in which STAs simply select the access point (AP) with the highest RSSI value to associate with. Other literatures either highlight link quality or load balancing solely or make some impractical assumptions. Several works on association mechanisms in WMNs propose a cross-layer framework considering jointly the association cost of access links and cost of the multi-hop wireless backbone, which suits well in WMNs.

Based on the cross-layer association framework, we propose a dynamic association mechanism in the context of IEEE 802.11 based WMNs. Our dynamic association mechanism takes wireless link quality, load balancing and association oscillation avoidance into consideration. The metric introduced in this association mechanism measures the real traffic load through channel based load detection and suits both coordinated and uncoordinated networks. Because of the random characteristics of wireless links and the variability of network conditions, we introduce oscillation avoidance schemes, which consist of periodic STA scan and re-association threshold. We further evaluate our dynamic association mechanism through elaborate simulation, which shows that the proposed dynamic association mechanism outperforms other association mechanisms and improve network performance significantly. Furthermore, our mechanism can accelerate the convergence speed of WMNs. The simulation additionally shows there exists optimal values for both re-association threshold and STA scan period, corresponding to specific network scenarios (e.g., network topology, scale, traffic load, etc.).

Our dynamic association mechanism characterizes the dynamic network scenarios in real time, hence improve network performances significantly. But there are still some further work to do in order to perfect our association mechanism, as will be elaborated in the last chapter of future work.

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Symbol	**Description**
WPANs	Wireless Personal Area Networks
WLANs	Wireless Local Area Networks
WMANs	Wireless Metropolitan Area Networks
WWANs	Wireless Wide Area Networks
WMNs	Wireless Mesh Networks
WSNs	Wireless Sensor Networks
STAs	End Stations
APs	Access Points
MAPs	Mesh Access Points (equipped with access interfaces and relay interfaces)
MPs	Mesh Points (equipped with relay interfaces)
Wi-Fi	Trademark of Wi-Fi Alliance, which is based on the IEEE 802.11 standards
WiMax	Worldwide Interoperability for Microwave Access, trademark of WiMax forum, w
Bluetooth	wireless technology based on the IEEE 802.15.1 standard for WPANs
ZigBee	wireless technology based on the IEEE 802.15.4 standard for WPANs
GSM	Global System for Mobile communications
GPRS	General Packet Radio Service

DSL	Digital Subscriber Line
RSSI	Received Signal Strength Indication
ns-2	network simulator version 2
GT-ITM	Georgia Tech Internetwork Topology Models
FHSS	Frequency Hopping Spread Spectrum
OFDM	Orthogonal Frequency Division Multiplexing
UWB	Ultra-Wide Band
MIMO	Multiple-Input and Multiple-Output
MAC	Multiple Access Control
HWMP	Hybrid Wireless Mesh routing Protocol
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
SSs	Subscriber Stations
PMP	Point-to-Multipoint
MBWA	Mobile Broadband Wireless Access
BER	Bit Error Rate
SINR	Signal Interference Noise Ratio
SNR	Signal Noise Ratio
DBPSK	Differential Binary Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
CCK	Complementary Code Keying
LAETT	Load Aware Expected Transmission Time
GAB	Global Association information Base
LAB	Local Association information Base
PER	Packet Error Rate

CBR	Constant Bit Rate
ATTBW	Attainable Bandwidth
VoIP	Voice over Internet Protocol
$AC_{a,i}^{WMNs}$	the total association cost of STA i if associated with MAP a in WMNs
$AC_{a,i}$	the association cost of the access link between STA i and MAP a
$RC_{a}^{Backbone}$	the association cost of the backbone route from MAP a to the destination STA

Chapter 1

Introduction

1.1 Wireless Networks

Network communication with end devices is increasingly wireless. From wireless wide area networks (WWAN), wireless metropolitan area networks (WMANs) and wireless local area networks (WLANs) to wireless personal area networks (WPANs), many standards have been proposed as shown in Table 1.1. Many industrial alliances and forums are also established, such as WiMAX [1], Wi-Fi [2], [3], Bluetooth [4] and ZigBee [5], to promote the commercial application of all the proposed wireless technologies.

Table 1.1: Wireless Network Standards.

Wireless Networks	Standards
Wireless Wide Area Networks (WWANs)	GSM, GPRS, 3G
Wireless Metropolitan Area Networks (WMAN)	IEEE 802.16
Wireless Local Area Networks (WLANs)	IEEE 802.11
Wireless Personal Area Networks (WPANs)	IEEE 802.15.1, IEEE 802.15.4

Actually, the most general form of wireless networks are ad-hoc networks. There are no constraints on network topology, node roles and services. In ad-hoc networks, all nodes can move freely and all nodes are peers to each other. It is extraordinarily complex in this general form due to its lack of constraints. Hence many prerequisites and assumptions are introduced to simplify the study and real application of this general wireless networks. All other wireless networks in some sense could be considered as the specific examples and particular application oriented scenarios, which involves wireless sensor networks, commercial applications of wireless standards (e.g., Wi-Fi, cellular networks). While most of the wireless technologies applied widely today involve only one hop wireless links (connecting to traditional wired networks) such as Wi-Fi, cellular networks and Bluetooth, multi-hop wireless networks are studied more and more due to their attractive advantages. Therefore, wireless mesh networks (WMNs) [6], [7], [8], a simplified form of ad-hoc networks, are emerging as a promising wireless network technology which is attracting numerous academia and industrial interest. All these wireless networks can be categorized according to their unique characteristics as in Fig. 1.1.

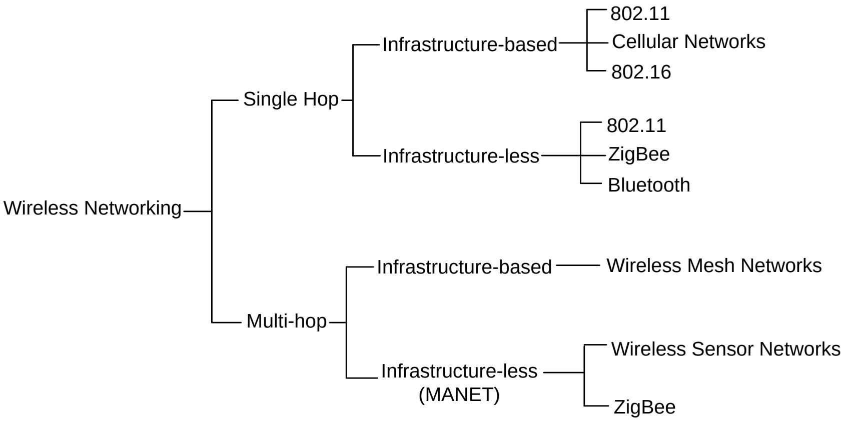


Fig. 1.1: Taxonomy of wireless networks.

1.2 Association Mechanisms

To date, the most broadly deployed wireless networks are wireless local area networks (WLANs), except cellular networks. IEEE 802.11 WLANs are deployed widely in campuses, communities and other public areas. In this kind of WLANs, there exist two kinds of nodes, access points (APs) and end stations (STAs). STAs must associate with APs, which are connected to the Internet directly using wired cables, to obtain network access. Because STAs' traffic communications must go through APs, the association mechanism which is responsible for choosing APs is very important in WLANs. WMNs also involve association mechanisms for STAs to choose mesh access points (MAPs). Similarly, association mechanisms are also significant in WMNs.

1.3 Thesis Overview

In this thesis, we propose a dynamic association mechanism in WMNs that takes load balancing, link quality and association oscillation avoidance into consideration. The metric introduced in this association mechanism measures the real traffic load through channel based load detection and suits both coordinated and uncoordinated networks. Because of the random characteristics of wireless links and the variability of network conditions such as node mobility and traffic requirements, dynamic re-association should be involved. To avoid association oscillation during re-association, we introduce oscillation avoidance schemes, which consist of periodic STA scan and re-association threshold. The performance of this dynamic association mechanism is evaluated in the context of 802.11 based wireless mesh networks.

The rest of this thesis is organized as follows. In chapter 2, WMNs are introduced, which covers network architecture, typical features, application scenarios and advantages of WMNs. Of course, there exist limitations and challenges in WMNs. These should also be mentioned. Nowadays, many existing standards are revisited to extend support for mesh functionalities. This brings out many new specifications, such as IEEE 802.11s and mesh in 802.16. Furthermore, some cities over the world have deployed real WMNs, which validate the advantage and feasible of WMNs.

Association mechanisms in wireless networks, especially in WLANs, are presented in chapter 3. The classic association mechanism in the IEEE 802.11 specification is based on received signal strength indication (RSSI). STAs simply choose the APs with the highest RSSI to associate with, which is simple but non-optimal. Therefore, there has been increasing interest in this topic and many new association mechanisms are designed. Furthermore, the association procedure is modeled as an association game in some literature to find the theoretical optimal solutions.

The association mechanisms in WMNs are introduced in chapter 4. To improve the performance of WMNs, many factors should be considered during the association procedure. Wireless link quality, load balancing, cross-layer association, association time overhead, how to reflect dynamic network conditions and accelerating network convergence speed are analyzed here.

Chapter 5 elaborates on our proposed association mechanism in 802.11 based wireless mesh networks. To explain our mechanism, the system model where our association mechanism is applied is introduced first. Because our mechanism is based on a cross-layer framework, the association costs of the access link and multi-hop wireless backbone are described respectively then. Finally, the detailed procedure and important factors we take into account are specified.

To validate the advantages of our association mechanism, we evaluate it in chapter 6. Network simulator ns 2 and topology generator GT-ITM are used together as the evaluation tool. We have carried out a series of experiments to verify the performance comprehensively, which involves performance of the basic association mechanism, dynamic re-association, oscillation avoidance schemes and network convergence speed and so on. We obtain convincing results from these experiments and are confident that our mechanism outperforms other existing mechanisms in WMNs.

Chapter 7 states the conclusion and future work.

Chapter 2

Wireless Mesh Networks

2.1 Introduction

In recent years, IEEE 802.11 WLANs have been widely deployed in campuses, communities and other public areas. During WLANs' fast development, there rise some constraints and problems. It is not suitable for outdoor deployment due to its very limited transmission range and wired backbone. Furthermore, its single hop wireless link to wired APs limits the mobility of STAs. To overcome all these limitations, the wired backbone is replaced by a multi-hop wireless backbone and hence a completely new network – wireless mesh network (WMN) is introduced. WMNs are emerging as a promising technology for next generation wireless networks. WMNs are dynamically self-configured, self-organized and self-healing, with the nodes in the network automatically establishing mesh connectivity. There are mainly two types of nodes in mesh networks: mesh routers and mesh clients. Mesh routers with routing functionality form the multi-hop wireless backbone. Mesh clients associate with mesh routers to access the whole network. Some mesh routers are further integrated with gateway functionalities that can be connected to the Internet through wired cables. All these features bring many advantages to WMNs, such as rapid deployment with lower cost backbone, easy to provide coverage in hard-to-wire areas, greater range due to multi-hop forwarding, higher bandwidth due to shorter hops, etc.

2.2 Characteristics of Wireless Mesh Networks

2.2.1 Network Architecture

As a new networking technology, WMNs can be classified into three types in terms of their architecture [6].

Infrastructure/Backbone WMNs. In this architecture, mesh routers form an multi-hop wireless infrastructure/backbone for STAs/mesh clients, as shown in Fig. 2.1. Without routing functions, all the STAs must associate with mesh routers to access other networks and STAs. Some mesh routers are equipped with gateway/bridge functionalities, which can be connected to other types of traditional networks, such as Wi-Fi, cellular networks, WiMax, wireless sensor networks and the Internet, etc. with wireless technologies or wired cables. Hence, in this kind of WMN architecture, existing networks can be integrated together with the multi-hop wireless infrastructure/backbone, if gateway/bridge functionalities are provided. Of course, the wireless backbone can be built using various types of radio technologies, in addition to the most commonly used IEEE 802.11 technology. In order to integrate different networks and optimize the channel resource assignment, mesh routers may be equipped with multiple radios with different radio technologies. For conventional clients/STAs with the same radio technologies as mesh routers, they can directly communicate with mesh routers. If different radios are used, STAs must communicate with their base stations that have connections to mesh routers with gateways.

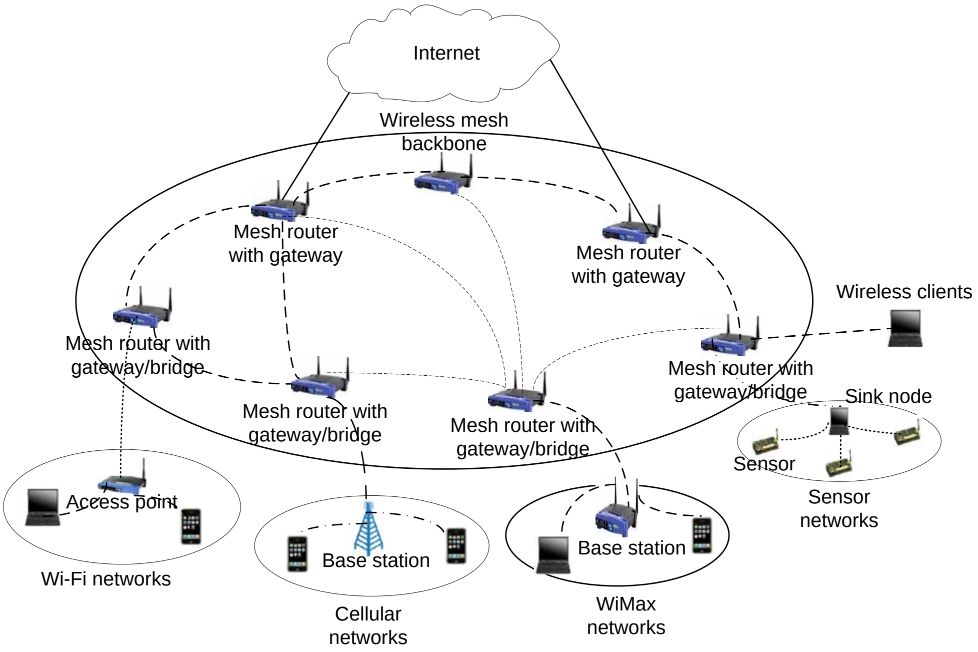


Fig. 2.1: Infrastructure/Backbone wireless mesh networks.

Client WMNs. In client WMNs, all STAs/client devices form a peer-to-peer wireless network and relay traffic for each other. So, unlike the STAs in infrastructure/backbone WMNs, the STAs here are not only the end user applications providers, but also the traffic relays/routers. Thus, a client WMN is actually the same as traditional ad hoc network. The STAs initiate and relay traffics themselves.

Hybrid WMNs. Hybrid WMNs are the combination of infrastructure and client WMNs, which are depicted in Fig. 2.2. In this architecture, there also exists a multi-hop infrastructure/backbone, which can be used to integrate different types of networks, with some of the mesh routers equipped with gateway functionalities.

While as in client WMNs, STAs in hybrid WMNs can also act as traffic routers for other STAs. This means STAs can communicate with each other without the help of mesh routers. Anyhow, if STAs want to communicate with STAs in other networks, they should associate with mesh routers directly or indirectly. Combining the advantages of both infrastructure and client WMNs, hybrid WMNs are very flexible and will be the most applicable case. While nowadays, due to the wide deployment of IEEE 802.11 based WLANs, 802.11 based WMNs are proposed as the most realistic implementation of WMNs, to maintain the backward compatibility with existing WLANs. So, in our study of the association mechanisms in WMNs, we take the infrastructure/backbone architecture as the association context.

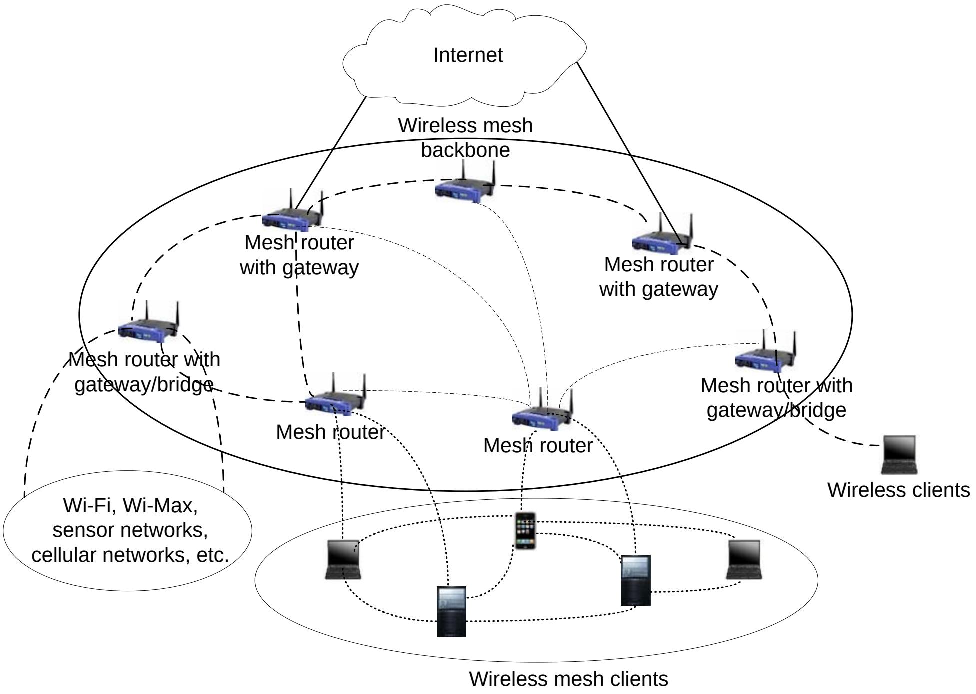


Fig. 2.2: Hybrid wireless mesh networks.

2.2.2 Typical Features

A WMN has many unique features that differentiate it from other wireless networks [9].

Multi-hop wireless network. One objective of WMNs is to extend the coverage area of current wireless networks while not sacrificing the channel bandwidth. Thus, multi-hop wireless backbone is introduced. Additionally, WMNs can improve channel capacity due to their shorter hops. Shorter hops means lower transmission power, hence improves power efficiency.

Capabilities of self-organization, auto-configuration and self-healing. All the mesh routers self-organize to form the multi-hop mesh backbone, and they auto-configure and self-heal themselves to maintain the mesh connectivity, in case some mesh routers were down. This self-organizing and flexible architecture enables WMNs' rapid deployment with lower upfront cost and gradual growth as needed.

Mobility depending on the type of mesh nodes. The two types of mesh nodes in WMNs have different mobility characteristics. Mesh routers in the multi-hop mesh backbone have minimal mobility, while STAs/mesh clients can be stationary or mobile. This simplifies the design of the management protocols (eg. routing protocols, channel assignment mechanisms, etc.) while not constraining the mobility freedom of STAs.

Multiple types of network access. In WMNs, STAs can access the Internet through multi-hop mesh backbone and communicate with each other through both the mesh backhaul and peer-to-peer networks (client mesh). Additionally, the integration of WMNs with other wireless networks enables STAs to access the applications provided by other networks.

Power consumption constraints depending on the type of mesh nodes.

The two types of mesh nodes in WMNs also have different power consumption constraints. Mesh routers are usually powered by power cables and do not have strict constraints on power consumption. However, STAs (eg. hand phones, PDAs, laptops, etc.) may require power efficient protocols to facility their free mobility. Therefore, the protocols applied in mesh routers and STAs shall be designed respectively, because of their unique requirements.

Compatibility and interoperability with existing wireless networks. To promote the realization and popularity of WMNs, they must be backward compatible with existing wireless networks, such as Wi-Fi, cellular networks, Bluetooth, etc. when integrating with these existing networks.

2.2.3 Application Scenarios

The unique characteristics and advantages make WMNs a promising network technology in many applications. Actually, the research and development of WMNs are motivated by real applications which cannot be full satisfied by traditional wireless networks. Therefore, WMNs are introduced accordingly and aimed to fulfill these real application scenarios.

Residential networking. Nowadays, residential networking is realized through IEEE 802.11 WLANs. While residential WLANs usually have dead zones without service coverage. Deploying multiple APs may solve this problem but is very expensive. In addition, all APs should be connected to the Internet though wired Ethernet, which makes it also inconvenient. A WMN is a desirable candidate in such a scenario. The primary purposes for WMNs are to create low cost, easily deployable, high performance wireless coverage throughout the home. WMNs should help to eliminate service dead-spots and areas of low quality wireless coverage throughout the home. In WMNs, STAs could communicate with each other through a multi-hop mesh backbone rather than going back to the wired backhaul network access modem or hub. Hence, network congestion due to backhaul access can be avoided. All these enable WMNs to support bandwidth demanding applications such as video transfer within home networks. Consequently, WMNs suits residential networking well.

Community networking. The common solutions for network access in communities are based on cables or DSL connecting to the Internet, and the last hop is wireless by connecting a wireless router to a cable or DSL modem. This kind of solutions has several drawbacks, such as having all traffic flowing through the Internet, much area in between houses is not covered by wireless services and only a single path may be available for a home to communicate with the Internet or neighbors, etc. WMNs can mitigate these drawbacks through self-organized mesh connectivity between homes. In community networking, WMNs rapidly provide connectivity to locations where the wired infrastructure is not available or is cost prohibitive. With self-healing wireless mesh backbone, WMNs also enable advanced applications/services through ubiquitous access and reliable connectivity, compared with the single access path in traditional community networking.

Metropolitan area networks. Metropolitan area network is one of WMNs' typical application scenarios. WMNs outperform existing metropolitan area networks in several aspects. The data rate provided by WMNs is much higher than traditional networks such as cellular networks. Multi-hop wireless mesh backbone taking the place of wired backhaul significantly decreases the deployment cost, which makes WMNs economical alternatives to broadband networking, especially in developing countries and cities. Furthermore, WMNs scale very well due to the flexible wireless mesh backbone, which is very important for metropolitan area networks.

Transportation systems. Currently, limited IEEE 802.11 or 802.16 network access is available at stations, stops and buses in some cities. WMNs can extend network access into buses, trains, even cars. Thus, convenient passenger information services, remote monitoring of in-vehicle security video and driver communications can be supported. To enable such WMNs in transportation systems, high speed mobile backhaul from a vehicle (bus, train or car) to the Internet are needed.

Public safety usage case. Public safety mesh networks provide wireless network access to emergency and municipal safety personnel such as fire fighters, policemen and emergency workers responding to an incident. The network may be used for video surveillance, tracking emergency workers with sensors, voice and data communication between emergency workers, uploading images, downloading information, etc.

Military usage. Military usage of WMNs has much more requirements. It involves more node mobility, a heavy reliance on fully automated network management, self-healing property and power constraint.

2.3 Issues and Challenges

The distinct features and advantages of WMNs bring many issues and challenges to be solved when building a large scale high performance wireless mesh networks. The issues and challenges exist at all layers of the ISO model. Here it follows a bottom-up layered approach to elaborate these issues and challenges.

A. Physical Layer

To increase the capacity of WMNs, challenges at the physical layer are similar to that in other wireless networks. All advanced physical layer techniques can be used in WMNs. Schemes such as Frequency Hopping Spread Spectrum (FHSS), Orthogonal Frequency Division Multiplexing (OFDM) and Ultra-Wide Band (UWB) are commonly applied to increase the reliability of the high speed transmission. In order to mitigate the wireless interference, multi-channel, multi-radio, MIMO and directional antennae can be considered. Besides, several other characteristics shall be taken into account, which are mobility, link adaption, variable transmission power, multiple transceivers and link quality feedback, etc.

B. MAC Layer

Due to the advanced underlying physical layer techniques, designing an efficient MAC protocol is a challenging task. Furthermore, the distinct features of WMNs such as multi-hop, self-organization and mobility make MAC design an even tougher problem. MAC protocols in WMNs can be single-channel or multi-channel. In the multi-channel case, how to assign channels to nodes and transceivers efficiently so as to maximize the network capacity and minimize the interference is critical. When directional or smart antennae are used, cross-layer design is required. In addition, WMNs consist of hundreds of nodes which are distributed in a relatively wide area. So, the deployed MAC protocol must be scalable, which implies a distributed MAC protocol may be better. During the design of an efficient MAC protocol, self-organization must be supported by the MAC protocol, and problems in network layer should also be considered, because the formed topology may impact the routing algorithm.

C. Network Layer

Although WMNs and ad hoc networks are both multi-hopped, the traffic requirements of them are different. In WMNs, most of the traffic is between gateways and mesh clients, while in ad hoc networks, traffic is flowing between arbitrary pair of nodes. Additionally, nodes mobility situations in WMNs and ad hoc are very different. Hence, the routing algorithms proposed for ad hoc networks may not work well in WMNs. Specific customized routing protocol shall outperform general ad hoc routing protocols. Furthermore, conventional routing metrics (e.g., hop count) may be inefficient in WMNs. Some new routing metrics (e.g., link quality, loss rate, etc.) should be considered. Besides, fairness may be another concern in routing design in WMNs. Because users relaying traffic for the source client along the route between source client and gateway may starve the source client by sending their own data, which may be more serious if all nodes just use a single forwarding queue. Of course, scalability, robustness, reliability and flexibility should be kept in mind also. Multi-radio routing, multi-path routing, hierarchical routing and geographic routing are all the open research issues in WMNs.

D. Transport Layer

Today, no specific transport protocol has been proposed for WMNs. Due to the distinct characteristics of WMNs, the current widely deployed TCP transport protocol in Internet can not be used in WMNs directly. TCP is designed specifically for wired networks, in which the packet losses are mostly caused by buffer overflow in routers. While this prerequisite is not true in WMNs. In WMNs, packet losses may be caused by poor wireless links, medium access contention or user mobility. So, TCP cannot be used in WMNs. New transport protocols shall be designed specifically for WMNs, or an adaptive TCP may work well in WMNs.

E. Other Challenges

Additionally, other challenges such as security, authentication and privacy should not be neglected.

2.4 Standard Activities

Many standards for wireless networking are now taking the next step to support mesh architecture in which data is commonly forwarded on paths consisting of multiple wireless hops. Special task groups have been established to define the requirements for mesh networking in WPANs, WLANs and WMANs.

2.4.1 IEEE 802.11s

IEEE 802.11 based WLANs do support a mesh operating mode. Laptops and PDAs with 802.11 interfaces can be configured to operate in mesh mode. All the participants can exchange information among themselves without the help of APs. Due to the limited transmission range and lack of routing protocols, it is not scalable and cannot operate efficiently. Hence 802.11 standards are revisited. WLAN is extended and multi-hop wireless backbone takes the place of traditional wired backbone. All these are introduced in IEEE 802.11s [10], [11]. In IEEE 802.11s mesh networks, there exists three kinds of nodes: mesh access points (MAPs), mesh points (MPs) and STAs. MAPs and MPs self-organize to form the multi-hop wireless backbone and relay end-to-end traffic from and to STAs. Whereas MPs just function as traffic relay, MAPs also provide wireless access links to STAs. STAs are unaware of the backbone connectivity and not involved in routing procedure. They associate with MAPs to obtain network access. Some of the MAPs are integrated with gateway functionalities and named as mesh portals. They can connect to the Internet and other types of networks. In order to determine the best path between STAs or between STA and other networks (e.g., the Internet), IEEE 802.11s proposes Hybrid Wireless Mesh routing protocol (HWMP) as the default routing protocol. HWMP combines the flexibility of on-demand route discovery with the efficiency of proactive routing to a mesh portal. When determining the best route, HWMP applies a simple metric based on airtime as default, with support for other metrics. Unlike in traditional ad hoc networks, where all nodes are involved in routing procedure, in IEEE 802.11s mesh networks, to find the route to the destination STA, the associated MAP of the source STA must get knowledge of which MAP is associated by the destination STA. To handle this association information, Local Association Base (LAB) and Global Association Base (GAB) are introduced to MAPs. Referring to the LAB and GAB, MAPs can find the destination MAP to which the final STA is associated with. Due to the aforementioned unique characteristics of 802.11 based wireless mesh networks, some conventional management procedures especially the association mechanism that affects the network performance significantly should be reconsidered.

2.4.2 Other Standards for Wireless Mesh Networks

Although IEEE 802.11s standard is relatively mature within all emerging standards which support mesh networking, there are other standards for WMNs.

IEEE 802.15.5 in WPAN [12]. In November 2003 the IEEE 802.15.5 Mesh Network Task Group was formed to determine the necessary mechanisms that must be presented in the PHY and MAC layers of WPANs to enable mesh networking. The use of mesh networking in WPAN environments is motivated by the power limitations of mobile devices. Specifically, applying multi-hop mesh communications increases the coverage of WPANs and allows shorter links to be used, which provides both higher throughput and lower transmission power. Actually, the current IEEE 802.15.1 (Bluetooth) and IEEE 802.15.4 (Zigbee) standards already partially support mesh networking, although they are not exactly as “mesh” as aforementioned. In IEEE 802.15.1, it supports a cluster architecture which is called piconets. All the piconets (a quasi-cluster) can be inter-connected to form a mesh network. While in IEEE 802.15.4, it supports three topologies, star, tree and mesh. But this mesh topology is flat, not like WMNs’ which can be hierarchical.

IEEE 802.16 in WMAN [1]. In IEEE 802.16, WiMax supports mesh operation mode, besides the basic point-to-multipoint (PMP) mode. Unlike the MAC protocols in other wireless networks, WiMax applies a time division multiple access (TDMA) based MAC to support mesh networking. In mesh mode, all subscriber stations (SSs) may have direct links with other SSs, and the data traffic can be routed through other SSs and occur directly between SSs. Due to the TDMA based MAC, link scheduling mechanisms should be provided. There exist two kinds of link scheduling in WiMax, centralized and distributed algorithms. Although the definitive standards have already been released, the protocols and mechanisms in WiMax are still under study.

IEEE 802.20 [13]. In December 2002, IEEE 802.20, the Mobile Broadband Wireless Access (MBWA) Working Group was established. IEEE 802.20 systems are intended to provide ubiquitous mobile broadband wireless network access in a cellular architecture, supporting the mesh networking in both indoor and outdoor scenarios.

2.5 Real Deployments

Although there exist many issues and problems to bring WMNs into realization, the unique characteristics and advantages of WMNs have been attracting many companies to commercialize WMNs applications, such as Strix, Nortel, etc. There are also some cities across the world which have already deployed city wide WMNs to facilitate public network access. Take Oulu, the largest city in northern Finland for example, the people in Oulu Finland have free access to the Internet through wireless services almost everywhere in the city. It's due to the city wide outdoor WMNs using Strix systems' technology.

Chapter 3

Association Mechanisms in Wireless Networks

3.1 Association Procedure in IEEE 802.11 Specifications

In the IEEE 802.11 [2] specifications, the association procedure consists of three phases. First, the un-associated STA scans the channels and listens to the beacons from available APs (passive scan) or broadcasts probe request frames to available APs and waits for the probe response frames responded by available APs (active scan). The STA uses the information broadcast by the APs (in the beacons or probe response frames) to make its association decision. In the second phase, the STA selects the AP that is the most appropriate to associate with. Finally, in the third phase, the STA sends an authentication request frame to the selected AP and then sends an association request frame to the AP after the authentication request is approved. If the association is successful, the STA becomes part of the network and is able to communicate with other STAs. In the specification of the IEEE 802.11, the information that is used by STAs to make their association decision in the second phase is the Received Signal Strength Indicator (RSSI) value in the management frames transmitted by APs. STAs select the AP with the highest RSSI value to associate with.

3.2 Association Mechanisms Already Proposed

In IEEE 802.11 standards, they define RSSI based association policy for WLANs. STAs make association decisions solely based on the received signal strength from available APs and associate with AP that has the highest RSSI. This policy, however, does not consider many important factors in wireless networks and may lead to poor network performance [14], [15]. Therefore, there has been increasing interest in this topic and many new association mechanisms are designed. Association mechanisms to balance the network load have already been introduced by various works. While very few of them measure real network traffic load practically. For example, [16] takes the number of STAs currently associate with an AP as the AP selection metric. It considers that an AP with fewer STAs associating with should have less traffic load. Hence, to avoid hot-spot phenomena and balance the traffic load, STAs will choose the AP with the minimum number of associating STAs to associate with. In the network model of [15], it assumes that adjacent APs use non-interfering channels and all STAs are greedy which always have traffic to send or receive. In [17], the load definition assumes that each STA has the same traffic characteristic. Obviously, all these assumptions are not practical in real wireless networks. Due to the unreliability of wireless links, many other association mechanisms consider link quality as the main factor. In [18], the authors estimate the link quality using Signal to Interference and Noise Ratio (SINR) in the uplink and downlink in the context of IEEE 802.11h wireless networks. As mentioned before, wireless links are not reliable and nodes share wireless channel based on MAC layer contention. All these features suggest that both load balancing and link quality should be considered in the association mechanisms of wireless networks.

3.3 Association Game in Wireless Networks

In wireless networks, wireless links fluctuate randomly and network conditions (e.g., traffic requirements and node mobility) vary with time. To characterize the network status, dynamic re-association should be involved. With dynamic re-association, how to model the association problem in wireless networks and analyze the performance of specific association mechanisms theoretically is another difficulty. Several works [19], [20] model the association problem as an association game and study the convergence and steady state performance of association using game theory. In [19], the author models the association procedure as an association game and proofs that the association scheme converges to a Nash equilibrium after finite steps. But how to avoid association oscillation and accelerate convergence speed requires further detailed study.

Chapter 4

Factors Considered in the Association in Wireless Mesh Networks

Based on the introduction of association mechanisms in wireless networks, this chapter will go further to present the association in WMNs. Due to the unique characteristics of WMNs, there must be something new to consider in the association in WMNs. We will introduce all important factors that should be considered in the association mechanism in WMNs to improve network performance.

4.1 Association Mechanisms in WMNs Proposed Previously

In WMNs, a multi-hop wireless backbone is introduced. All traffic among STAs or between STAs and other networks is routed through this wireless backbone.

Therefore, in addition that the access links between STAs and MAPs may be bottlenecked, the multi-hop wireless backbone routes could also be the bottleneck. Based on this observation, several cross-layer association mechanisms have been devised especially for WMNs [21], [22], [23]. [21] is the first to introduce cross-layer association in WMNs. STAs combine the association airtime cost of access links with the routing airtime cost of the backbone, and choose the MAP with the minimum total airtime cost to associate with. The authors extend their work in [21] to reach a general cross-layer framework for association control in WMNs in [23]. To suit general WMNs, they differentiate coordinated and uncoordinated mesh networks and design corresponding association mechanism to them respectively. In the framework, they further integrate these two types of associations into a hybrid association that smoothly transits from coordinated association to uncoordinated association according to the network situation. The framework also gives different weights to the access link cost and backbone route cost, and adjusts the weights dynamically. In [22], a smart association that also takes into account the cost of backbone routes is proposed. It improves the end-to-end performance of WMNs. Nevertheless, coordinated networks is assumed. Concluding these previous works, several important factors in the association in WMNs are highlighted below.

4.2 Link Quality

As in common wireless networks, link quality should also be considered when associating in WMNs. What metrics could be used to denote the link quality, Signal Interference and Noise Ratio (SINR) or anything else? Due to the characteristics of wireless communication, links between a STA and APs within range may have different data transmission rates. Additionally, wireless transmitters should adapt data transmission rate in real-time when they are roaming in the environment or when wireless links fluctuate randomly, in order to improve transmitting performance. So, data rate can be one of the metrics denoting wireless link quality. Furthermore, unlike wired links, wireless links are not reliable. Bit error rate (BER) in wireless networks are much higher than that in wired networks. Packet error rate (PER) is another metric to indicate link quality. Therefore, we involve data rate and packet error rate into our association mechanism.

4.3 Load Balancing

STAs in IEEE 802.11 specification just select the AP with the highest RSSI to associate with. This association mechanism is simple, but it will easily cause hot-spot phenomena, where some APs are heavily loaded even congested while others may be very light loaded even idle. This unbalanced traffic load distribution degrades network performance significantly and should be avoided with no doubt. To balance the traffic load, the loads of APs must be known first, which means we must know which AP is heavily loaded and which AP is light loaded during the association procedure. Given the traffic loads of all the available APs, a STA then should choose that AP with the minimum traffic load to associate with. Hence, how to obtain the knowledge of traffic loads of all the available APs becomes the difficulty. Some mechanisms predict the traffic load basing on some unpractical assumptions (e.g., assuming every STA has the same traffic requirement), while other mechanisms measure the traffic load basing on some nontypical packet transmissions (e.g., just management packets not real data packets). Both these schemes cannot reflect the real traffic situation practically. In order to indicate the real traffic load and reflect it in real-time, our association mechanism measures the real traffic load through channel based load detection. Every AP detects its channel occupancy ratio periodically and updates the channel occupancy ratio basing on the current measurement and historical values, thus smoothening then measurement procedure. This real-time measurements and updates reflect the real traffic load throughout wireless networks, although it may incur additional measurement overhead.

4.4 Cross-layer Association

In IEEE 802.11 based WLANs, there exists only one hop wireless link between STAs and wired networks (e.g., the Internet) which are connected through APs. Although the wired cable between APs and wired networks may be bottlenecked, the single hop wireless link is more vulnerable to limited capacity and packet loss. Thus, most of the association mechanisms in WLANs just take the single hop wireless link into consideration. To improve WLANs, WMNs replace the wired cable with a multi-hop wireless backbone, thus introducing multi-hop wireless routes between STAs and other networks (e.g., the Internet, Wi-Fi, WiMax, etc.). Due to the unreliability of wireless links, association mechanisms in WMNs should consider the multi-hop wireless backbone also. Within the multi-hop wireless backbone, there are multiple paths between every MAPs pair. To transfer packets between STAs and STAs or between STAs and other networks, routing protocols must be provided. Furthermore, if only access links between STAs and MAPs are considered, high performance cannot be guaranteed. Specifically, if STAs choose MAPs just according to access links, the quality of the multi-hop route from the selected MAP to the destination node may be poor, which leads to poor performance. So, the routing protocols should take link quality and/or other factors which are important to association into consideration during the procedure of routes finding. In considering a comprehensive approach, association mechanisms in WMNs should consider the access links and multi-hop wireless backbone jointly. Namely, this is a cross-layer association mechanism. Our dynamic association mechanism in 802.11 based WMNs is based on this cross-layer association framework.

4.5 Reflecting Dynamic Network Conditions

As in common wireless networks, characteristics of wireless access links and multi-hop wireless backbone fluctuate randomly. Furthermore, the traffic requirements of STAs vary with time. This results in random traffic loads in MAPs. All these dynamic network conditions may make the current association decision out of date. Specifically, STAs make their association decision to choose an optimum MAP to associate with just basing on the current network status (e.g., link quality, traffic load, etc.). Because network status varies randomly as time goes by, the current optimum choice may not be optimum in the very near future. This means that the MAP currently chosen by a STA to provide optimum performance may not provide good performance in the future. In order to improve network performance as much as possible, association decisions should be optimum to the network conditions persistently. Therefore, dynamic re-association is introduced to characterize the randomly varying network conditions. All MAPs detect and update their traffic load periodically. STAs will trigger re-associations if they find other MAPs providing better performance than the current one. This is also the rationale of our dynamic association mechanism.

4.6 Association Time Overhead

The whole association procedure shall take some time. Before a STA associates with a MAP, it cannot communicate with other STAs or networks. As stated in the previous section, dynamic re-association is introduced when association in WMNs is concerned. During the procedure of dynamic re-association, STAs stand alone and all the traffic transmitted by STAs will be dropped directly. Thus, the time overhead of association should be diminished. The longer the association procedure lasts, the more data will be dropped. In dynamic association mechanisms, two factors will affect the aggregate association time overhead, the actual duration of the association procedure and the re-association number/re-association times. So, association time overhead can be decreased in two ways, shortening the duration of association procedure and reducing re-association number/re-association times. How to shorten association duration is widely studied in works related to “supporting fast handoff in WLANs”. We just focus on how to reduce re-association times, which is obtained by introducing re-association threshold and periodic STA scan.

4.7 Accelerate Network Convergence Speed - Association Oscillation Avoidance

All the association mechanisms proposed for wireless networks so far are greedy schemes, where each STA chooses to associate with the AP/MAP from which it expects to obtain the best performance. In this setting, STAs are non-cooperative and behave selfishly to optimize their own performance. When a STA associates with an arbitrary AP/MAP, those STAs already associated with the same AP/MAP may experience performance degradation. Thus, this new association may trigger re-associations throughout the networks, since those STAs associated with the current AP/MAP may now find some other AP/MAP with better performance. When dynamic re-association is introduced in WMNs, one (re-)association may trigger a burst of re-associations throughout the network. This means that dynamic re-association may incur association oscillation in the network. Whether the network will converge to a stable state and how fast it will converge to the stable state if there exists a convergence status should be considered in this context. [19] claims that the network will reach a Nash equilibrium within a finite number of steps when modeling the association mechanism as an association game using game theory. Now that the convergence status exists, the converging speed should be accelerated.

4.8 Conclusion

As mentioned above, there are several important factors that should be considered when dealing with association mechanisms in WMNs. In addition, how to tradeoff among these factors to maximize network performance is essential and this will be discussed in Chapter 5 and Chapter 6.

Chapter 5

Dynamic Association in 802.11 Based Wireless Mesh Networks

To improve network performance in IEEE 802.11 based WMNs, especially in terms of end-to-end transmission delay, throughput and accelerating network convergence speed, we propose a dynamic association mechanism based on the cross-layer association framework. The elaboration of our association mechanism is described below.

5.1 System Model

Assume an IEEE 802.11 based WMN which is connected to the Internet through wired cables (Actually, it can also be connected to other networks, such as cellular, WiMax and wireless sensor networks, etc.) as shown in Fig. 5.1, it consists of MAPs, MPs and STAs. All the nodes are distributed randomly in a geographical area. The MAPs and MPs self-organize to form a multi-hop wire-

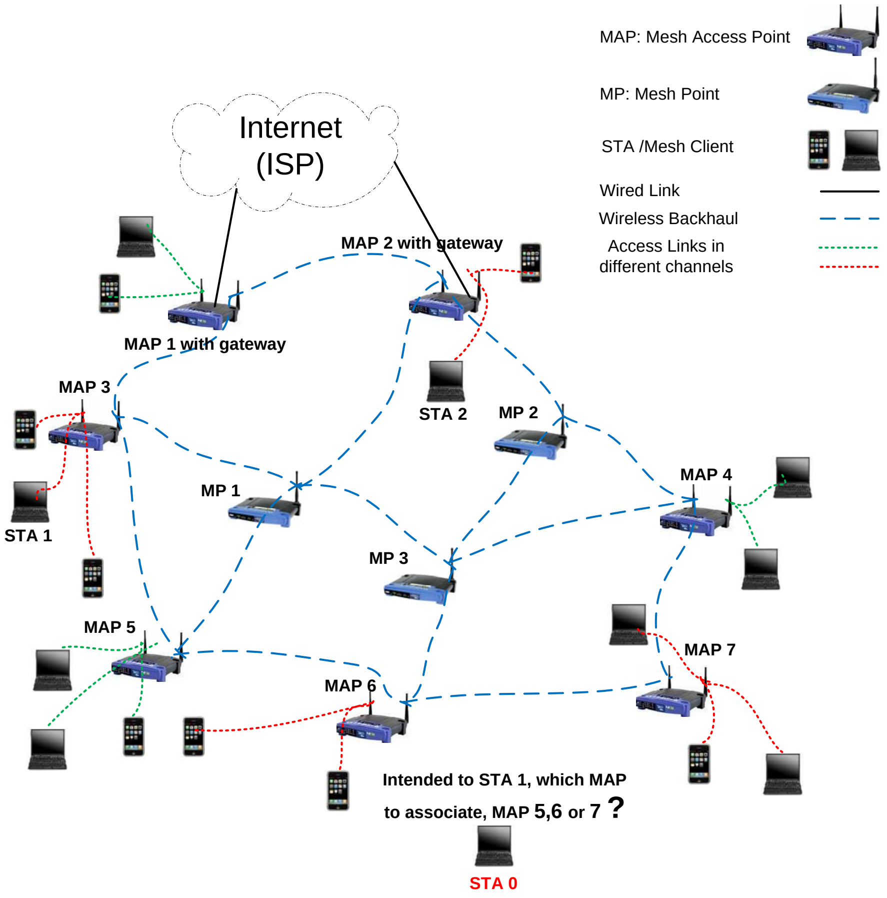


Fig. 5.1: System model for association in 802.11 based WMNs.

less backbone and take the responsibility to relay traffic between STAs or between a STA and the Internet, using a suitable routing protocol. Some of the MAPs have gateway functionalities and act as portals to other networks. STAs associate with MAPs to gain network access and become part of the whole mesh network. STAs are equipped with one wireless network interface, MAPs and MPs can be equipped with multi-interfaces. In MAPs, one interface acts as an access interface for communication between themselves and STAs, others act as relay interfaces in the backbone. Interfaces in MPs are special for relay purpose. The access interface and relay interfaces can either apply different radio technologies or just adopt the same radio technology but operate on different channels. Access interfaces in neighboring cells can operate either on the same channel or on different channels, corresponding to uncoordinated and coordinated networks. To improve the entire mesh network performance, a proper association mechanism is required.

5.2 Framework of Dynamic Association Mechanism

We propose a dynamic association mechanism basing on the cross-layer association framework, which is defined as

$$AC_{a,i}^{WMNs} = \omega_1 AC_{a,i} + \omega_2 RC_a^{Backbone}, \tag{5.1}$$

where $AC_{a,i}^{WMNs}$ is the total association cost of STA i if associated with MAP a in the wireless mesh network, $AC_{a,i}$ is the association cost of the access link between STA i and MAP a, $RC_a^{Backbone}$ is the backbone route cost from MAP a to the destination MAP associated by the destination STA or to the MAP connected to other networks, ω_1 and ω_2 ($\omega_1 + \omega_2 = 1, 0 \leq \omega_1, \omega_2 \leq 1$) are the weights assigned to the access link and the backbone route. This dynamic association mechanism jointly takes traffic load balancing, link quality and association oscillation avoidance into consideration. During the (re-)association procedure, STAs choose the MAP in range with the minimum total association cost to associate with. STAs trigger dynamic re-associations periodically to adjust to the current network status in real time.

5.3 Elaboration of Dynamic Association Mechanism

5.3.1 Association Cost of the Access Link

We define the association cost of the access link by estimating the expected transmission time of a test frame as

$$AC_{a,i} = \frac{s}{ABW_{a,i}}, \tag{5.2}$$

where s is the number of bits in the test frame, $ABW_{a,i}$ is the attainable bandwidth between STA i and MAP a. So, to obtain the expected transmission time in access links, attainable bandwidth should be determined first.

Due to the characteristics of the time varying wireless communication channel, the transmission rate of wireless interfaces should be chosen adaptively because of STA mobility, time varying interference and location dependent errors. There are rate adaptation strategies in many wireless nodes, including 802.11 based networks. Thus, the attainable bandwidth is directly affected by the adapting data rate. In IEEE 802.11 based networks, neighbor nodes operating on the same channel share radio resources coordinately basing on CSMA/CA and virtual carrier sense MAC mechanisms. Therefore, we should also consider channel occupancy ratio when predicting the attainable bandwidth. In addition, we include packet error rate due to wireless links' unreliability. As a result, we define the attainable bandwidth as

$$ABW_{a,i} = (1 - e_{a,i})(1 - Ch_a^t) r_{a,i}, \tag{5.3}$$

where Ch_a^t is the channel occupancy ratio of the channel where MAP a is operating at time t, $r_{a,i}$ is the data transmission rate in the access link between STA i and MAP a, and $e_{a,i}$ denotes the packet error rate in the access link if packets of size s are transmitted at data rate $r_{a,i}$.

During the (re-)association procedure, STAs may determine their data rate $r_{a,i}$ basing on the applied rate adaptation strategy. On the other hand, the packet error rate $e_{a,i}$ needs to be separately considered.

Association mechanisms in [21], [23] calculate the packet error rate basing on previous measurements. However, we need to consider how a new STA determines the packet error rate to make its association decision before it becomes a part of the existing network. Even if some overhead packets (e.g., probing packets, etc.) are introduced with the specific purpose of packet error measurement, this measurement takes a long time and its accuracy is still doubtful. Therefore, this measurement based packet error rate estimation is not suitable for fast handoff and association. In our association mechanism, we determine the packet error rate basing on real-time analysis. In the context of 802.11 based wireless networks, we can determine the packet error rate with the availability of measured Signal Noise Ratio (SNR) [24]. STAs can get the received signal strength from all the received packets. Noise power at receiver side consists of thermal noise and platform noise. Once SNR is obtained, Bit Error Rate (BER) can also be determined. In the IEEE 802.11 specifications, several different modulation schemes are supported to provide flexible data transmission rates. For example, in 802.11b, DBPSK, DQPSK, CCK 5.5 and CCK 11 operate at 1Mbps, 2Mbps, 5.5Mbps and 11Mbps, respectively. Thus, the BER of different modulation schemes can be obtained as described in [25], [26], rather than via empirical means. In this way, STAs can determine packet error rate in a fast, real time and reasonably accurate fashion.

Next we determine the channel occupancy ratio Ch_a^t. The channel occupancy ratio Ch_a^t indicates the traffic load in the neighborhood of MAP a operating on that channel at time t. MAPs detect the channel occupancy ratio to obtain the traffic load on the channel. Load Aware Expected Transmission Time (LAETT) based association mechanism in [22] just detects the traffic load in cell a where MAP a belongs to. This cell based load detection holds when all neighboring MAPs (to be precise, it is their access interfaces) operate in a coordinated fashion on different channels. In other words, it works only in coordinated mesh networks. On the other hand, in uncoordinated mesh networks, MAPs in neighboring cells may operate on the same channel. The detected load is not the exact traffic load in the very cell MAP a belongs to but the aggregate load in the neighborhood of the channel MAP a operates on. Hence, cell based load detection cannot differentiate candidate MAPs for STAs during association in uncoordinated mesh networks. In this situation, the more important factor that affects the association decision is link quality [23]. This is why we also consider link quality (which is indicated by the packet error rate $e_{a,i}$) in our association mechanism. To adapt the association mechanism to suit both coordinated and uncoordinated mesh networks, [23] differentiates these two kinds of network conditions and apply different association mechanisms accordingly. While we jointly consider link quality, channel based load detection and adaptive data rates, our association mechanism can suit both coordinated and uncoordinated network conditions in a unified way. In our association mechanism, MAPs detect the traffic load in the channel they operate on and update the channel occupancy ratio periodically as

$$Ch_a^t = (1-p)Ch_a^{t-1} + p.Ch_a \tag{5.4}$$

where Ch_a^t and Ch_a^{t-1} denote the channel occupancy ratio in the channel MAP a operates on at detection cycle t and $t-1$, Ch_a is the channel occupancy ratio detected by MAP a at the current detection cycle, and p is the channel occupancy ratio updating parameter. Just as RED (Random Early Detection) queuing management algorithm calculates the average queue size in [27], MAPs with our mechanism update the channel occupancy ratio smoothly with an updating parameter p ($p = 0.5$ in our implementation) incorporating current load detection and historical values. This makes our association mechanism more tolerable to traffic burst and mitigate association oscillation. In (5.4), the current channel occupancy ratio Ch_a is defined as:

$$Ch_a = \frac{T_{busy}}{T_{det}}, \tag{5.5}$$

where T_{busy} denotes the amount of channel busy time during the detection period T_{det}.

5.3.2 Association Cost of the Multi-hop Wireless Backbone

Since this is a cross-layer association mechanism, besides the cost of access links between STAs and MAPs, the association cost of the multi-hop wireless backbone is also considered. In IEEE 802.11s [10], [11], it proposes Hybrid Wireless Mesh routing Protocol (HWMP) as the default routing protocol in the multi-hop wireless backbone formed by MAPs and MPs. The default routing metric is airtime based, which is defined to be the amount of channel resources consumed by transmitting the frame over a particular link:

$$C_a = [O_{ca} + O_p + \frac{B_t}{r}]\frac{1}{1-e_{pt}} \tag{5.6}$$

In (5.6), C_a is the airtime cost of the backbone link MAP or MP a belongs to, r and e_{pt} are the data rate and packet error rate, respectively. The channel access overhead O_{ca}, protocol overhead O_p and test frame size B_t are defined to be constant in the 802.11 specifications. Additionally, MAPs should know which MAP the destination STA is associated with in finding when to find the optimal route to the STA. Hence Global Association Base (GAB) and Local Association Base (LAB) are introduced in 802.11s. MAPs could know which MAP the destination STA is associated with by referring to GAB and LAB. With this airtime metric based HWMP routing protocol and information in GAB/LAB , MAPs can find the optimal route to the destination STA and obtain the airtime based association cost of the multi-hop wireless backbone, which is the summation of the airtimes of all the links along the route to the intended STA.

5.3.3 Procedure of Dynamic Association Mechanism

Our dynamic association mechanism is based on the cross-layer association framework introduced in [23]. [23] states that the cross-layer association scheme still cannot balance network load effectively as network load increases. To avoid any overloaded MAPs, it introduces a weight selection mechanism to update the weights of the association cost of the access link and the multi-hop route cost in the backbone. The reason why the weights should be adjusted when network load increases is because some of the MAPs can provide routes with low cumulative airtime costs to popular destinations such as the Internet. These MAPs are preferred by STAs and may become overloaded. In our system model, traffic is not just between STAs and the Internet, which means that popular destinations do not exist. So the weights ω_1 and ω_2 in (5.1) are not required to be updated when network load increases. They are kept constant throughout the association ($\omega_1 = 0.55, \omega_2 = 0.45$ etc.). Hence, the dynamic association mechanism proceeds as follows:

1) The STA scans the channels and broadcasts Probe Request frames which contain the address of the intended receiver.

2) MAPs responds with Probe Response frames indicating the backbone routing costs and the channel occupancy ratios.

3) The STA extracts required information from the Probe Response frames and calculates packet error rate, data transmission rate corresponding to all the candidate MAPs.

4) The STA calculates the total association costs and selects the MAP with the minimum cost to associate with.

5) The STA repeats the previous steps periodically and initiates a re-association if $AC_{a,i}^{WMNs} - AC_{b,i}^{WMNs} > T\%.AC_{a,i}^{WMNs}$, where T is the re-association threshold.

Our dynamic association mechanism is in the context of 802.11 based wireless mesh networks. MAPs are responsible for finding the optimal routes, detecting channel occupancy ratios and informing STAs in Probe Response frames. STAs initiate association procedures and make the association decision basing on the information from MAPs. All the required information and procedures can be obtained and implemented by extending the IEEE 802.11 framework, which makes the association mechanism compatible with the existing IEEE 802.11 standards.

5.3.4 Dynamic Re-association, Association Oscillation Avoidance and Network Convergence

In wireless networks, characteristics of wireless links fluctuate randomly, and as such, the network conditions such as node distribution and traffic requirements vary frequently. Therefore, the current association may be outdated when network conditions change. To cope with such variations and to optimize network performance in real-time, periodic dynamic re-association is introduced in our association mechanism, with all MAPs updating the required information (channel occupancy ratio, etc.) continuously.

During the association procedure, every STA chooses the MAP with the minimum association cost to associate with. This means that all the STAs are non-cooperative and behave selfishly in a greedy way to optimize their own performance. When a new STA associates with a MAP, those STAs already associated with that MAP may experience performance degradation. With dynamic re-association, those STAs may find other MAPs having lower association cost and initiate re-associations. These re-associations may trigger further re-associations. This frequent re-associations lead to association oscillation in the network, hence degrading the network performance. In order to overcome these detrimental effects, association oscillation avoidance mechanisms should be applied. As described in step 5 of the association process, STAs initiate a re-association only if the re-association threshold $AC_{a,i}^{WMNs} - AC_{b,i}^{WMNs} > T\%.AC_{a,i}^{WMNs}$ is satisfied. This means, the STA initiates a re-association only when it finds another MAP which can significantly improve the performance by T% than the current associating one. Furthermore, STAs will not calculate the association costs of available MAPs within range continuously, but only check the network conditions at regular intervals. This could also mitigate frequent re-association.

Could the network with dynamic re-association reach a stable state when a burst traffic is injected or network conditions change dramatically? And if it could, how soon will the network converge to the stable state? [19] models the association procedure as an association game and claims that the entire network converges to a Nash equilibrium within finite time. In our dynamic association mechanism, the re-association threshold is introduced with the aim also to accelerate the network convergence speed. Additionally, the STA re-association period can also influence network convergence speed. In order to alleviate frequent re-association, avoid association oscillation and accelerate network convergence speed jointly, further consideration is required to determine the optimal value of re-association threshold and period. All these will be discussed in the simulation in the next chapter.

5.4 Basic Analysis of Dynamic Association Mechanism

5.4.1 New Aspects of Dynamic Association

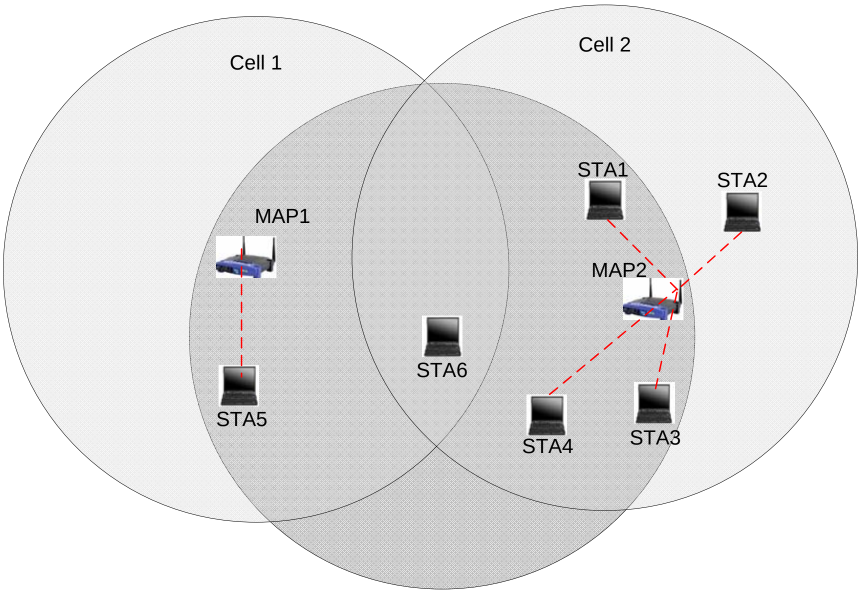
As aforementioned, our dynamic association mechanism introduces several new strategies into the association in WMNs, compared with previous proposed association mechanisms. First, it jointly considers several important factors for association in WMNs. Just as presented in Chapter 4, in order to improve network performance more significantly, link quality (data rate/link capacity, packet loss rate), load balancing (real time load detection), cross-layer association, dynamic re-association and association oscillation avoidance are taken into account together in the proposed dynamic association mechanism. Whereas existing mechanisms just highlight one or two such factors. Second, it brings in channel based load detection to detect practical traffic load real timely. This channel based load detection suits both coordinated WMNs and uncoordinated WMNs in a unified fashion. Hence, there is no need to make some unpractical assumptions (e.g., all neighboring MAPs operate coordinately on different channels) or differentiate coordinated and uncoordinated WMNs through some complex schemes. Third, association oscillation avoidance mechanisms, which consist of periodical STA scan and re-association threshold, are devised during the procedure of dynamic re-association. These oscillation avoidance mechanisms can further accelerate network convergence speed.

5.4.2 Basic Analysis

As validated in Chapter 5, the proposed dynamic association mechanism indeed improves network performance significantly. But what's the underlying rationale of all these new aspects?

Why load detection and channel based load detection? We know that load balancing is one of the important concerns when associating in WMNs. To balance the network load, traffic load distribution in the neighborhood of any STA should be known first. While to get the knowledge of load distribution without any assumptions or prerequisite conditions, load detection should be considered. This means, we can know the exact practical loads of MAPs in range through real time traffic load detection. There are two ways to detect traffic load in the context of 802.11 based WMNs. One is detecting load through carrier sensing just as CSMA/CA mac protocol in IEEE 802.11 specs. It considers the MAP as busy if the channel is sensed busy. The other is detecting load through monitoring wireless interfaces. If status of wireless interfaces is busy (e.g., transmitting or receiving), the MAP is considered as busy. Both methods can neatly detect traffic load if used properly. The first one actually senses the traffic load in the neighborhood of the operating channel. Hence it can only detect the actual traffic load of a MAP when MAPs operate coordinately on different channels. While the second method can detect the actual traffic load of MAPs both in coordinated and uncoordinated WMNs. In other words, the first one is channel based, the second one is cell based.

Actually, load detection has already been introduced in some previous association mechanisms, such as the load aware expected transmission time (LAETT) based association mechanism in [22], it proposes a cell based load detection. LAETT based association mechanism assumes that channels are carefully assigned to MAPs' access interfaces so that inter-cell interference is minimized. MAPs with this association mechanism just detect the traffic load of the cell they are belong to. This cell based load detection works well in coordinated WMNs, where channels are assigned to MAPs' access interfaces coordinately. But does it work in uncoordinated WMNs where access interfaces of neighboring MAPs may operate on the same channel? We can have an intuitive view in Fig. 5.2. As shows in Fig. 5.2, in the context of IEEE 802.11 based WMNs, the two neighboring MAPs, MAP1 and MAP2 operate on the same channel (actually, it is their access interfaces operate on the same channel). MAP1 is associated by only one STA, STA 5. MAP2 is associated by 4 STAs. The new coming STA, STA6 can hear both MAP1 and MAP2. How can MAPs detect traffic load in this situation? Of course, traffic load can not be detected according to the number of associating STAs. If cell based load detection is applied here, it indeed can obtain the actual traffic load of MAPs. But because this two MAPs are



An association scenario (MAPs operate on the same channel)

Fig. 5.2: Association in uncoordinated wireless mesh networks.

operating on the same channel, even if STA6 chooses the MAP with lighter traffic load to associate with, it still have no chance to transmit as long as there exists transmission in the cell of the other MAP. Since 802.11 uses a shared medium, what is really important for a STA is not the load of the associated MAP but the load of the STAs in its coverage area. Hence cell based load detection is meaningless in uncoordinated WMNs. In our dynamic association mechanism, we use channel based load detection here. Because it is based on carrier/channel sensing, all nodes overhear each other, the load observed by MAP1 is the same as by MAP2. In order to differentiate this two MAPs and improve network performance, the key point in the association of STA6 is link quality. Therefore, in uncoordinated WMNs, we use channel based load detection and link quality together to select MAP to associate with. Furthermore, this channel based load detection together with link quality works well in coordinated WMNs also. This is to say, with the combination of channel based load detection and link quality, our association mechanism suits both coordinated and uncoordinated WMNs in a unified way. There is no need to differentiate this two kinds of WMNs and design association mechanisms for them respectively as in [23].

Why association oscillation avoidance and accelerating network convergence speed? The reason why to introduce association oscillation avoidance has already been presented in Chapter 4. With regards to accelerating network convergence speed, it is to reduce re-association numbers, alleviate association oscillation and packet dropping when network conditions vary dramatically. Besides re-association threshold and STAs' periodical scan, shortening STA's actual duration of association procedure (it takes 30 - 40 ms in our implementation.) can further accelerate network convergence speed. While currently, it is not our concern.

5.5 Conclusion

In this chapter we have described that our dynamic association mechanism takes link quality, load balancing and association oscillation avoidance jointly into consideration. In the next chapter, we show that this mechanism can improve network performance significantly due to its characterizing network conditions in real time.

Chapter 6

Evaluation of the Dynamic Association Mechanism

6.1 Introduction of Network Simulation Tools

To evaluate the performance of our dynamic association mechanism, we have carried out simulations using the network simulator version 2 (ns2) [28], which is a discrete event simulator. Ns2 provides substantial support for simulation of wired and wireless networks. Currently, the mobile node model in ns2 supports only single wireless interface and single channel, as shown in Fig. 6.1 from [29]. Recently, multiple channels and multiple interfaces are very common in wireless networks. Our implementation is based on the IEEE 802.11b protocol, which supports 11 channels. Furthermore, to emulate coordinated and uncoordinated networks, multi-channel and multi-interface should be supported. Thus, we extend the mobile node model in ns2 to support multiple interfaces as elaborated in [30]. The extended node model is shown in Fig. 6.2. In our extension, every MAP is

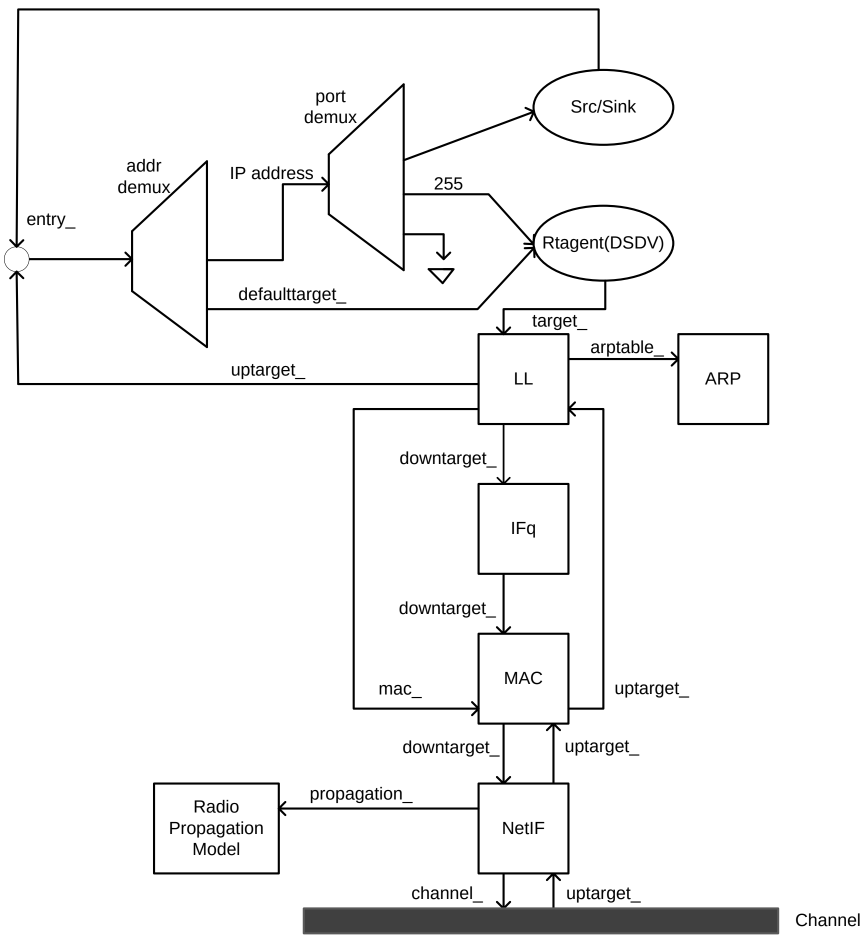


Fig. 6.1: Schematic of a mobilenode under the CMU monarch's wireless extensions to ns.

equipped with two interfaces, one for connecting with STAs and one for relaying traffic in the backbone. Because our association mechanism is 802.11 based, we implement the core functionalities based on the basic procedure defined by the IEEE 802.11 standard and modify the Beacon, Probe Request, Probe Response frames to carry the information required by our association mechanism. We further implement HWMP routing protocol together with GAB/LAB in the multi-hop wireless backbone to find the optimal routes and the routing costs.

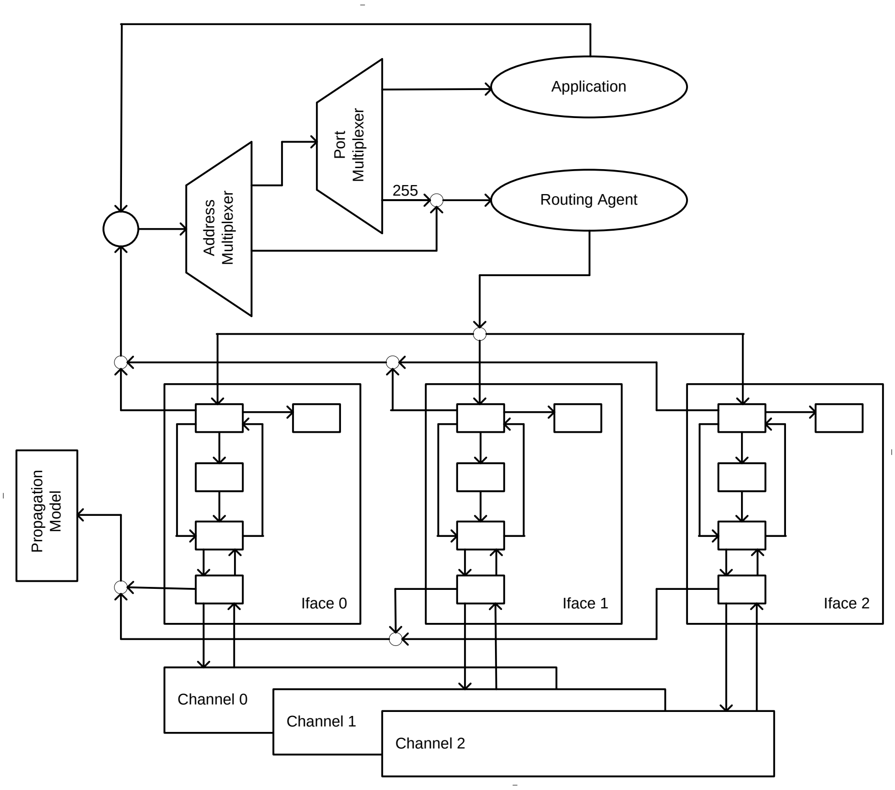


Fig. 6.2: Modified mobile node architecture supporting multiple interfaces.

There are also network simulation animator and network topology generator in ns2 installation package. In our simulation, we use the Georgia Tech Internetwork Topology Models (GT-ITM) [31] topology generator to generate the topology of the 802.11 based WMNs. GT-ITM topology generator can be used to create flat random graphs and two types of hierarchical graphs, the N-level and transit-stub. In IEEE 802.11s WMNs, there exists three types of nodes, MAPs, MPs and STAs. Without routing functionality, STAs should associate with MAPs to obtain network access. MAPs provide connectivity to STAs and relay traffic together with MPs among STAs or between STAs and other networks. This means, in WMNs, all the nodes are not peer to peer, and the topology of WMNs is hierarchical. Therefore, the transit-stub topology mode in GT-ITM suits our 802.11 based WMNs model very well. Fig. 6.3 shows one of the random topologies generated using GT-ITM transit-stub mode in a $1000m \times 1000m$ area. This involve 30 MAPs, 20 MPs and 300 STAs which are randomly distributed in the area. MAPs are equipped with two wireless interfaces, one access interface and one relay interface. MPs are equipped with just one relay interface. STAs are equipped with one interface to connect with MAPs. Relay interfaces in MAPs and MPs operate on the same channel to maintain the connectivity of the multi-hop wireless backbone. Access interfaces of adjacent MAPs may operate on either the same channel or different channels, which means this is neither coordinated nor uncoordinated networks, but a hybrid WMNs (in terms of channel assignment rather than architecture as introduced in Chapter 2). One of the MAPs is connected to the Internet through wired cable. The maximum transmission range of all the nodes is 150m. In our rate adaptation strategy, we use a simple wireless channel model in which the data transmission rate depends only on the distance between transmitters and receivers. Specifically, the distance thresholds for data rates 11Mbps, 5.5Mbps, 2Mbps and 1Mbps are 50m, 80m, 120m and 150m, respectively, just as advertised commonly by 802.11b vendors [32]. The simulation runs for 1000 seconds every time.

6.2 Performance of the Association Mechanism

All the performance evaluation here is based on the topology shown in Fig. 6.3 and configurations described above. First of all, we are to validate the merit of channel based load detection through a simple experiment based on a simplified simulation scenario. There involve 7 MAPs, 7 MPs and 21 STAs randomly dis-

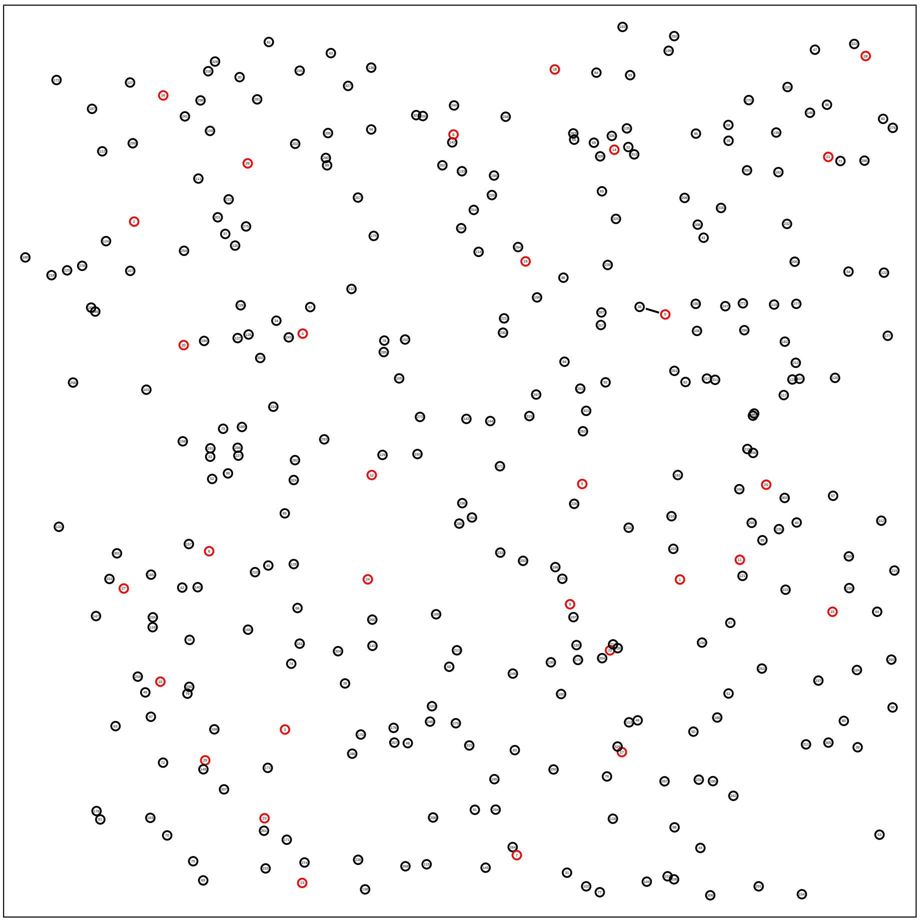
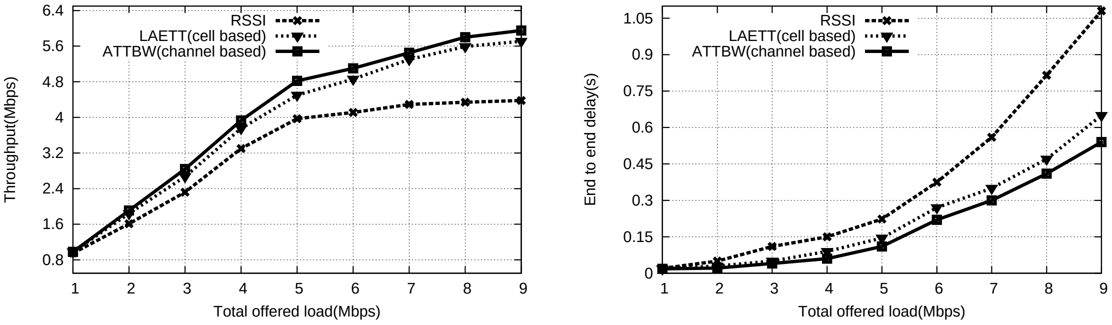


Fig. 6.3: One of the random topologies of the Wireless Mesh Networks for performance evaluation.

tributed in a $500m \times 500m$ area. Access interfaces of all 7 MAPs operate on the same channel. All other configurations are the same as the description above. This is to emulate pure uncoordinated WMNs. CBR traffic is injected to the network. No dynamic re-association is considered here. We compare our association mechanism which uses channel based load detection with load aware expected transmission time (LAETT) based association mechanism proposed in [22] which applies cell based load detection. We also include received signal strength indication (RSSI) based association in IEEE 802.11 as a reference. All these mechanisms are denoted by “ATTBW (channel based)” (our mechanism is attainable bandwidth based), “LAETT (cell based)” and “RSSI” in Fig. 6.4. It shows that our association mechanism outperforms the other two in terms of aggregate throughput and end-to-end transmission delay. Obviously, “ATTBW (channel based)” and “LAETT (cell based)” improve network performance significantly when compared with the classic “RSSI”. It is convincing that channel based load detection is better than cell based load detection in uncoordinated WMNs. Although channel based and cell based load detection both suit coordinated WMNs, in real cases, WMNs shall not be purely coordinated or uncoordinated. Thus, channel based load detection is more adaptive to general WMNs. Next is the main part of evaluation.



(a) Throughput.

(b) End-to-end transmission delay.

Fig. 6.4: Channel based load detection versus cell based load detection.

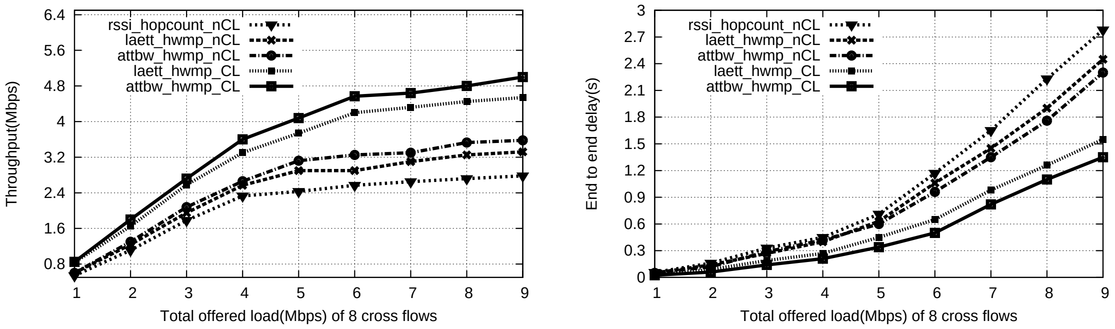
To validate the advantages of our association mechanism, we compare it with the classical RSSI based association mechanism recommended in IEEE 802.11, and with the LAETT based association mechanism proposed in [22]. We also show the merit of the cross-layer association framework compared with non cross-layer association. In our association procedure, STAs need to know the routing cost to the destination STA. This implies that the destination STA is already associated with some MAP. This is true in real situations. When you enter an existing network and want to exchange data with others, all your intended destinations are always there already. In the initial period of the simulation process, all the STAs are not associated with MAPs and there is no traffic requirement throughout the network. We start with random background traffic noise at the MAPs. All STAs except 8 traffic flow initiators associate with MAPs according to the association cost of access links. After the network reaches stability, the 8 remaining STAs initiate 8 CBR traffic flows throughout the network and associate with MAPs using our association mechanism. At this point, we do not consider dynamic re-associations. Furthermore, 3 traffic scenarios are involved, 8 flows around network edge, 8 parallel flows and 8 cross flows. We study the behavior of our association mechanism when the total offered load in the network increases from 1Mbps to 9Mbps, where all nodes are randomly placed as in Fig. 6.3.

Fig. 6.5 shows the scenario where 8 cross flows are injected into the network. 5 schemes with different combination of access link metrics and backbone routing protocols are considered. In the first 3 schemes, STAs select MAPs only based on the association cost of access links without taking the backbone routing cost into account, that is, non cross-layer associations are employed. The first scheme uses RSSI from MAPs to associate and hop count based AODV routing to relay traffic in the backbone. The second employs LAETT to associate and airtime based HWMP routing in the backbone. While the third applies our proposed metric – attainable bandwidth (ATTBW) in access links to associate and HWMP to relay traffic. The two remaining schemes apply cross-layer association framework which considers access link and backbone jointly, LAETT with HWMP and ATTBW with HWMP together. All the 5 schemes are referred to as "rssi_hopcount_nCL", "laett_hwmp_nCL", "attbw_hwmp_nCL", "laett_hwmp_CL" and "attbw_hwmp_CL", where "nCL" and "CL" denote non cross-layer and cross-layer, respectively.

It is apparent in Fig. 6.5(a) that our association mechanism "attbw_hwmp_CL" outperforms other schemes in terms of the aggregate throughput in the network. Compared with "rssi_hopcount_nCL", our mechanism can improve throughput dramatically by nearly 75%. It can also be seen that cross-layer association behaves better than non cross-layer. When traffic load is light, all schemes can improve throughput as total offered load increases. When total offered load goes beyond 5Mbps, non cross-layer association cannot improve throughput any more, but cross-layer association can still improve throughput. This means that cross-layer association mechanisms can expand effective network capacity when the network is heavy loaded. Additionally, we see that ATTBW is superior to LAETT which outperforms RSSI. Hence, association basing on real traffic load and link quality is very important.

Fig. 6.5(b) shows the average packet transmission delay in the network as total offered load increases. As expected, our mechanism "attbw_hwmp_CL" is the best. It can reduce the average delay approximately by 1.4 seconds compared to "rssi_hopcount_nCL". This is of remarkable significance in time constrained applications, such as VoIP. We can also see that the transmission delay is relatively small when the total offered load is low (within 5Mbps). When the offered load increases, transmission delay of non cross-layer schemes increases significantly. Because our mechanism takes the real traffic load of candidate MAPs into consideration, it balances traffic load and mitigates network congestion, hence decreasing packet transmission delay. This is shown that when traffic load becomes heavier, transmission delay of our mechanism increases much slower than others.

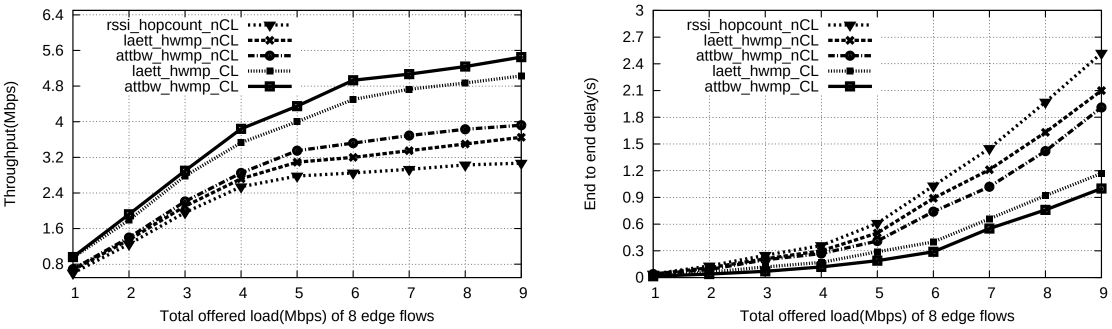
Here we only examine the network behaviors with 8 cross traffic flows. In the other two scenarios with 8 edge flows and 8 parallel flows shown in Fig. 6.6 and Fig. 6.7, respectively, our association mechanism also outperforms other schemes with the same trend. The only difference is that in the 8 cross flows scenario the aggregate throughput is lower than those in the other two, and the transmission delay is a little longer than those in the other two. This is caused by more severe MAC contention and hidden node phenomenon. These measurements validate our association mechanism having better performance than previous proposed ones in terms of the two typical network performance metrics, throughput and end-to-end delay. In the following section, we focus on dynamic re-association.



(a) Throughput.

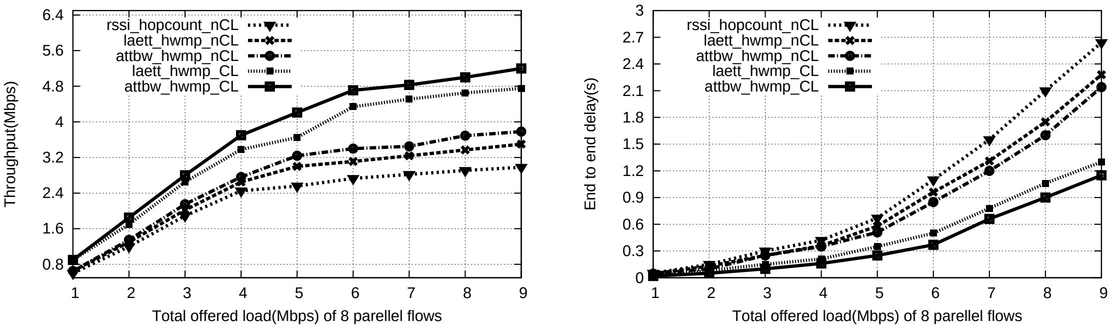
(b) End-to-end transmission delay.

Fig. 6.5: Basic performance evaluation with 8 cross flows.



(a) Throughput. (b) End-to-end transmission delay.

Fig. 6.6: Basic performance evaluation with 8 edge flows.



(a) Throughput. (b) End-to-end transmission delay.

Fig. 6.7: Basic performance evaluation with 8 parellel flows.

6.3 Dynamic Re-association versus Static Association

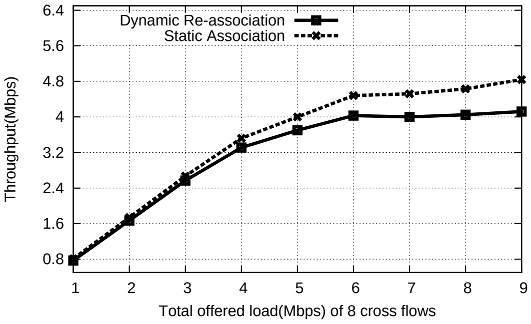
In the previous measurements, we merely considered static associations, wherein STAs having associated with MAPs never turn to other MAPs even when wireless network conditions change. However, in real wireless networks, wireless links fluctuate all the time and traffic requirements throughout the network vary randomly. To deal with such changing network conditions, we introduce dynamic re-association and evaluate its performance here. In order to simulate the random network conditions, we introduce poisson background traffic noise into MAPs. 8 poisson cross flows are chosen as the traffic scenario. During the dynamic re-association procedure, STAs scan channels in every 4 seconds interval and re-calculate the total association costs of candidate MAPs. If the MAP with the minimum total association cost is not the MAP the STA currently associates with, which means, the condition $AC_{b,i}^{WMNs} < AC_{a,i}^{WMNs}$ is satisfied, the STA i will initiate a re-association and transfer from MAP a to MAP b. Compared with the steps of dynamic re-association described before, no re-association threshold is involved.

Fig. 6.8 shows the performance of dynamic re-association compared with static association. Intuitively, dynamic re-association can reflect network conditions in real time, and therefore should improve network performance. In Fig. 6.8(a), we see that dynamic re-association degrades network throughput. When the network is heavy loaded, it causes approximately 0.8 Mbps throughput degradation compared with static association. On the other hand, in Fig. 6.8(b), dynamic re-association outperforms static association in terms of average end-to-end packets transmission delay. The heavier the network is loaded, the better the dynamic re-association behaves. To understand the underlying reasons for this unexpected behavior, we further measure the dropped data of these two mechanisms in Fig. 6.8(c). We can see that dynamic re-association causes more dropped data, especially when network load is heavy. This more severe data dropping causes throughput degradation directly. We further find that it costs STAs 30 to 40 milliseconds to transfer to another MAP after carefully analyzing the simulation trace file. This means that during the process of re-association, the re-associating STA stands alone and all packets transmitted out of the STA cannot be relayed by the backbone. It is the re-association transition time overhead that causes more data dropping. These experiments indicate that dynamic re-association indeed reacts to random network conditions in a meaningful manner (dynamic re-association reduces end-to-end packets transmission delay), but it causes more data dropping due to the re-association transition time overhead. Therefore, how to alleviate this re-association time overhead is very important.

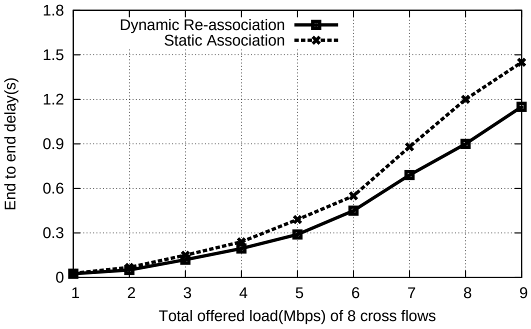
6.4 Oscillation Avoidance

In the experiments of dynamic re-association described in the previous section, no re-association threshold is involved. This means STAs will initiate re-association as long as there exists another MAP with lower total association cost than the current associated one. As pointed out before, the association of a new STA or re-associations may trigger frequent re-associations and association oscillation throughout the network. Additionally, re-association time overhead may lead to packet dropping, as described in the former section. Therefore, to reduce packet dropping, we should reduce the number of re-associations and avoid association oscillation. Therefore, the oscillation avoidance mechanism – re-association threshold is verified in this section.

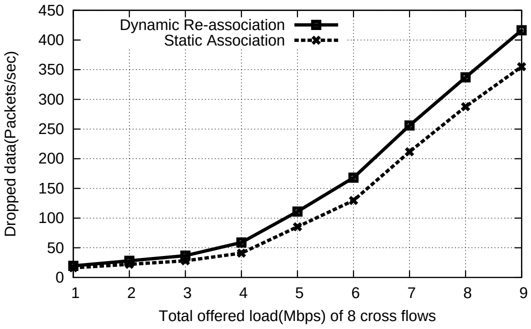
The re-association threshold, $AC_{a,i}^{WMNs} - AC_{b,i}^{WMNs} > T\%.AC_{a,i}^{WMNs}$, indicates that STAs initiate re-associations only when there exists another MAP which can improve the performance significantly enough by $T\%$ (T is the re-association threshold), hence expecting to reduce re-association frequency and avoid association oscillation. The performance of the re-association threshold is shown in Fig. 6.9.



(a) Throughput.



(b) End-to-end transmission delay.



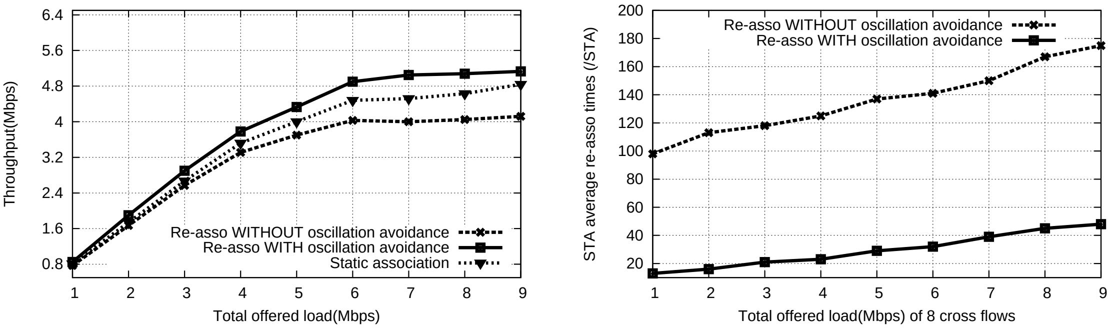
(c) Dropped data.

Fig. 6.8: Dynamic re-association versus static association.

In this simulation, poisson background traffic noise and 8 poisson cross flows are injected to the network. STAs scan channels periodically with 4 seconds intervals. The re-association threshold is kept constant at 5%. In Fig. 6.9(b), it depicts STA's average re-association number when the total offered traffic load increases in the network. We can see that the re-association threshold ("Re-asso WITH oscillation avoidance") can reduce the re-association number dramatically by 100 per STA. It can also slow down the re-association number's increasing speed when compared with "Re-asso WITHOUT oscillation avoidance". Since the re-association number is reduced by the oscillation avoidance mechanism – re-association threshold, the aggregate throughput should be increased, which is validated by Fig. 6.9(a). In this throughput measurement, we observe that oscillation avoidance increases the throughout when compared with without oscillation avoidance and static association. As is also shown previously, in terms of throughput, static association is superior to re-association without oscillation avoidance, while re-association with oscillation avoidance outperforms static association. Therefore, as aforementioned in this two sections, re-association threshold should be covered when dynamic re-association is concerned. These two mechanisms together can reflect the network conditions in real-time and achieve better performance.

Now, we will further find out how it affects network behaviors when varying the re-association threshold and varying STA scan period.

First, we consider how network performance varies when re-association threshold is increased from 0% to 7%. 8 poisson cross flows with 6 Mbps total offered load are involved in the traffic scenario. Fig. 6.10 shows network behaviors with STAs scanning the channels in 4 seconds and 6 seconds interval. Regardless of the STA scan period, the network behaves in the same fashion towards re-association



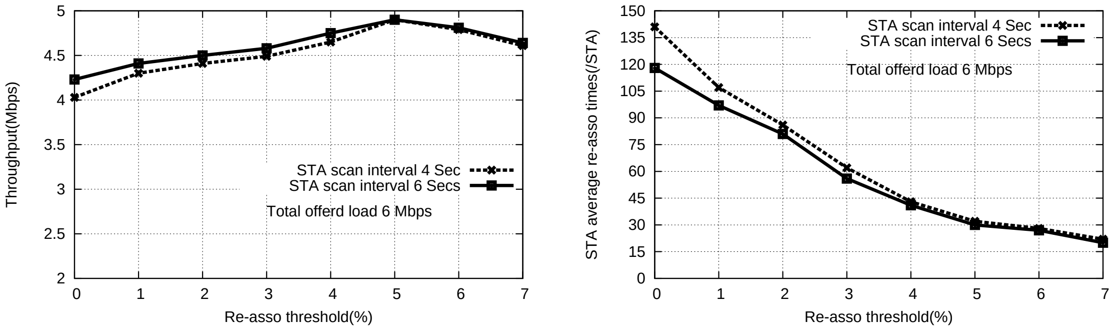
(a) Throughput.

(b) Average reassociation times.

Fig. 6.9: Oscillation avoidance.

thresholds. We can see in Fig. 6.10(a) that the aggregate throughput is affected by re-association threshold remarkably, with nearly a 1Mbps gap between max. and min. throughput value. When the re-association threshold increases, throughput increases as well and it reaches a peak as the re-association threshold arrives at 5%. After this point, throughput decreases hereafter. This means that an optimal value exists for the re-association threshold and 5% is that optimal value for our simulation scenario. All this can be explained intuitively. When there is no re-association threshold or the re-association threshold is small, there may be frequent re-associations throughout the network. Frequent re-associations will lead to severe data dropping, hence lower throughput. As the re-association threshold increases, re-association numbers in the network will be reduced. When the re-association threshold is too large, there will be very few re-associations even if the network conditions vary significantly. This may equal to no re-association threshold to a certain extent. For a specific network scenario, too small or too large re-association thresholds are both not suitable. There must exist an optimal value which can characterize this specific scenario closely. Additionally, through more elaborate simulations, we observe that different network scenarios have different optimal re-association thresholds. It is the optimal value of re-association threshold that indicates the extent of the network conditions' fluctuation or variation. The more severer the network conditions vary, the larger the optimal value of re-association threshold will be.

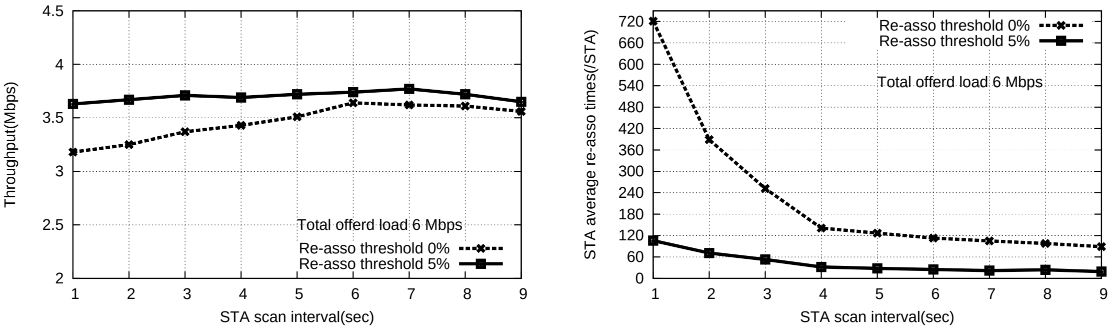
Fig. 6.10(b) shows how the STA average re-association number (or times) varies as re-association threshold increases. When the re-association threshold changes from 0% to 7%, the STA average re-association number decreases accordingly 100 times/STA. The re-association number (or times) per STA is larger when STAs scan the channels every 4 seconds. This measurement further validates the network's behavior in terms of throughput. There is an observation which is worthy of consideration. As the re-association threshold increases from 0% to 7%, the STA re-association number (or times) decreases continuously, but the aggregate throughput increases to a peak value and then decreases. Actually, because STAs stand alone during the process of re-association, data transmitted by STAs during this time overhead is dropped directly. Hence reducing re-association number can benefit throughput. But why throughput decreases when STA re-association number further decreases after threshold 5%? This is because when the re-association threshold is larger than the optimal value, the dynamic association mechanism is unable to choose the optimal MAP to reflect the network condition relevantly. The benefit from reduced re-association number is counteracted by the non-optimal association choice. It indicates that in our dynamic association mechanism there exists two factors which will cause data dropping, frequent re-association and non-optimal association choice. When the re-association threshold is small, frequent re-association is dominant leading to data dropping. On the other hand, non-optimal association choice is the main reason for data dropping when re-association threshold is too big. How to avoid these two factors jointly is important (to find out the optimal threshold value). In Fig. 6.10(a), it also shows that network behaves better when STAs scan the channels in 6 seconds interval. Therefore, STA scan period also affects network performance. This is further examined below.



(a) Throughput. (b) Average re-association times.

Fig. 6.10: Varying re-association threshold.

To illustrate how STA scan period affects network performance, we introduce 8 poisson cross flows with 6 Mbps total offered load into the network as before. STA scan period is increased from 1s to 9s. Re-association thresholds are kept constant at 0% and 5% respectively. As shown in Fig. 6.11(b), the STA average re-association number can be reduced when STA scan period increases. It decreases dramatically from 721 times/STA to 89 times/STA in the absence of re-association threshold. While with re-association threshold (5%), STA re-association number decreases more slowly, from 106 times/STA to 19 times/STA. In Fig. 6.11(a), the throughput without re-association threshold increases and reaches a peak as STA scan period increases to 6s, and then decreases slowly thereafter. While throughput with re-association threshold (5%) varies indistinctively, only a little decrease is observed when STAs scan above 6s intervals. All these measurements indicate that there also exists an optimal STA scan period in dynamic association, though its effect is not as observable as that of re-association threshold. In addition, the re-association threshold can lighten the effect of STA scan period.



(a) Throughput. (b) Average re-association times.

Fig. 6.11: Varying STA scan period.

From the simulations in this section, we can see that both re-association threshold and STA scan period affect the performance of the dynamic association mechanism, with re-association threshold playing a more dominant role. Nevertheless, this two factors should be considered jointly.

6.5 Network Convergence

As pointed out in [19], the association mechanism converges to a Nash equilibrium after a finite number of steps. This means the network will converge to a stable state within finite time. The rate at which the network converges is very important. Here we look at the network convergence speed with different re-association thresholds and STA scan period combinations. We introduce CBR background traffic noise into MAPs. STAs initially associate according to the load introduced by the traffic noise. After the network stabilizes, a burst of 6Mbps CBR traffic is injected at time point 50s, which will trigger re-associations throughout the network. Fig. 6.12 depicts the percentage of STAs re-associated in each STA scan interval as the simulation time proceeds over a time window of [44s, 68s]. We observe that the burst of traffic triggers severe re-associations in the network. In particular, when there is no re-association threshold, nearly 45% of STAs re-associate in one STA scan interval. It also shows that the re-association threshold can reduce the number of re-associations. It is important to note that only re-association threshold (5%) together with suitable small enough STA scan period (2s) would accelerate network convergence speed. This combination of re-association threshold of 5% together with STA scan period 2s, requires only 6s to converge. It costs other combinations more than 10s to stabilize. Therefore, the oscillation avoidance mechanisms, which consist of re-association threshold and STA scan period, can also accelerate network convergence speed. But the optimal values for these two purposes (oscillation avoidance and accelerating network convergence speed) are different. Considering all factors jointly, the optimal choice is taking 5% as the re-association threshold and 4s as STA scan period according to our simulations so far.

6.6 Conclusion

In this chapter, we evaluate our dynamic association mechanism through elaborate simulations. All the simulations show that jointly considering wireless link quality and load balancing can improve network performance, and cross-layer asso-

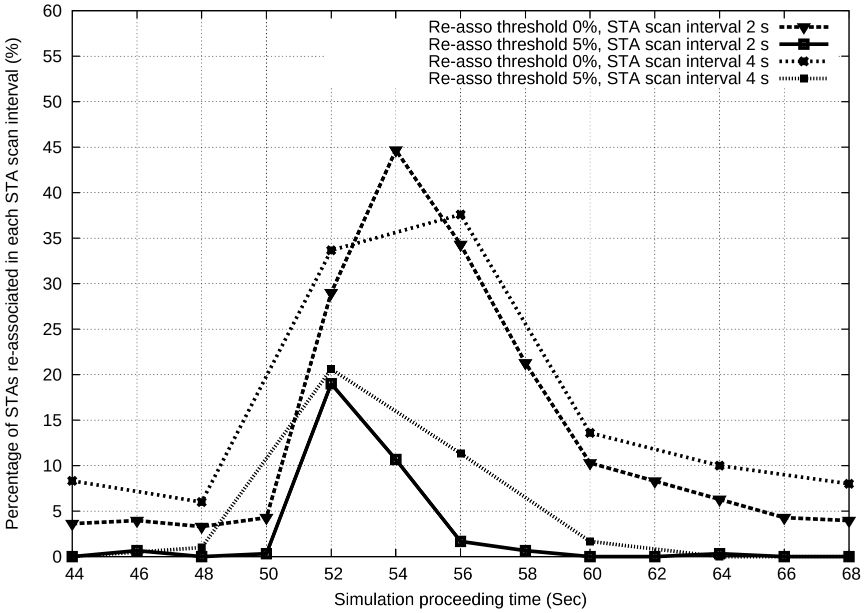


Fig. 6.12: Network convergence speed.

ciation outperforms non-cross-layer association. Also dynamic re-association with the re-association threshold and STA scan period can characterize the random network conditions in real time and improve network performance further, even accelerate network convergence speed. Furthermore, through varying re-association threshold value and STA scan period, we notice that these two values affect network behaviors indeed, and there exists optimal values for re-association threshold and STA scan period, corresponding to specific network scenarios (e.g., network topology, traffic load, network scale, etc.). In order to maximize network performance, we should trade off carefully among these several important factors, which consist of re-association threshold value, STA scan interval, etc.

Chapter 7

Conclusion and Future Work

Network communication with end devices is increasingly wireless. Most of the wireless networks widely used today are single hop wireless networked, such as IEEE 802.11 based WLANs, cellular networks, Bluetooth and so on. This single hop wireless link limits the wireless transmission range, data rate, and the mobility of wireless STAs. To overcome all these limitations, improve network performance and reduce network deployment cost, multi-hop wireless networks are introduced. Actually, ad-hoc networks and wireless sensor networks both involve multi-hop wireless links. Although these two kinds of wireless networks have been studied for a long time, they are very difficult to integrate with the Internet, which leads to very limited commercial application and industrial deployment. In order to simplify the commercial application of ad-hoc networks while keeping the advantage of multi-hop wireless networks, wireless mesh networks (WMNs) are brought in. Mesh routers are stationary and self-organize to form a multi-hop wireless backbone, which relays traffic for mesh STAs. All STAs can move or roam freely. Because of the lack of routing functionality, mesh STAs should associate with mesh routers to be a part of the whole wireless network and gain network access. With gateway functionalities in some of mesh routers, WMNs can be connected to other networks, such as the Internet, Wi-Fi, WiMax and so on. This unique network architecture brings many advantages to WMNs, such as rapid deployment with lower cost backhaul, high bandwidth, self-organization, self-healing and easy scalability and so on. Due to all these attractive advantages, WMNs have emerged as a promising technology for next generation wireless networks.

Many existing wireless network standards are now revisited and extended to support mesh architectures in which data is commonly forwarded on paths consisting of multiple wireless hops. Take the new IEEE 802.11s specification as an example, it extends the traditional IEEE 802.11 standards by replacing the wired backhaul to the Internet with a multi-hop wireless backbone. To support mesh architecture, IEEE 802.11s introduces three types of wireless nodes, MAPs, MPs and STAs, within which MAPs and MPs form the multi-hop wireless backbone, STAs associate with MAPs to join the network.

Because of these new features, many conventional management mechanisms that have important effect in the efficiency of wireless networks should be redefined. Such a mechanism is the association of STAs with MAPs of the wireless backbone. The association mechanism defined in IEEE 802.11 standards just bases on the Received Signal Strength Indicator (RSSI) and misses many important factors (e.g., link quality, load balancing, etc.), thus easily resulting in hot-spot phenomenon and poor performance. Other proposed association mechanisms either take link quality or load balancing into consideration, and some of them are based on impractical assumptions... All these association mechanisms are not suitable for WMNs. Based on the cross-layer association framework, we propose a dynamic association mechanism in this thesis in the context of IEEE 802.11 based WMNs. Our dynamic association mechanism takes wireless link quality, load balancing and association oscillation avoidance into consideration. The metric introduced in this association mechanism measures the real traffic load through channel based load detection and suits both coordinated and uncoordinated networks. Because of the random characteristics of wireless links and the variability of network conditions, we introduce oscillation avoidance schemes, which consist of periodic STA scans and re-association threshold. We further evaluate our dynamic association mechanism through elaborate simulations, which show that the proposed dynamic association mechanism outperforms other association mechanisms and improve network performance significantly. Furthermore, our mechanism can accelerate the convergence speed of WMNs. Simulations additionally show that optimal values for both the re-association threshold and STA scan period exist, corresponding to specific network scenarios (e.g., network topology, scale, traffic load, etc.).

Our dynamic association mechanism characterizes network conditions in real time and improve network performance observably. However, to perfect this mechanism will require further work. How to confirm the optimal re-association threshold and STA scan period empirically for specific network scenarios? Or, how to model general network scenarios to obtain the theoretical optimal values? Adjusting the association cost weights of access links and backbone routes adaptively; Modeling association procedure in WMNs; Implementing the association mechanism into real network interface card... All these are the important works to be done in the future.

Appendix A

List of Publications

Hui Wang, Wai-Choong Wong, Wee-Seng Soh and Mehul Motani, “Dynamic Association in IEEE 802.11 Based Wireless Mesh Networks”, Proceedings of International Symposium on Wireless Communication Systems (ISWCS), Sep. 2009.

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