CHANNEL ASSIGNMENTS UTILIZING PARTIALLY OVERLAPPING CHANNELS FOR WIRELESS MESH NETWORKS

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Channel Assignments Utilizing Partially Overlapping Channels for Wireless Mesh Networks

by

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Abstract

Wireless mesh networking is one of the most promising next generation network technologies. A wireless mesh network is a decentralized, self-organizing, self-configuring and self-healing multi-hop wireless network. In this thesis, we introduce the development, architectures, characteristics and applications of wireless mesh networks and present the existing channel assignments and routing protocols for wireless mesh networks.

In recent years, many efforts have been taken to better exploit multiple non-overlapping channels for wireless mesh networks, e.g. IEEE 802.11 a based wireless mesh networks, in which 12 or 24 non-overlapping channels are available. Although the IEEE 802.11 b/g standards, which govern the unlicensed 2.4 GHz industrial, scientific and medical (ISM) band, provide 11 channels, only three of them, namely 1, 6 and 11 are non-overlapping. In order to better utilize communication bandwidth and improve quality of service, in this thesis, we propose a channel assignment exploiting partially overlapping channels (CAEPO). In CAEPO, the interference a node suffers within its interference range is the main metric for channel assignment. It is defined to be a combination of the overlapping degree between channels and busy time proportion, i.e. channel utilization ratio of interfering nodes. In addition to that, packet loss ratio is another major consideration in the implementation of channel assignment.

To further improve the aggregated network performance, we propose Load-Aware CAEPO scheme based on the original CAEPO. In Load-Aware CAEPO, instead of

using the busy time proportion of interfering nodes, we employ the traffic load as another main factor of the interference metric besides the channel overlapping degree. In addition, the concept of self-interference is introduced to estimate the interference metric. To facilitate the implementation of our channel assignment scheme, we modify the original AODV to be bandwidth-aware, where end-to-end delay and available bandwidth are both used as the routing constraints. Simulation results demonstrate that the proposed scheme can significantly improve the aggregated network performance.

For large networks, we introduce a node grouping algorithm in Load-Aware CAEPO and name the new channel assignment scheme Load-Aware CAEPO-G. Compared to Load-Aware CAEPO, Load-Aware CAEPO-G leads to a fairer channel assignment and achieves a minor improvement of the aggregated network performance.

Finally, performance of Load-aware CAEPO scheme is studied under voice applications over wireless mesh networks. To address the two challenges in voice over packet (VOP) applications, end-to-end delay and delay jitter, we propose VOP-AODV routing protocol. Along with VOP-AODV routing protocol, Load-aware CAEPO scheme can effectively decrease end-to-end delay and delay jitter.

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List of Abbreviations and Symbols

WMN	: Wireless Mesh Network
WLAN	: Wireless Local Area Network
QoS	: Quality of Service
DSDV	: Destination Sequenced Distance-vector Routing Protocol
AODV	: Ad Hoc On-Demand Distance Vector Routing Protocol
RREQ	: Route Request Packet
RREP	: Route Reply Packet
CAEPO	: Channel Assignment Exploiting Partially Overlapping Channels
AQOR	: Ad Hoc QoS On-Demand Routing in Mobile Ad Hoc Networks
VOP	: Voice over Packet

Chapter 1

Introduction

1.1 Wireless Mesh Networks

Wireless mesh networking is one of the most promising next generation network technologies. When access points in wireless local area networks (WLANs) start to communicate and get networked in an ad hoc fashion and relay packets on behalf of their neighbor access points, a general wireless mesh network (WMN) comes into being. Therefore, wireless mesh networks (WMNs) inherit the features of both wireless local area networks and ad hoc networks.

These access points in wireless mesh networks are called mesh routers and the clients are called mesh clients, accordingly. Mesh routers in wireless mesh networks can be divided into two types [1]. One type is the access point, which provides connectivity to mesh clients and has routing function and packet forwarding ability. Besides, some routers with gateway or gateway/bridge functionalities can connect to existing wired networks, e.g. the Internet, and some wireless networks. The other is the mesh point, which only forwards packets for other mesh routers but does not provide connectivity to mesh clients. Mesh clients only have routing function, thus, they are simpler than mesh routers in the implementations of hardware and software.

1.1.1 Development of Wireless Mesh Networks

The development of wireless mesh networks has gone through three stages. The first stage is the single radio ad hoc wireless mesh network. This type of mesh network is based on mobile ad hoc networks. In the whole network, there is only one radio not only for backhaul (links between mesh routers) but also for mesh client access. Since all nodes share and contend for one radio channel, the capacity and latency of the network are very poor.

Dual-radio wireless mesh network is the second generation of wireless mesh networks. In this type of network, there are two radios in the whole network, one for mesh backhaul and the other for mesh client access. The design improves the capacity and latency of the network through separating the backhaul radio and client access radio. However, since the mesh routers need to share and contend for the bandwidth of one radio channel, thus, the performance of the whole network is still not ideal. This kind of mesh can also be called shared mesh.

The third stage is multi-radio wireless mesh network. One radio is for mesh client access and two or more radios are for mesh backhaul in this type of network. Multi-radio wireless mesh network separates the mesh backhaul and mesh client access like dual-radio wireless mesh network and also provide multiple radios for mesh backhaul. We can also call this type of mesh as switched mesh. Compared to the first and second generation, the capacity and latency of multi-radio wireless mesh network greatly improve.

1.1.2 Architectures of Wireless Mesh Networks

There may be two types of components in a wireless mesh networks. They are mesh routers and mesh clients. The architectures of wireless mesh networks can be classified into three types. They are client WMN, backbone WMN and hybrid WMN, respectively [3].

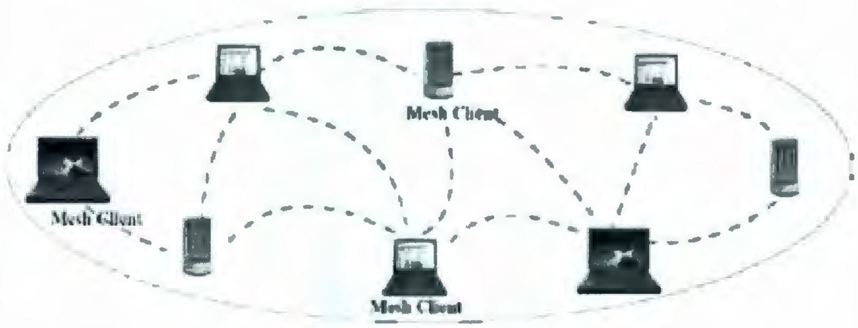

Figure 1.1: Example of Client WMN [3]

Client WMN only contains mesh clients. All mesh clients constitute a self-organizing, self-configuring network, very similar to an ad hoc network. In a client WMN, gateways and mesh routers are not necessary because every node in this type of network has routing functionality and can forward packets for its neighbors. Like in ad hoc network, usually, only one radio is used in client WMN. Figure 1.1 shows an example of client WMN.

Among the three types of architectures, backbone WMN is the most common and prevalent type and it is also the type, for which, we focus on studying channel assignments in this thesis.

In backbone WMN, mesh routers form an ad hoc network and forward packets on behalf of their neighbors. Mesh clients do not directly communicate with each other but forward packets through mesh routers. There are fewer requirements on mesh clients in backbone WMN compared to those in client WMN. In client WMN, mesh clients are required to route packets, self-organize and self-configure the network, while in backbone WMN, these responsibilities are taken by mesh routers. Mesh routers with gateway functionalities in backbone WMN can connect to Internet and mesh routers with gateway/bridge functionalities can integrate with some existing wireless networks, such as Wi-Fi, WiMAX, sensor networks and cellular networks [3]. In backbone WMN, two or multiple radios are used. One is for mesh client access and the others are for mesh backhaul. An example of backbone WMN is shown in Figure 1.2.

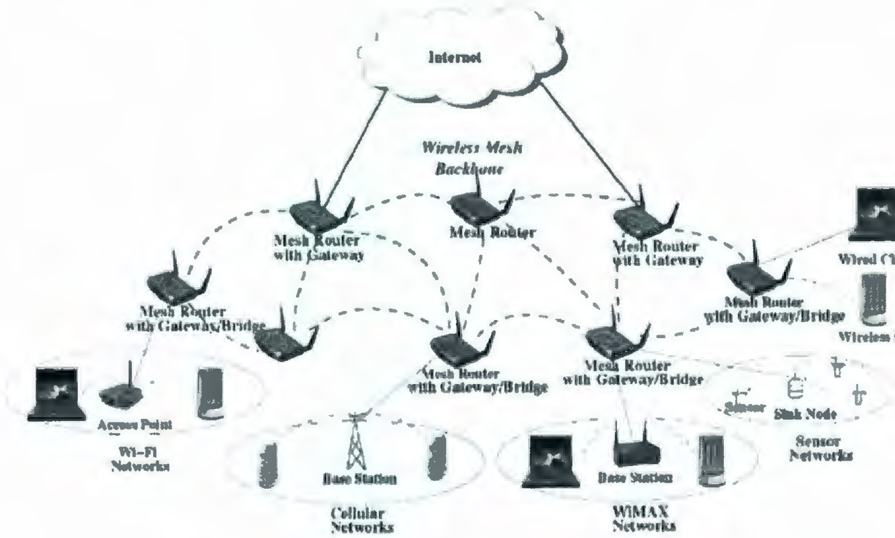

Figure 1.2: Example of Backbone WMN [3]

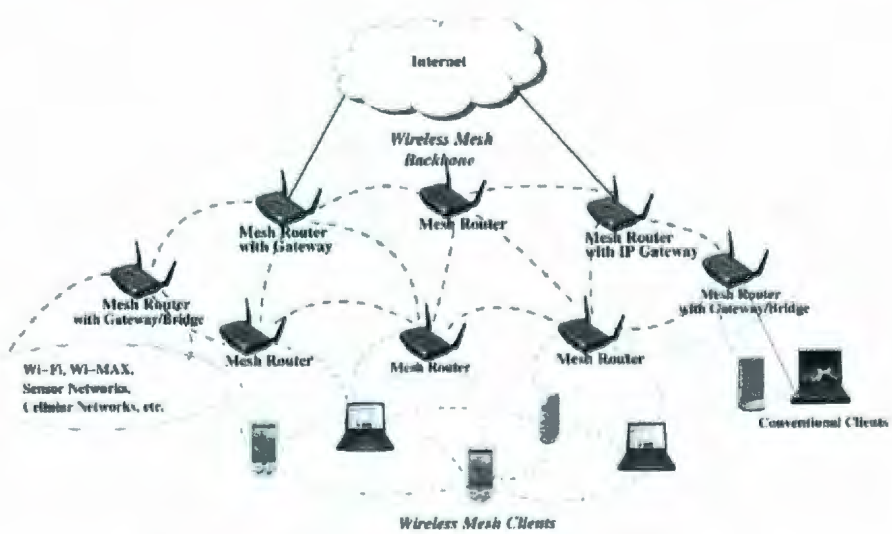

Figure 1.3: Example of Hybrid WMN [3]

As shown in Figure 1.3, hybrid WMN combines client WMN and backbone WMN, that is, mesh clients can either directly communicate with each other or communicate relying on mesh routers.

1.1.3 Characteristics of Wireless Mesh Networks

A wireless mesh network (WMN) is a decentralized, multi-hop network and it has the characteristics of self-organizing, self-configuring and self-healing. In a WMN, there is no fixed wired infrastructure since all nodes can communicate with their neighbors via wireless links. Mesh routers in a WMN have minimal mobility and generally no strict requirements on power consumption [3].

Since mobile ad hoc network is the prototype of the first wireless mesh network, wireless mesh network has some common features with ad hoc network. For instance, they both are self-organizing, self-configuring and multi-hop networks and they both do not need wired infrastructure.

Nevertheless, wireless mesh network (WMN) is not anther form of ad hoc network, but has diverse features compared to ad hoc network. The differences between them are as follows.

a) The topology of ad hoc network, especially of mobile ad hoc network is highly dynamic while the topology of WMN is relatively static because mesh routers are basically not mobile.
b) Generally, WMN has infrastructure comprised of mesh routers while ad hoc network has no fixed infrastructure.
c) In WMN, packets are mainly forwarded by static nodes, namely, mesh routers while in ad hoc network, all nodes act as routers and forward packets [2].
d) Usually, only one radio is used in ad hoc network, but multiple radios are being more employed in WMN.
e) Ad hoc network is mainly applied in emergency area while WMN is not only

employed in emergency area but very applicable in civilian area [2].

In most IEEE 802.11-based ad hoc networks, only one radio, and hence one channel, is used for both backhaul (link between mesh routers) and mesh client access. All nodes in the network share and contend for one radio, therefore, the aggregated capacity is greatly degraded. Although wireless mesh networks are evolved from wireless ad hoc networks, wireless mesh networks allow the utilization of multiple radios and multiple channels. Due to the simultaneous use of multiple channels, the aggregated capacity and latency of multi-radio multi-channel wireless mesh networks greatly improve.

1.1.4 Applications of Wireless Mesh Networks

Wireless mesh networks can be established and applied in many areas such as university campuses, convention centres, airports, hotels, shopping malls and sport centres [1]. Wireless broadband home networking, enterprise networking, broadband community networking, health and medical systems and security surveillance systems, emergency services, transportation services and building automation are some of the applications wireless mesh networks can support [3].

Wireless broadband home networks implemented over wireless local area networks afford various facilities for us. Despite this, some drawbacks exist in this type of networking. Dead spot is a typical problem. Because of deployed positions of access points, some zones, especially corners, may not be in the coverage of those access points. Increasing the number of access points is a solution, but linking access points to the access modem with wires brings us inconvenience. Besides, any two access points cannot communicate with each other directly, but through the access modem. If wireless mesh networking is employed for broadband home networks, these problems can be solved easily. In wireless mesh networks, mesh routers will take the place of those access points. It is efficient because wiring mesh routers to the access modem is not required. Also, we can improve the dead spot problem effectively just through establishing more mesh routers. An example of wireless broadband home networking is given in Figure 1.4.

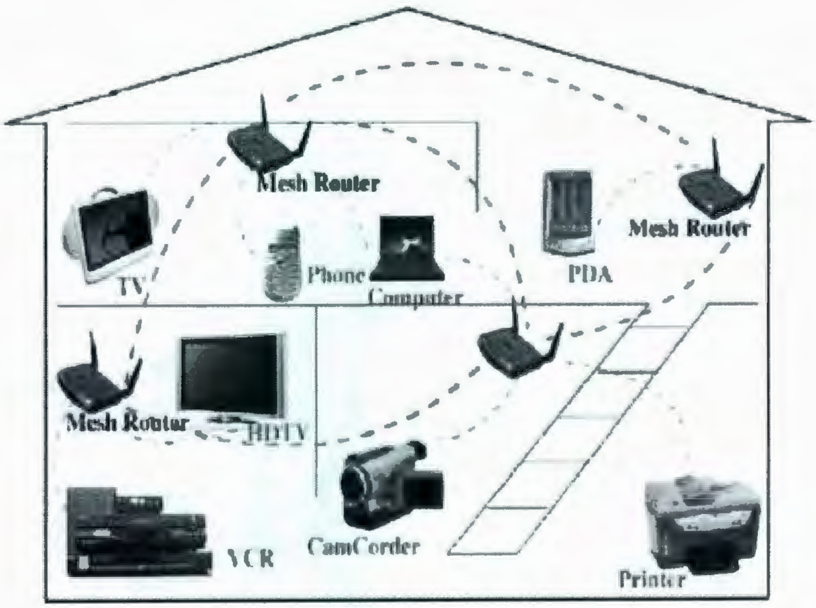

Figure 1.4: Example of Wireless Broadband Home Networking [3]

Currently, offices in many companies are equipped with wireless enterprise networks. These wireless networks are realized based on wireless local area networks. If these networks need to be connected, the wired Ethernet connection is the only way, which is a high network cost for enterprises. If those access points in wireless local area networks are substituted with mesh routers, the Ethernet wiring becomes unnecessary and all nodes in the networks can share access modems in the whole network through mesh routers. Compared to the conventional wireless local area based method, Wireless mesh networking is an effective solution for wireless enterprise networks because the networks become more robust and the network resources are more sufficiently utilized. Figure 5 shows an example of enterprise networking.

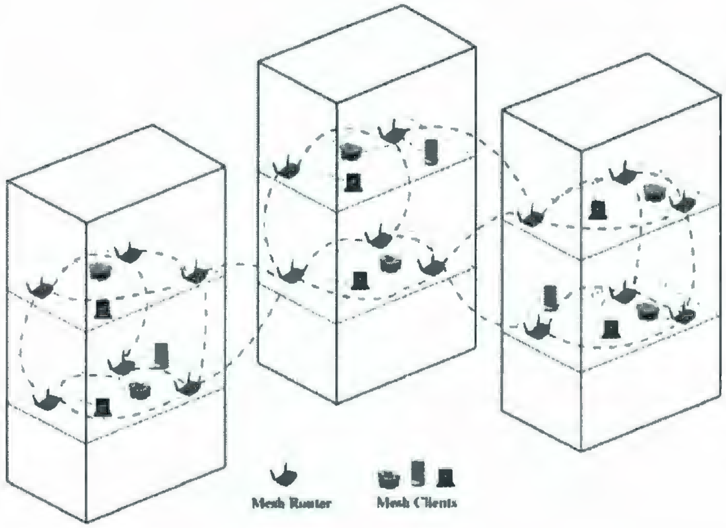

Figure 1.5: Example of Enterprise Networking [3]

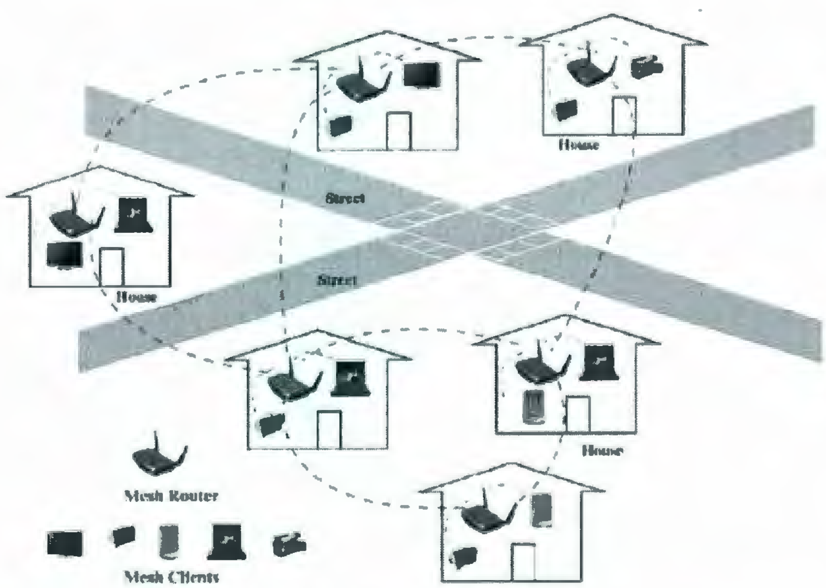

Figure 1.6: Example of Broadband Community Networking [3]

Connecting to DSL or a cable through a wireless router is the most common home Internet access method in community. Accessing Internet is the only way if information sharing needs to be realized in community. With the wireless mesh networking establishment, homes can share information faster and more conveniently communicate with each other in community. In addition, the high bandwidth gateway can be shared by multiple homes, which greatly reduces the cost. Roofnet is a typical example of broadband community networking. An example of broadband community networking is given in Figure 1.6.

1.2 IEEE 802.11 Standards

IEEE 802.11 is a set of standards which are created and maintained by the IEEE LAN/MAN Standards Committee (IEEE 802). They are responsible for carrying out computer communication in the 2.4, 3.6 and 5 GHz frequency bands for wireless local area networks (WLANs). In this thesis, we introduce 802.11a in 5 GHz band, 802.11b/g in 2.4 GHz band and 802.11n in 2.4/5 GHz band [4].

1.2.1 IEEE 802.11 a

802.11a uses orthogonal frequency-division multiplexing (OFDM) modulation scheme and operates in the 5 GHz band. It has a maximum net data rate of 54 Mbit/s. However, its realistic net achievable throughput is in the mid-20 Mbit/s due to the error correction code and other overheads in the link layer.

The effective overall range of 802.11a is shorter than that of 802.11b/g due to the high carrier frequency. Since 802.11a signals have smaller wavelength, they are more easily absorbed by solid objects such as buildings. Therefore, 802.11a is not able to penetrate as far as 802.11b and 802.11g.

1.2.2 IEEE 802.11 b/g

The IEEE 802.11 b and 802.11 g standards operate on the unlicensed 2.4 GHz industrial, scientific and medical (ISM) band. In North America, it provides 11 channels. Among the 11 channels, only three of them, namely 1, 6 and 11 are non-overlapping channels separated by 25 MHz at their center frequencies. 802.11 b/g equipments suffer interference from other devices operating in the 2.4 GHz band, such as Bluetooth devices, cordless telephone and baby monitors and microwave ovens and so on. Bluetooth uses a frequency hopping spread spectrum signaling method (FHSS), while 802.11b and 802.11g use the direct sequence spread spectrum signaling (DSSS) and orthogonal frequency division multiplexing (OFDM) methods, respectively.

The transmit spectrum mask for IEEE 802.11 standards using Direct Sequence Spread Spectrum (DSSS) modulation is depicted in Figure 1.7. And the distribution of the IEEE 802.11 b/g 11 channels over the 2.4GHz ISM band and the channel overlapping degree is shown in Figure 1.8.

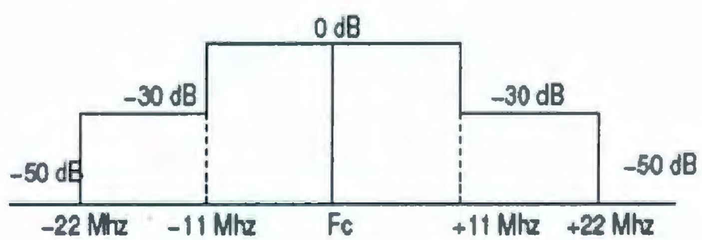

Figure 1.7: Transmit spectrum mask for IEEE 802.11 standards using DSSS

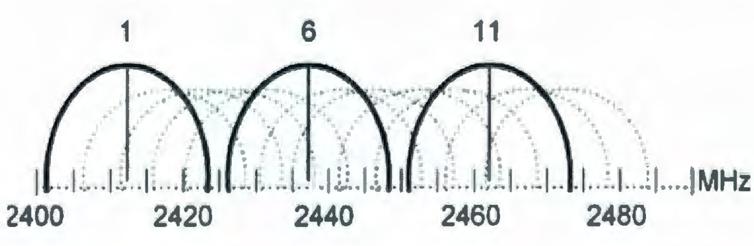

Figure 1.8: Distribution of IEEE 802.11 b/g 11 channels over 2.4GHz ISM band [5]

802.11b uses the same CSMA/CA media access method in the original standard. Its maximum raw data rate is 11 Mbit/s but the net achievable throughput is about about 5.9 Mbit/s using TCP and 7.1 Mbit/s using UDP due to the overhead of the CSMS/CA protocol and TCP overheads.

Like 802.11b, 802.11g, which is the third modulation standard operates in the 2.4 GHz band. It has a maximum raw data rate of 54 Mbit/s and an about 19 Mbit/s net achievable throughput. Hardware under 802.11g standard is fully backwards compatible with those under 802.11b standard. Since both 802.11g and 802.11b operate in 2.4GHz band, the interference between 802.11b signals and 802.11g signals will reduce the data rate of each other.

802.11g uses orthogonal frequency-division multiplexing (OFDM) modulation scheme, the same as the one 802.11a uses. Therefore, it has data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbit/s. At the same time, it has the data rates of 1, 2, 5.5 and 11Mbit/s due to its backward compatibility to 802.11b.

In this thesis, we focus on studying the channel assignments exploiting partially overlapping channels for IEEE 802.11 b/g based multi-radio multi-channel wireless mesh networks.

1.2.3 IEEE 802.11 n

IEEE 802.11n, which can operate either in 2.4GHz band or 5GHz band is an amendment to the IEEE 802.11-2007 wireless networking standard based on 802.11a and 802.11g. It uses multiple-input multiple-output (MIMO) architecture and doubles the channel width from 20 MHz to 40 MHz in the PHY (physical) layer. Beside, it adds frame aggregation to the MAC layer. It significantly increases the maximum raw data rate from 54 Mbit/s to 600 Mbit/s. Therefore, it can lead to more improvement of network throughput over 802.11a, 802.11b and 802.11g.

1.3 Quality of Service

Quality of service (QoS) [6] is the capability of a network to manage network traffic in a cost effective manner and provide better service to selected network traffic. The primary goal of QoS is to provide different priority such as dedicated bandwidth, controlled delay and delay jitter, and improved packet loss to different applications.

Quality of service is of importance where the network capacity is limited. It is required for certain types of network traffic, such as online games, streaming multimedia, Voice over IP, IP TV, and Alarm signaling and so on.

Bandwidth, delay, delay jitter and packet loss are main QoS parameters.

Bandwidth refers to the rate of data transfer. It is the effective number of data units transferred per unit time and measured in bits per second (bps). In general, High bandwidth is required by multimedia applications.

Delay is defined as the time from the start of the packet being transmitted at the source to the end of the packet being received at the destination in communication system. It is a significant property of real-time applications.

Delay jitter is the variation of end-to-end delay between successive packets. It may be caused network congestion, timing drift or route changes. Besides delay, delay jitter is another important property of real-time applications, such as audio or video conference.

Packet loss happens if a packet fails to reach the destination. It may be caused by oversaturated network links, signal degradation, corrupted packets and other factors.

In this thesis, these four main QoS parameters are all considered. We use packet loss ratio as one of cost considerations of the channel assignment in Chapter 3 and use bandwidth and end-to-end delay as routing metrics in Chapter 4 and Chapter 5. Finally, in Chapter 6, we take into account end-to-end delay and delay jitter in voice over packet applications.

1.4 Motivation and Contributions

Unlike most IEEE 802.11-based ad hoc networks, in which only a single channel is used, wireless mesh networks support the use of multiple radio and multiple channels [1]. As a result of the availability of multiple simultaneous channels, the aggregated network performance can be dramatically improved. Channel assignments utilizing multiple radio and multiple channels for wireless mesh networks have been extensively investigated in recent years. However, a majority of them only exploit the use of non-overlapping channels. Although the IEEE 802.11 b/g standards, which govern the unlicensed 2.4 GHz industrial, scientific and medical (ISM) band, provide 11 channels, only three of them, namely 1, 6 and 11 are non-overlapping. In a network with high node density, only three non-overlapping channels can not provide enough bandwidth for high traffic load. Therefore, it is very important to exploit partially overlapping channels.

The objective of our research to investigate channel assignment exploiting not only the non-overlapping channels but also partially overlapping channels for wireless mesh networks under IEEE802.11b/g standards.

Channel assignment exploiting partially overlapping channels (CAEPO) is the first channel assignment scheme we propose to exploit partially overlapping channels. In the proposed scheme, the interference a node suffers within its interference range to be the main factor, which is defined to be a combination of the overlapping degree between channels and busy time proportion, i.e. channel utilization ratio of interfering nodes. In addition to that, packet loss ratio is another major consideration in the development of our proposed channel assignment scheme. By exploiting more available bandwidth, CAEPO effectively improves the network performance.

Based on the original CAEPO, we propose Load-Aware CAEPO scheme. In Load-Aware CAEPO, the interference metric is defined to be a combination of channel overlapping degree, self-interference factor and traffic load, which leads to a more precise estimation compared to the original CAEPO scheme. Moreover, we modify the original Ad Hoc On-Demand Distance Vector Routing Protocol (AODV) to be bandwidth-aware, where the available bandwidth and end-to-end delay are both used as the routing constraints. With the bandwidth-aware AODV, Load-Aware CAEPO further significantly improves the aggregated network performance.

For large networks, we propose Load-Aware CAEPO-G scheme by employing a node grouping algorithm in Load-Aware CAEPO. Compared to Load-Aware CAEPO, Load-Aware CAEPO-G derives a fairer channel assignment and achieves a minor improvement of the aggregated network performance.

Finally, we study Load-Aware CAEPO scheme for voice applications over wireless mesh networks. To overcome end-to-end delay and delay jitter, our routing protocol VOP-AODV employs the end-to-end delay estimation approach and the distributed delay jitter control mechanism. In the end-to-end delay estimation approach, route request packet (RREQ) is used to expect the end-to-end delay during the transmission of voice or data packets. In the distributed delay jitter control mechanism, delay bound is divided among all intermediate nodes along a path. Along with VOP-AODV routing protocol, Load-Aware CAEPO scheme effectively decreases the end-to-end delay and delay jitter for voice applications.

1.5 Thesis Organization

In Chapter 2, we introduce existing channel assignments and routing protocols for wireless mesh networks. In Chapter 3, we present the channel assignment exploiting partially overlapping channels (CAEPO). In Chapter 4, we propose a new channel assignment called Load-Aware CAEPO based on the original CAEPO. In Chapter 5, we present a channel assignment scheme called Load-Aware CAEPO-G by introducing the concept of node grouping in Load-Aware CAEPO. In Chapter 6, we study Load-Aware CAEPO scheme for voice applications over wireless mesh networks. In Chapter 7, we conclude this thesis and introduce the future work.

Chapter 2

Channel Assignments and Routing Protocols for Wireless Mesh Networks

2.1 Classifications of channel Assignments

Based on different criteria, there are multiple classifications for wireless mesh network channel assignments. Depending upon whether a central network controller is used, channel assignment can be classified into centralized channel assignment and distributed channel assignment. In [7] and [8], centralized channel allocations are described. In the centralized schemes, a network controller is used to collect the topology information of the network and assign the channels for each node. In [9], [10], [11], [12] and [13], no central controller is needed in distributed mechanisms, while nodes locally collect information and assign channels.

According to the duration of an interface tuned on a specified channel, channel assignment can be divided into static channel assignment, dynamic channel assignment and hybrid channel assignment. In [14] and [15], every network interface of each node is assigned to a specified channel by static assignment algorithms permanently or for a long duration of time. In [16] and [17], each interface could dynamically change its channel on demand among available channels in some short or long intervals. Unlike the static algorithms, a coordination mechanism is required in distributed schemes to ensure that the sending and the receiving routers use the same frequency channel at the same time. In hybrid channel assignment [18], the interfaces of each node are divided into two group, "fixed interfaces" and "switchable interfaces". The fixed interfaces stay on a specified channel for long intervals while switchable interfaces can frequently switch among the remaining non-fixed channels. Different nodes could select different channels for their fixed interfaces. When a sender has packet to transmit, it switches its switchable interface to the fixed channel of the receiver to transmit the packet.

Besides the above classifications, some channel assignments combine routing problems. In [7], [11], [19], [20], [21], [22] and [23], the joint channel assignment and routing problems are studied.

2.2 Existing Channel Assignments

Jain *et al.* [24] proposed a multi-channel CSMA MAC protocol. This protocol employs channel reservation scheme and dynamically selects channels.

Marina *et al.* [25] proposed a polynomial-time heuristic channel assignment (CLICA) for wireless mesh networks. CLICA uses a weighted conflict graph to model the interference among logical links and assigns channels depending on the weight of each other.

Ramachandran *et al.* [17] proposed a centralized interference-aware channel assignment for wireless mesh networks by using non-overlapping channels. The channel assignment selects channels to minimize the interference both within wireless mesh network and between wireless mesh network and other co-located wireless networks.

In [26], Kareem and Matthee proposed a dynamic channel assignment scheme, the

Adaptive Priority Based Distributed Dynamic Channel Assignment. In this scheme, an iterative adaptive priority algorithm recursively assigns channels by taking into account the spatial channel reuse and interference. Fast switching time and process coordination modules are the advantages of the mechanism.

A centralized load-aware channel assignment algorithm was proposed by Raniwala *et al.* in [8]. However, in their scheme, source-destination pairs with associated traffic demands and routing paths are required to be known by the central controller before the channel assignment. They further proposed a network architecture called *Hyacinth* for 802.11-based multi-radio mesh networks and a distributed channel assignment algorithm for the architecture [16]. However, *Hyacinth* is specifically designed for the wireless Internet access applications, and the channel assignment scheme only works for the routers with tree connectivity.

Ko *et al.* [27] proposed a distributed channel assignment under the assumption that a node could transmit packets on a single channel but could listen to all available channels at the same time. In this channel assignment scheme, each node selects the channel to minimize the interference it suffers from the nodes in its interference range.

Skalli *et al.* [28] proposed a traffic and interference-aware channel assignment called MesTic. Mestic uses the multi-radio conflict graph, the connectivity graph, the traffic matrix, the number of radios at each node and the number of non-overlapping channels as the input of the algorithm and uses ranking technique to assign channels.

To better explore the available bandwidth, a partially overlapping channel model was proposed by Mishra *et al.* [29] for two scenarios, wireless local area networks (WLANs) and wireless mesh networks. For wireless mesh networks, they employed the channel assignment scheme from [23] and modified the link flow scheduling constraints to fit with their needs. However, the assumption of optimal traffic load balancing is required in [23], which is unrealistic for practical mesh network applications, where network traffic can be very dynamic. Hence, a more adaptive channel assignment scheme is highly desired.

A joint channel assignment and congestion control algorithm (JOCAC) was proposed to exploit partially overlapping channels by Rad and Wang [30]. JOCAC combines congestion control problem and channel assignment problem to maximize utilization and uses a channel weighting matrix to model channel overlapping. However, the model is difficult to implement in practical mesh networks due to its non-linearity.

Hoque *et al* also proposed a channel assignment scheme using partially overlapping channels and defined the interference factor using geographical distance and channel separation [31]. However, the influence of traffic load on interference was not considered in their work.

2.3 Classifications of Routing Protocols

Among several different classifications of routing protocols for ad hoc networks and wireless mesh networks, here we introduce a typical classification based on the routing information update mechanism. Under this classification, there exist three types of routing protocols. They are proactive routing protocols, reactive routing protocols and hybrid routing protocols. In this thesis, along with our channel assignment schemes, we employ a most popular reactive routing protocol, AODV, which is based on a typical proactive routing protocol, Destination Sequenced Distance-vector Routing Protocol (DSDV).

2.3.1 Proactive Routing Protocols

Proactive routing protocols can be also called table-driven routing protocols. In this type of protocols, the information about network topology is exchanged regularly so that the view of the whole network can be maintained at each node. The advantage of this type of protocol is that, the delay to determine the route to a certain destination node is minimal. This is especially important for time-critical traffic transmission. However, some drawbacks also exist in this kind of routing protocol. One is that, when the mobility of nodes in a network increases, the life of a link becomes significantly short. This phenomenon renders the routing information in the tables kept in nodes invalid quickly. In addition, if during a long time nodes do not need to transmit data, then those regular updates, actually become overheads.

The typical examples of proactive routing protocols are DSDV, Clusterhead Gateway Switch Routing Protocol (CGSR) and Wireless Routing Protocol (WRP).

DSDV [32] is a table-driven algorithm based on the classical Bellman-Ford routing mechanism. The improvements made to the Bellman-Ford algorithm include freedom from loops in routing tables. Every mobile node in the network maintains a routing table in which all of the possible destinations within the net-work and the number of hops to each destination are recorded. Each entry is marked with a sequence number assigned by the destination node. The sequence numbers enable the mobile nodes to distinguish stale routes from new ones, thereby avoiding the formation of routing loops. Routing table updates are periodically transmitted throughout the network in order to maintain table consistency.

2.3.2 Reactive Routing Protocols

In reactive routing protocols, instead of exchanging network topology information regularly, a source node only finds a route to the destination node when it needs to send data. Therefore, reactive routing protocols are also called on-demand routing protocols. The source node starts to find a route by transmitting route request through the network. The source will wait for the destination or intermediate nodes (that have routes to the destination) during a period to respond with a route, namely, a list of intermediate nodes between the source node and the destination node. Therefore, under this type of routing protocol, the route setup time is significant, compared to proactive routing protocols. However, if the nodes are relatively mobile, reactive routing protocols often have better performance than proactive routing protocols.

AODV and Dynamic Source Routing Protocol (DSR) are typical examples of this kind of routing protocol.

AODV [33] is developed from the proactive routing protocol, DSDV. Under AODV, a route is only set up when a source node needs to transmit data. Like under DSDV, the destination sequence number is also used to tag a route under AODV. If a source node has no route to a desired destination, it will broadcast a route request packet through the network. The route request packet carries the source identifier, the destination identifier, the source sequence number, the destination sequence number and so forth. When an intermediate node receives the route request packet, if it has a route to the destination, it will send a route reply packet to the source node, otherwise, it will forward the packet. If a node receives the same packet more than once, it will reject those duplicates. When the destination receives the route request packet, it will send a route reply packet to the source node. Finally, the source node will select a route and start transmitting.

2.3.3 Hybrid Routing Protocols

Hybrid routing protocols combine proactive routing protocols and reactive routing protocols. Under hybrid routing protocols, in some areas, proactive routing protocols are used to reduce the route setup delays and in the rest of the network, reactive routing protocols are used to save resources effectively.

2.4 Routing Metrics for Wireless Mesh Networks

Effective routing metrics are crucial factors for the design of routing protocols. In this section, we describe six existing routing metrics available for wireless mesh networks.

1) Hop Count

Hop count is the most common routing metric and used by most existing routing protocols, such as DSDV, AODV and DSR. Except the path length, hop count does not consider other environment elements of wireless media. Although it is simple and direct, in many situations, it can not achieve a very good performance [34].

2) Expected Transmission Count (ETX)

ETX is the number of a successful transmission of a data packet through a link. The number includes the transmission number and retransmission number. The weight of a path used by routing protocols is the summation of the ETXes of all links along the path. Besides the path length, the ETX metric considers the packet loss ratio. However, this metric does not take interference and transmission rate into consideration [35].

3) Expected Transmission Time (ETT)

The ETT metric is based on ETX metric. Besides those elements considered by ETX, ETT considers the transmission rate.

$$ETT = ETX * \frac{S}{B} , \tag{2.1}$$

where S in the formula is the size of the packet transmitted, and B is the bandwidth of the link. Similarly, the weight of a path is the summation of the ETTs of all links along the path. Although the link capacity is calculated by the metric, the inter-flow interference and intra-flow interference are not taken into account [36].

4) Weighted Cumulative Expected Transmission Time (WCETT)

$$WCETT(p) = (1-\beta)\sum_{l \in p} ETT_l + \beta \max_{1 \le j \le k} X_j \ . \tag{2.2}$$

In the WCETT of a path p, β is a tunable parameter, ranging from 0 to 1. X_j is the number of the links using the same channel to deliver packets along a path, and k is the total number of channels available. The WCETT metric is developed from ETT and considers the intra-flow interference. This metric considers the channel diversity, that is, the higher channel diversity the less is the intra-flow interference along a path. Therefore, WCETT can be adopted in routing protocols for multi-radio, multi-channel wireless mesh networks. The shortcoming of the metric is that, it does not capture inter-flow interference [36].

5) Metric of Interference and Channel-Switching (MIC)

$$MIC(p) = \frac{1}{N \times \min(ETT)} \sum_{l \in p} IRU_l + \sum_{i \in p} CSC_i \quad . \qquad (2.3)$$

The MIC metric is composed of two parts. One is the interference-aware resource usage (IRU) and the other is the channel switching cost (CSC). This metric compensates the shortcoming of WCETT and considers the inter-flow interference [34].

6) Exclusive Expected Transmission Time (EETT)

$$EETT_l = \sum_{link i \in IS(l)} ETT_i \quad . \qquad (2.4)$$

Exclusive Expected Transmission Time (EETT) [37] is an interference-aware routing metric based on ETT metric. It selects routes with least interference and takes into account not only intra-flow interference but also inter-flow interference. For any given l, Interference set (IS) is defined to be the set of links that interfere with it, which includes the link itself.

2.5 Conclusions

In this chapter, we introduce two types of classifications of channel assignments for wireless mesh networks and existing channel assignments for wireless mesh networks. Based on the routing information update mechanism, routing protocols can be classified into three types of routing protocols, proactive routing protocols, reactive routing protocols and hybrid routing protocols. Depending upon whether a central network controller is used, channel assignment can be classified into centralized channel assignment and distributed channel assignment. According to the duration of an interface tuned on a specified channel, channel assignment can be divided into static channel assignment, dynamic channel assignment and hybrid channel assignment. The channel assignments we propose in this thesis are hybrid, distributed channel assignments. After that, we present a type of classification of routing protocols and six routing metrics for wireless mesh networks. Based on the routing information update mechanism, routing protocols can be classified as proactive routing protocols, reactive routing protocols and hybrid routing protocols. In this thesis, we employ a reactive routing protocol, AODV and make modifications to it to support multiple radios, multiple channels and quality of service.

Chapter 3

Channel Assignment Exploiting Partially Overlapping Channels (CAEPO)

3.1 Introduction

Unlike most IEEE 802.11-based ad hoc networks, in which only a single channel is used, wireless mesh networks allow the simultaneous use of multiple channels to increase the aggregated capacity. In recent years, many efforts have been taken to better exploit multiple non-overlapping channels. Although the IEEE 802.11 b/g standards, which govern the unlicensed 2.4 GHz industrial, scientific and medical (ISM) band, provide 11 channels, only three of them, namely 1, 6 and 11 are non-overlapping. In this chapter, we propose a distributed channel assignment scheme named Channel Assignment Exploiting Partially Overlapping Channels (CAEPO). CAEPO can not only assign non-overlapping channels, but also exploit partially overlapping channels. In the proposed scheme, the interference a node suffers within its interference range is the main factor, which is defined to be a combination of the overlapping degree between channels and busy time proportion, i.e. channel utilization ratio of interfering nodes. In addition to that, packet loss ratio is another major consideration in the development of our proposed channel assignment scheme.

From simulation results, we can see that using 11 channels, CAEPO effectively improves the network performance.

3.2 Cost Consideration for CAEPO

We use the interference that a node suffers within its interference range as the channel assignment metric. In the estimation of the interference metric, we take into account channel overlapping degree and busy time proportion.

3.2.1 Channel Overlapping Degree

Table 3.1: Channel Overlapping Degree [38]

OIf	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11
CH1	1	0.7272	0.2714	0.0375	0.0054	0.0008	0.0002	0	0	0	0
CH2	0.7272	1	0.7272	0.2714	0.0375	0.0054	0.0008	0.0002	0	0	0
CH3	0.2714	0.7272	1	0.7272	0.2714	0.0375	0.0054	0.0008	0.0002	0	0
CH4	0.0375	0.2714	0.7272	1	0.7272	0.2714	0.0375	0.0054	0.0008	0.0002	0
CH5	0.0054	0.0375	0.2714	0.7272	1	0.7272	0.2714	0.0375	0.0054	0.0008	0.0002
CH6	0.0008	0.0054	0.0375	0.2714	0.7272	1	0.7272	0.2714	0.0375	0.0054	0.0008
CH7	0.0002	0.0008	0.0054	0.0375	0.2714	0.7272	1	0.7272	0.2714	0.0375	0.0054
CH8	0	0.0002	0.0008	0.0054	0.0375	0.2714	0.7272	1	0.7272	0.2714	0.0375
CH9	0	0	0.0002	0.0008	0.0054	0.0375	0.2714	0.7272	1	0.7272	0.2714
CH10	0	0	0	0.0002	0.0008	0.0054	0.0375	0.2714	07272	1	0.7272
CH11	0	0	0	0	0.0002	0.0008	0.0054	0.0375	0.2714	0.7272	1

The IEEE 802.11 b/g standards governing the unlicensed 2.4 GHz band provide 11 channels in North America. Among the 11 available channels, only three of them, namely 1, 6 and 11 are non-overlapping channels, separated by 25 MHz at their center frequencies. Channel overlapping degree is the overlapping level between channels [38] under the IEEE 802.11 b/g standards. From Table 3.1, we can see that a channel separation of 2 (e.g., using channel 1 and 3) produces 27.14% interference, channel separation of 3 produces about 3.75% interference, and channel separation of 5 and above produces very little interference and can often be neglected. Therefore, two channels with a channel separation of 5 or higher are regarded as mutually non-overlapping channels, for example, in the case of channel 1, 6 and 11.

3.2.2 Interference Metrics for CAEPO

In the initial phase of channel assignment, the overlapping degree between channels (in Table 3.1) is considered to be the only factor of the interference metric, which is defined in Equation (3.1)

$$X[i][c] = \sum_{j \in I(i)} O[i_c][j], \tag{3.1}$$

where $X[i][c]$ is the total interference that node i suffers from the nodes in its interference range when any channel c is assigned to the node i. $I(i)$ is the set of the nodes within the interference range of node i and j is any node in the set $I(i)$. $O[i_c][j]$ is the channel overlapping degree between the channels used by node i and node j.

In the update phase of channel assignment, the overlapping degree between channels is not the only consideration in the estimation of interference a node suffers within its interference range. The interference metric is defined to be a combination of channel overlapping degree and busy time proportion, i.e. channel utilization ration of interfering nodes in Equation (3.2).

$$X[i][c] = \sum_{j \in I(i)} O[i_c][j] \times B(j), \tag{3.2}$$

where $X[i][c]$ is the total interference node i suffers from the nodes in its interference range when channel c is assigned to node i. $O[i_c][j]$ is the channel overlapping degree between the channel of node i and the channel of node j. $B(j)$ is the proportion of the busy time of node j, that is, $B(j) = busytime(j) / (busytime(j) + idletime(j))$. $N(i)$ is the set of the nodes in the interference range of node i.

3.3 CAEPO Scheme

In the proposed scheme, we set the interference range of a node to two hops from it. We assume that each node in the network has two interfaces. Each node divides its two interfaces into two groups, fixed interface and switchable interface. The fixed interface is tuned on specified channels for intervals longer than the duration of a packet and responsible for receiving packets. The switchable interface can be frequently switched among the remaining non-fixed channels. When a node has no data to transmit, its switchable interface stays on a default channel. When the node has packets to send, the switchable interface switches to the receiver's fixed channel. The interference that a node suffers within its range is considered to be the channel assignment metric and turned to be the combination of traffic load, self-interference factor and overlapping degree between channels.

In the initial phase of channel assignment, the initialization algorithm is used to select the initial fixed channel for each node and in the update phase, the update algorithm is used to select the current fixed channel for each node. The following symbols are defined for the rest of the chapter, which are summarized in Table 3.2.

Table 3.2: Important Symbols in CAEPO

Symbol	Definition
S	Set of the nodes in the network
i	Any node in S
$I(i)$	Set of the nodes in the interference range of node i
j	Any node in $I(i)$
$B(j)$	Proportion of the busy time of node j
C	Set of available channels in the network
c	Any channel in C

3.3.1 Initialization Algorithm of CAEPO

Initialization Algorithm

1 : For $i \in S$

Randomly select a channel as its fixed channel

2 : For $i \in S$

For $c \in C$

Calculate $X[i][c]$ in Equation (3.1).

3 : For $i \in S$

If, when $c = m$ ($m \in C$) is assigned to the fixed interface of node i, the metric $X[i][c]$ in Equation (3.1) reaches the minimum

Then select m as the initial fixed channel of the node i

Figure 3.1: Initialization Algorithm of CAEPO

3.3.2 Update Algorithm of CAEPO

In the update algorithm, the optimal fixed channel is selected for the fixed interface of each node. $X[i][c]$ in Equation (3.2) is used as the channel assignment metric.

Update Algorithm

---

1 : For $i \in S$

  For $c \in C$

    Calculate $X[i][c]$ in Equation (3.2)

2 : For $i \in S$

    If, when $c = w$ ($w \in C$) is assigned to the fixed interface of the node i, the metric $X[i][c]$ in Equation (3.2) reaches the minimum

    Then select w as the current fixed channel of the node i

Figure 3.2: Update Algorithm of CAEPO

3.3.3 CAEPO Channel Assignment

At the beginning of the initial phase of channel assignment, each node randomly selects a channel as its fixed channel and tunes its switchable interface on a common channel. The common channel is not only able to ensure a basic connectivity between neighbor nodes but also able to be used to choose an alternate path when some link encounters failure. Besides, the common channel carries control information so that the neighbor nodes can exchange updated information with each other over the channel.

When a network is in operation, each node periodically broadcasts a "*HELLO*" message with its ID and fixed channel to all nodes within its interference range. Each "*HELLO*" message includes a flag, which indicates the message is received from the source node if it is "0"and received from an intermediate node if "1". When a node receives a "*HELLO*" message, it will check the flag. If the flag is "0", the node will forward the message to its neighbors and set the flag to "1"; otherwise, the node will ignore it. Each "*HELLO*" message can only be forwarded once, which ensures that the "*HELLO*" message only reaches its two-hop nodes. The duplicates from the same source node will be discarded.

In Initialization Algorithm, when any node i collects sufficient "*HELLO*" message from the nodes within its interference range, it uses $X[i][c]$ in Equation (3.1) to calculate the interference that it suffers within its interference range if any available channel c is assigned to node i. Node i selects the channel, which makes it suffer the least interference within its interference range as the channel for its fixed interface. Once it is selected, the node broadcasts the information to all nodes within its range like broadcasting "*HELLO*" messages.

In the update phase, Update Algorithm is employed to select optimal fixed channels for those fixed interfaces. Each node periodically calculates $X[i][c]$, and selects the channel which makes it suffer the least interference in its transmission range as its fixed channel for its fixed interface. Moreover, when packet loss ratio does not meet the requirement, the interference recalculation is also implemented and the channel assignment will be updated.

Once one node changes its fixed channel, it advertises this information within its interference range over the common channel like broadcasting "*HELLO*" messages. When a node has data to send, it tunes its switchable interface to the fixed channel of the receiver. The receiver can receive the packet since its fixed interface is always listening to the channel.

3.4 Routing Protocol for CAEPO Scheme

We use the modified AODV as the routing protocol for CAEPO, in which, the expected end-to-end transmission delay takes the place of hop count as the routing metric.

The expected end-to-end transmission delay [36] is the summation of the expected transmission time of a single packet over a route,

$$ETD = \sum ETT\ . \tag{3.3}$$

We could obtain the expected transmission time from the expected transmission count, the packet size and the bandwidth of the link as in Equation (3.4),

$$ETT = ETX \times \frac{S}{B}\ . \tag{3.4}$$

Probe packets are broadcast to measure the packet loss probabilities P_f and P_r probabilities in the forward and reverse directions. With P_f and P_r, the probability of the unsuccessful packet transmission from one node to its one hop neighbor is calculated,

$$P = 1 - (1 - P_f) \times (1 - P_r)\ . \tag{3.5}$$

And finally, the successful transmission probability $S(k)$ and the expected transmission count ETX from a node to its one hop neighbor after k attempts are derived,

$$S(k) = P^{k-1} \times (1 - P)\ , \tag{3.6}$$

$$ETX = \sum_{k=1}^{\infty} k \times S(k) = \frac{1}{1-P}. \tag{3.7}$$

3.5 Performance Evaluation

We implement our channel assignment scheme using the Network Simulator 2 (ns-2). Modification to the original module has been made to support multiple radios and multiple channels [39]. In our simulations, the network is a 100-node square-grid network. 10 traffic profiles are generated and each contains 20 pairs of randomly chosen (on the uniform distribution) source and destination nodes. The ratio between interference and communication range is set to 2. For each profile, the traffic between each source-destination node pair is selected randomly between 0 and 3 Mbps. We use the modified AODV as the routing protocol, in which ETD replaces the hop count metric. The packet loss ratio parameter λ is set to 0.10. The simulation time is 300 seconds.

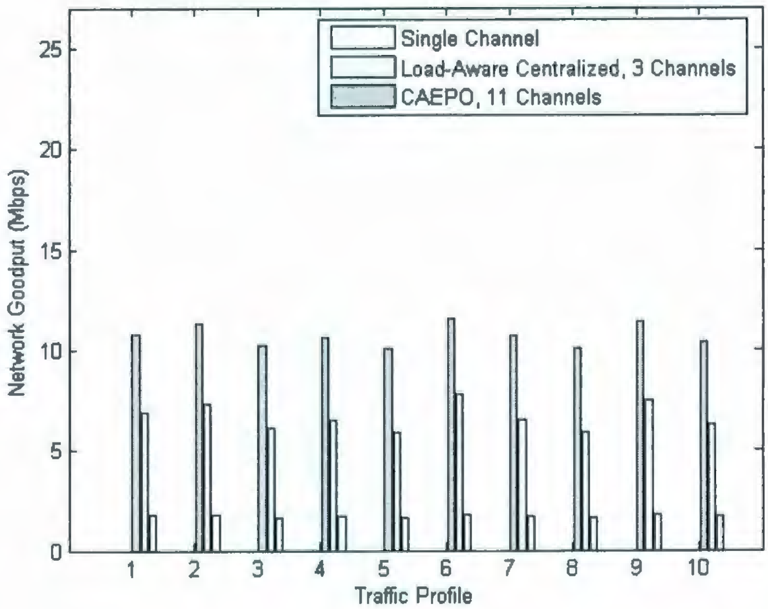

Figure 3.3: Network Goodput vs. Traffic Profile

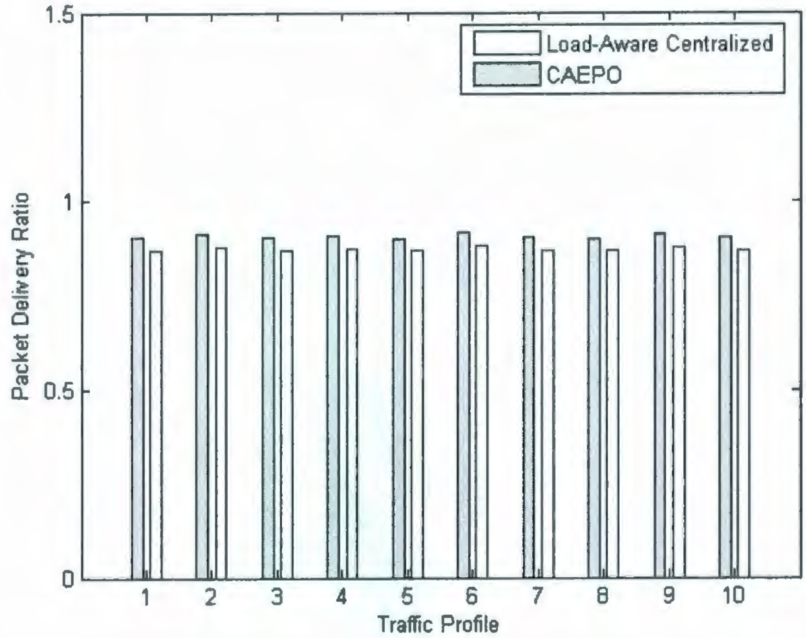

Figure 3.4: Packet Delivery Ratio vs. Traffic Profile

In Figure 3.3, the goodput of the channel assignment CAEPO is compared to that of single channel network and that of a load-aware centralized channel assignment using only 3 non-overlapping channels, which was proposed in [8]. "Goodput" is the number of useful bits per unit of time forwarded by the network, excluding protocol overhead and retransmitted data packets.

From Figure 3.3, we can observe that the network goodput of the channel assignment CAEPO using 11 channels is much better than the goodput of a single channel network. In the load-aware centralized channel assignment, because of the existence of a central network controller, the global topology information is collected and computed, a globally optimal channel assignment is implemented, whereas in the distributed CAEPO channel assignment, each router gathers and computes the local information, thus, the channel assignment is not globally, but locally, optimal. Despite that, as can be seen in Figure 3.3, the performance of CAEPO utilizing 11 channels is higher than that of the load-aware channel assignment using 3 non-overlapping channels. The reason is that in CAEPO, besides 3 non-overlapping channels, other partially overlapping channels are exploited as well. Thus, more available bandwidth can be utilized. Although some adjacent channel interference may be brought in, the using of the channel assignment CAEPO, which could mitigate interference by intelligent and effective algorithms improves the performance.

As Figure 3.4 shows, the packet delivery ratio of the channel assignment CAEPO using 11 channels is higher than that of the load-aware channel assignment with 3 non-overlapping channels. Hence, by exploiting partially overlapping channels, the channel assignment CAEPO not only exploits more available bandwidth but also improves the packet delivery ratio.

In Figure 3.5, the network goodput versus the number of source-destination pairs is studied. We perform the simulations with 10, 20, 30, 40 and 50 source-destination pairs in the network and generate 10 different traffic profiles for each. We use the average of goodput in the cases of 10 traffic profiles as the network goodput for a given number of source-destination pairs. The channel assignment CAEPO with 11 channels shows superiority over the load-aware channel assignment with 3 non-overlapping channels as more traffic load is introduced in the network.

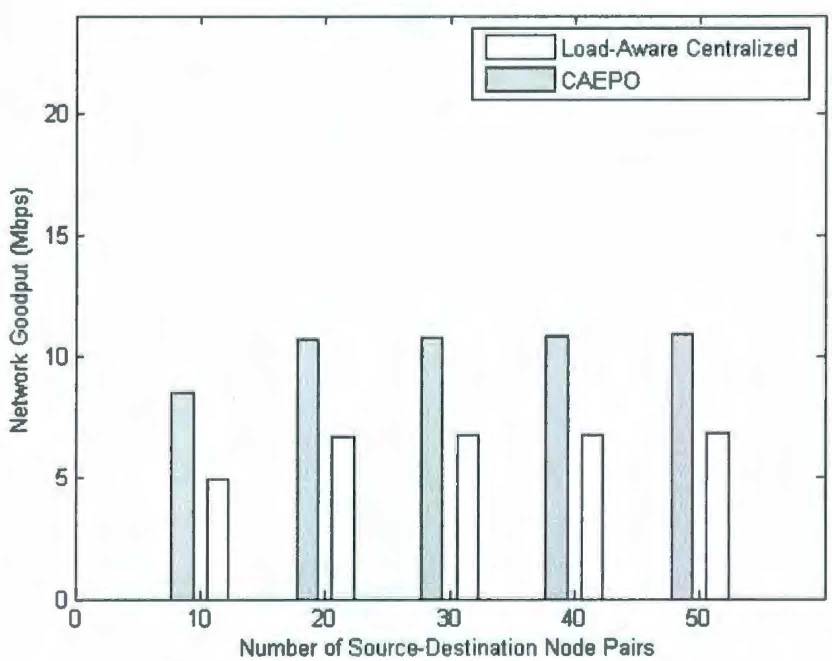

Figure 3.5: Network Goodput with Varying Traffic Load

3.6 Conclusions

In this chapter, we proposed a distributed channel assignment exploiting partially overlapping channels (CAEPO) for wireless mesh networks. In the scheme, the fixed interface of each node is responsible for receiving data and the switchable interface switches to the receiver's fixed channel to send data when the node has data transmission requirement. Compared to most of other channel assignments focusing on utilizing multiple non-overlapping channels, CAEPO not only uses non-overlapping channels but also exploits partially overlapping channels under IEEE 802.11 b/g standards. The exploitation and utilization of more available channels leads to more improvement of the aggregated network capacity.

Chapter 4

Load-Aware CAEPO

4.1 Introduction

In the original CAEPO scheme, we used the level of interference that a node suffers within its interference range as the main metric for channel assignment. The interference metric was defined to be the combination of overlapping degree between channels and busy time proportion, i.e., channel utilization ratio of interfering nodes. In this chapter, we introduce a new channel assignment based on the original CAEPO and we call it the load-aware channel assignment exploiting partially overlapping channels (Load-Aware CAEPO). In the new scheme, instead of using the busy time proportion of interfering nodes we employ the traffic load as another main factor of the interference metric besides the channel overlapping degree. In addition, the concept of self-interference is introduced to estimate the interference metric. Moreover, to facilitate the implementation of the channel assignment scheme, we modify the original AODV to be bandwidth-aware, where the available bandwidth and end-to-end delay are both used as the routing constraints. With the bandwidth-aware AODV, our channel assignment scheme significantly improves the aggregated network performance.

4.2 Load-Aware CAEPO Scheme

Like in the original CAEPO, in Load-Aware CAEPO channel assignment scheme, we assume that each node has two interfaces, which are divided into two groups, fixed interface and switchable interface. The fixed interface is tuned on the specified channels for a period longer than the duration of a packet and is responsible for receiving packets. The switchable interface can be frequently switched among the remaining non-fixed channels. When a node has no data to transmit, its switchable interface stays on a default channel. When the node has packets to send, the switchable interface switches to the receiver's fixed channel for communication. The interference range of a node is set to two hops from it. The channel assignment scheme is comprised of two phases, the initial phase and the update phase. The important symbols used for the rest of the chapter are defined in Table 4.1.

Table 4.1: Important Symbols in Load-Aware CAEPO

Symbol	Definition
S	Set of the nodes in the network
i	Any node in S
$I(i)$	Set of the nodes in the interference range of the node i
$N(i)$	Set of the neighbor nodes of the node i
j	Any node in $I(i)$
k, p	Any node in $N(i)$
$N(j)$	Set of the neighbor nodes of the node j
l	Any node in $N(j)$
$B[i][k]$	Traffic between the node i and its any neighbor k
$B[j][l]$	Traffic between the node j and its any neighbor l
C	Set of available channels in the network
c	Any channel in C

4.2.1 Cost Consideration for Load-Aware CAEPO

In the estimation of the interference metric, we take into account channel overlapping degree, self-interference factor and traffic load.

4.2.1.1 Self-Interference Factor

In the estimation of interference metric, we introduce the concept of self-interference. Self-interference, which is the interference between the channels of two links connected to a single node, is one of the most critical problems in channel assignment for multi-radio multi-channel WMNs [29].

The model in [31] justifies that two links at the same location (connected to the same node) will severely interfere with each other if their channels are partially or completely overlapped no matter how much the overlapping degree between the two channels because the distance between these two links is 0.

We use self-interference factor to formulate self-interference between the channels of two links connected to a single node and define the factor to be 0 if the separation of the channels of two links connected to a single node is more than or equal to 5 and to be 1 if the channel separation is less than 5.

4.2.1.2 Interference Metric for Load-Aware CAEPO

In the initial phase of channel assignment, the traffic load information in the network is unknown. Therefore, the overlapping degree between channels (from Table 3.1 in Chapter 3) is considered to be the only factor of the interference metric, which is has been defined in Equation (3.1) in Chapter 3.

$$X[i][c] = \sum_{j \in I(i)} O[i_c][j], \qquad (3.1)$$

where $X[i][c]$ is the total interference that node i suffers from the nodes within its interference range when any channel c is assigned to the node i. $I(i)$ is the set of the nodes within the interference range of node i and j is any node in the set $I(i)$. $O[i_c][j]$ is the channel overlapping degree between the channels used by node i and node j.

In the update phase, the overlapping degree between channels is not the only consideration in the estimation of interference because the traffic load information has been obtained by each node. Here, the interference metric is a combination of traffic load, self-interference factor and channel overlapping degree, as shown in Equation (4.1).

$$X[i][c] = \sum_{k \in N(i)} (B[i][k] \times X_{Self}[i_c][k]) + \sum_{j \in I(i)} \sum_{l \in N(j)} (B[j][l] \times Olf[i_c][l]), \qquad (4.1)$$

where $X[i][c]$ is the total interference that node i suffers from the nodes within its interference range when channel c is assigned to node i. $I(i)$ is the set of nodes within the interference range of node i. $N(i)$ is the set of neighboring nodes of node i. j is any node in set $I(i)$. $N(j)$ is the set of neighboring nodes of node j. k *is a*ny node in $N(i)$, namely any node within one hop range of node i. l is any neighbor of node j. $B[i][k]$ is the traffic from the node i to its neighbor k and $B[j][l]$ is the traffic from node j to its neighbor node l. $X_{Self}[i_c][k]$ is the self-interference factor between channel c and the fixed channel of node k.

Figure 4.1 illustrates the interference that node i suffers within its interference range. When node i transmits packets to its neighbor k, its switchable interface of node i is tuned on the fixed channel of node k. The transmission from node i may interfere with the transmission from another neighbor node p to node i if the fixed interface of node i is tuned on channel c and the fixed channel of node k and channel c are partially or completely overlapped, i.e., channel separation is less than 5. The link between nodes i and k and the link between nodes p and i are both connected to the same node, node i. Therefore, the communication between such pairs of links causes self-interference. We use the combination of $B[i][k]$ and $X_{Self}[i_c][k]$ to describe the interference caused by the transmission from node i to its neighbor k.

Similarly, if any node j within the interference range of node i has packets to transmit to any neighbor l, the switchable interface of node j is tuned on the fixed channel of node l. The transmission from node j may interfere with the transmission to node i when the fixed interface of node i is tuned on channel c. We define the interference caused by the transmission from node j to any neighbor l as the combination of $B[j][l]$ and the overlapping degree between channel c and the fixed channel of node l, that is, $O[i_c][l]$.

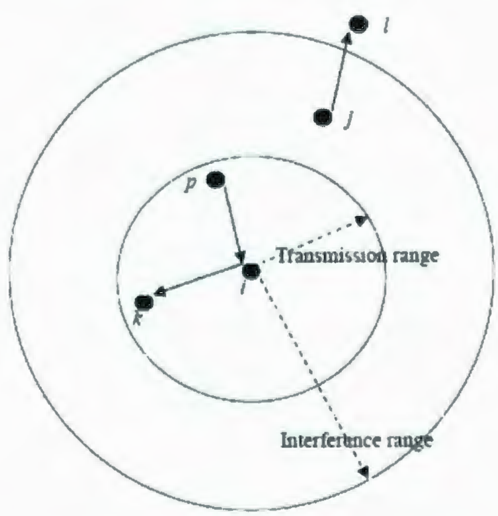

Figure 4.1: An example of the Interference Node i Suffers in Its Interference Range

4.2.2 Load-Aware CAEPO Channel Assignment

In the proposed channel assignment scheme, we employ an initialization algorithm and an update algorithm to select the fixed channel for each node in the initial phase and the update phase, respectively.

4.2.2.1 Initialization Algorithm of Load-Aware CAEPO

In the initial phase of the channel assignment, the traffic load information in the network is unknown. Therefore, only the overlapping degree between channels is considered in the interference metric. In the initialization algorithm, $X[i][c]$ in Equation (3.1) is used in the metric to select the initial fixed channel for the fixed interface of each node. The Pseudo code of the initialization algorithm is shown in Figure 4.2.

Initialization Algorithm

---

1 : For $i \in S$

Randomly select a channel as its fixed channel

2 : For $i \in S$

For $c \in C$

Calculate $X[i][c]$ in Equation (3.1).

3 : For $i \in S$

If, when $c = m$ ($m \in C$) is assigned to the fixed interface of node i, the metric $X[i][c]$ in Equation (3.1) reaches the minimum

Then select m as the initial fixed channel of node i

Figure 4.2: Initialization Algorithm of Load-Aware CAEPO

Like in CAEPO, at the beginning of the initialization algorithm, each node tunes its switchable interface on a default common channel and randomly selects a channel as its fixed channel. Then, any node i uses $X[i][c]$ to calculate the interference that it suffers within its interference range when any available channel c is assigned to node i.

Node i selects the channel, which makes it suffer the least interference within its interference range as the channel for its fixed interface. Once it is selected, the node broadcasts the information to all nodes within its range like broadcasting "*HELLO*" messages.

4.2.2.2 Update Algorithm of Load-Aware CAEPO

In the update phase, the update algorithm, as shown in Figure 3, is employed to select the optimal fixed channels for those fixed interfaces. In this phase, the traffic load is taken into account in addition to the overlapping degree between channels in the interference metric calculation. Hence, it becomes a combination of channel overlapping degree, self-interference factor and traffic load of the interfering nodes, which is given by Equation (4.1). The Pseudo code of the update algorithm is shown in Figure 4.3.

Update Algorithm

---

1 : For $i \in S$

For $c \in C$

Calculate $X[i][c]$ in Equation (4.1)

2 : For $i \in S$

If, when $c = w$ ($w \in C$) is assigned to the fixed interface of the node i, the metric $X[i][c]$ in Equation (4.1) reaches the minimum

Then select w as the current fixed channel of node i

Figure 4.3: Update Algorithm of Load-Aware CAEPO

Each node keeps track of the number of packets it sent to its neighbors to calculate its traffic load periodically. During each update, all nodes tune their switchable interfaces to the common channel, on which they exchange traffic load information like exchanging "*HELLO*" messages. After that, each node periodically calculates $X[i][c]$ and selects its fixed channel, which makes it suffer the least interference within its interference range as the fixed channel. Once one node changes its fixed channel, it will advertise this information over the default channel. When a node has data to send, it switches its switchable interface to the fixed channel of the receiver. The receiver can receive the packet since its fixed interface is always listening to the channel. When the link fails, the default channel will be used to select an alternate path.

4.3 Bandwidth-Aware AODV

In Chapter 3, we modified AODV by replacing the hop count with the expected end-to-end transmission delay as the routing metric. In this chapter, we extend AODV to be bandwidth-aware based on multi-radio multi-channel extensions to AODV [39]. We employ the route discovery process and the admission control mechanisms proposed in the routing protocol AQOR [40] and modify the available bandwidth estimation to support multiple partially overlapping channels. We name the routing protocol Bandwidth-Aware AODV.

4.3.1 RREQ Packet and Route Discovery in AODV

In AODV [33], when a node has data to transmit, it initiates the route discovery process by issuing a route request packet (RREQ). Each route request packet contains the following fields as shown in Figure 4: source identifier (Src ID), source sequence number (Src SeqNum), broadcast identifier (Bcast ID), destination identifier (Dest ID), destination sequence number (Dest SeqNum), hop count and time to live (TTL) field. Each RREQ is uniquely identified by its source identifier (Src ID) and broadcast identifier (Bcast ID).

Table 4.2: Sample of RREQ Packet in AODV

Src ID	Src SeqNum	Bcast ID	Dest ID	Dest SeqNum	Hop Count	TTL

The SeqNum is the indication of the freshness of a route and is used to determine an up-to-date route to the destination node. When an intermediate node receives an RREQ packet from one of its neighbors, it checks whether the packet has a valid path to the destination node or not. If it does have, the intermediate node will satisfy the RREQ request by acknowledging a route reply packet (RREP) to the source node following the reverse route. If it does not contain a path to the destination, the intermediate node will increase the hop count by one and broadcasts the RREQ to its neighbors, where the identifier of the previous node will be used as the broadcast identifier of the RREQ packet. The intermediate node keeps track of the destination identifier (Dest ID), the source identifier (Src ID), the source sequence number (Src SeqNum), the broadcast identifier (Bcast ID) and the time to live (TTL) to set up the reverse path and forward path by sending a route reply packet (RREP). If an intermediate node receives multiple copies of the same RREQ (identified by the Src ID and Bcast ID fields), duplicate copied will simply be discarded by the node. If an intermediate node does not receive any RREP packet during the time to live (TTL) period, it will delete the entry of the previous node ID and the Bcast ID from its routing table.

When the destination node receives the RREQ packet, it replies with an RREP packet along the reverse path to the source node. When an intermediate node receives the RREP, it stores the previous hop information so as to set up the forward path where the previous hop node on the reverse path will be used as the next hop along the forward path.

4.3.2 Extended RREQ in Bandwidth-Aware AODV

In the bandwidth-aware AODV, we take into account two quality-of-service (QoS) metrics (end-to-end delay and bandwidth) in the routing metric calculation, which is similar to [40]. To facilitate this new feature, we extend the RREQ packet by introducing two additional fields, $T_{\max}$ and $B_{\min}$ as shown in Table 4.3, where $T_{\max}$ gives the maximum end-to-end delay constraint and $B_{\min}$ is the minimum bandwidth required at each node.

Table 4.3: Sample of RREQ Packet in the bandwidth-aware AODV

Src ID	Src SeqNum	Bcast ID	Dest ID	Dest SeqNum	Hop Count	TTL	$T_{\max}$	$B_{\min}$

4.3.3 Routing metric of Bandwidth-Aware AODV

We use the available bandwidth at nodes and the end-to-end delay as the routing metrics. They should be satisfied according to constraints constraint functions given by in Equations (4.2) and (4.3), respectively.

$$T_{round} \leq 2T_{\max} \quad , \tag{4.2}$$

$$B_{avail}[i] \geq B_{\min} \quad , \tag{4.3}$$

where T_{round} is the round trip time of the RREQ packet. Based on the constraint functions, the available bandwidth at any node *i*, $B_{avail}[i]$ is given by

$$B_{avail}[i] = Ca[i] - \sum_{k \in N(i)} (B[i][k] \times X_{Self}[i][k]) - \sum_{j \in I(i)} \sum_{l \in N(j)} (B[j][l]) \times O[i][l]) \quad , \tag{4.4}$$

where $Ca[i]$ is the capacity of the fixed channel of node *i*. $X_{Self}[i_c][k]$ is the self-interference factor between the fixed channel of node *i* and that of its any neighbor *k* and $O[i][l]$ is the overlapping degree between the fixed channel of node *i* and that of node *l*. $B_{avail}[i]$ captures not only the intra-flow interference but also inter-flow interference.

4.3.4 Route Discovery of Bandwidth-Aware AODV

When a source node has data to transmit but the destination node is not in its routing table, the source node initiates an RREQ packet, which includes the two QoS constraints, $T_{\max}$ and $B_{\min}$. When an intermediate node receives the RREQ, it compares $B_{\min}$ with its B_{avail}. If $B_{avail} \geq B_{\min}$, the available bandwidth will meet the bandwidth requirement. The intermediate node then adds a new route entry indicating the reception of RREQ and forwards the RREQ to its neighbors. Otherwise, it simply discards the RREQ.

When the destination node receives the RREQ, it checks its bandwidth availability. If the bandwidth meets the requirement, the destination node acknowledges with an RREP packet along the reverse path.

When an intermediate node receives the RREP packet, it compares B_{avail} with B_{min} again. If the bandwidth meets the requirement, it updates the newly-added route entry and is ready to forward data packets. Otherwise, the intermediate node will discard the RREP. If it does not receive RREP in $2T_{max}$ after it forwards the RREQ, the intermediate node deletes that route entry from its routing table.

4.4 Performance Evaluation

Like in Chapter 3, we implement our channel assignment schemes using the Network Simulator (ns-2). Modifications to the existing ns-2 modules have been made to support multiple radios and multiple channels [39]. We perform the simulations in two different scenarios.

In the first scenario, the topology follows a 100-node square-grid network. A total of 10 traffic profiles are generated, each of which contains 20 pairs of randomly chosen (on the uniform distribution) source and destination nodes. For each profile, the data rate between each source-destination pair is randomly selected between 0 and 3 Mbps. The ratio between interference range and communication range is set to be 2. The simulation time is 300 seconds.

We compare the performance (goodput and packet delivery ratio) of Load-Aware CAEPO with the original CAEPO, the load-aware centralized channel assignment [8] and Q-JOCAC scheme [30].

In Figure 4.4, the aggregated network goodput of various schemes is compared. It is observed that Load-Aware CAEPO using 11 channels is 8.6 times that of the goodput of single channel network and it is 2.2 times the goodput of the load-aware centralized channel assignment using 3 non-overlapping channels. The reason is that Load-Aware CAEPO using 11 channels exploits more available bandwidth, which leads to better performance although some adjacent channel interference is presented. Besides, the goodput of Load-Aware CAEPO using 11 channels is 1.36 times the goodput of CAEPO and 1.27 times that of Q-JOCAC using the same number of channels. Load-Aware CAEPO judiciously combines channel overlapping degree, self-interference factor and traffic load to obtain a more precise estimation of the interference, which better exploits the space utilization of the available channels.

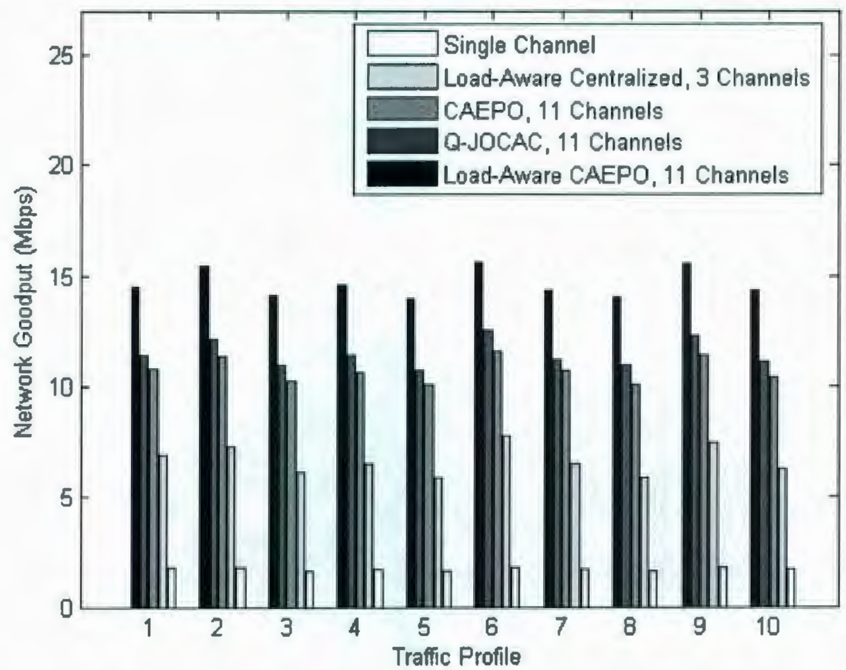

Figure 4.4: Network Goodput vs. Traffic Profile

In Figure 4.5, the packet delivery ratio of various schemes is compared. From the figure, the packet delivery ratio of the Load-Aware CAEPO is much higher than the load-aware centralized channel assignment and better than CAEPO and Q-JOCAC. The proposed scheme, along with the Bandwidth-Aware AODV, guarantees the required bandwidth for more flows and decreases the packet loss. Therefore, the Load-Aware CAEPO not only achieves higher goodput than the other three schemes but also improves the packet delivery ratio.

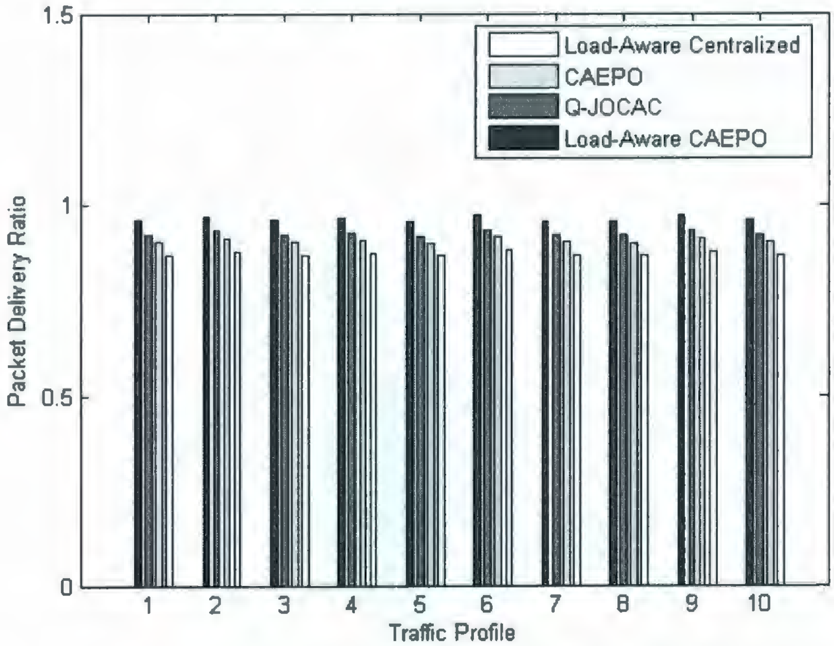

Figure 4.5: Packet Delivery Ratio vs. Traffic Profile

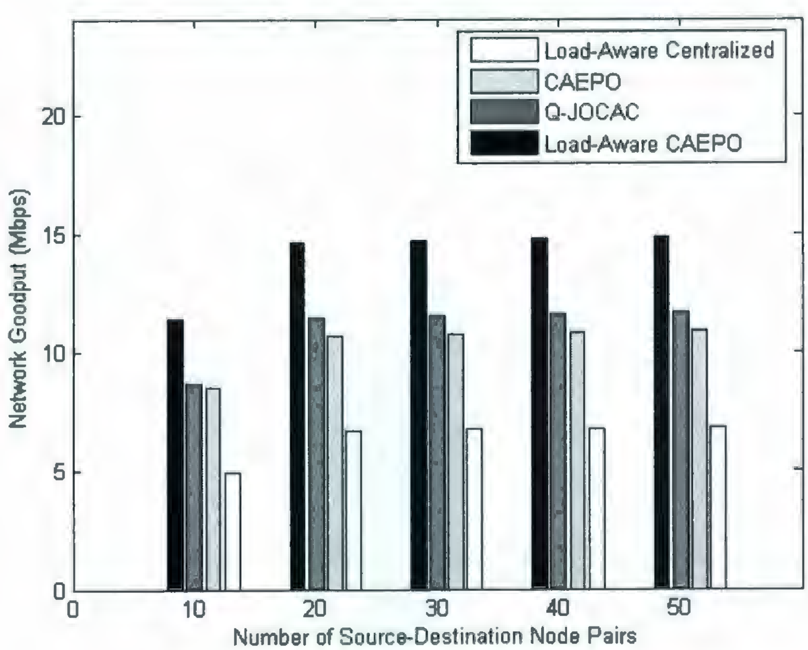

Figure 4.6: Network Goodput vs. Varying Traffic Load

In Figure 4.6, the network goodput versus the number of source-destination pairs is studied. We perform the simulations with 10, 20, 30, 40 and 50 source-destination pairs in the network and generate 10 different traffic profiles for each. We use the average of goodput in the cases of 10 traffic profiles as the network goodput for a given number of source-destination pairs. In the case of Load-Aware CAEPO scheme, the bandwidth-aware AODV routing protocol also takes into account the traffic load. Therefore, when more traffic is introduced in the network, Load-Aware CAEPO scheme clearly leads to the improvement of the aggregated network goodput over the other three channel assignment schemes.

In the second scenario, ten different topologies are randomly generated. Each topology consists of 2 gateways and 15 wireless mesh routers. For each topology, 20 different randomly generated traffic patterns are used, each of which contains 30 flows. 15 of them are always-on flows and the other 15 are randomly-on flows. The data rate for each flow is chosen at random between 0 and 3 Mbps. The simulation time is 300 seconds and the lifetime of each randomly-on flow follows a uniform distribution between 0 and 300 seconds. The ratio between interferee range and communication range is set to be 2.

In Figure 4.7, the goodput of various channel assignment schemes are compared. We observe that the goodput of the load-aware CAEPO is much higher than the goodput of single channel mesh network and that of the load-aware centralized channel assignment using only three non-overlapped channels. The reason is that the load-aware CAEPO can exploit more available bandwidth, hence possesses better performance although some adjacent channel interference is presented. Moreover, the goodput of the load-aware CAEPO is 1.35 times the goodput of the original CAEPO and 1.23 times that of Q-JOCAC. The results from the figure indicate that the load-aware CAEPO scheme judiciously combines channel overlapping degree, self-interference factor and traffic load to obtain a more precise estimation of the interference, and thus better exploits the space utilization of the available channels and achieves more improvement of the aggregated network performance.

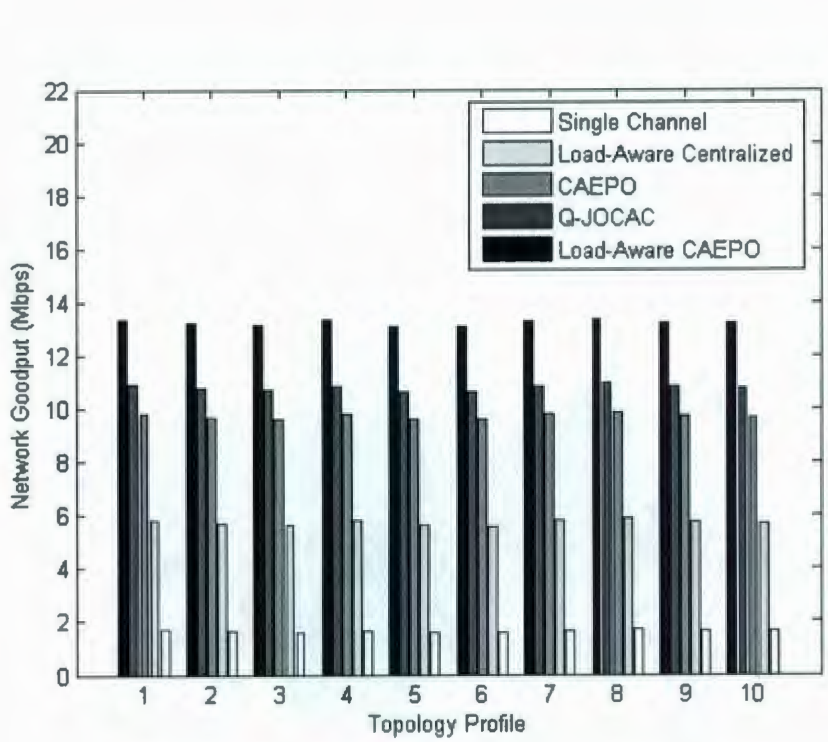

Figure 4.7: Network Goodput vs. Topology Number

4.5 Conclusions

In this chapter, based on the original CAEPO channel assignment, a load-aware channel assignment exploiting partially overlapping channels (Load-Aware CAEPO) is proposed. In Load-aware CAEPO scheme, the channel assignment metric is defined to be a combination of channel overlapping degree, self-interference factor and traffic load, which leads to a more precise estimation of compared to the original CAEPO. Besides improving the channel assignment scheme, we extend AODV routing protocol to be bandwidth-aware based on the multi-radio multi-channel extensions to AODV. In the bandwidth-aware AODV, two quality-of-service elements, bandwidth and end-to-end delay are considered to be the routing metrics to achieve higher network goodput and packet delivery ratio. The routing protocol captures only intra-flow interference but also inter-flow interference. The load-aware channel assignment scheme, when employed with the QoS-aware routing protocol, leads to much improved network-aggregated performance.

Chapter 5

Load-Aware CAEPO with Node Grouping

5.1 Introduction

In Chapter 4, we presented a new channel assignment scheme, Load-Aware CAEPO. In the update phase of Load-Aware CAEPO, the traffic load of the interfering nodes is considered to be another main factor of the interference metric in addition to the overlapping degree between channels. Besides, the concept of the self-interference is introduced in the estimation of interference metric. Therefore, we obtained a more precise estimation of the interference compared to the original CAEPO. Although Load-Aware CAEPO leads to more improvement of the network performance, it does not scale very well. In Load-Aware CAEPO, the earlier the nodes select channels, the better channels they obtain. Therefore, the nodes which select channels later may not obtain optimal channels. The unfairness becomes more obvious as the scale of the network increases. In this chapter, we further propose a grouping algorithm, which can be used with the load-aware CAEPO for networks of large scale.

5.2 Node Grouping Algorithm

Three constraints are considered in the proposed grouping algorithm.

1) Each ordinary node has and only has one group leader within its interference range.
2) Any two group leaders cannot be one-hop neighbors.
3) Each group leader has a maximum number of its member nodes, which is denoted by *MaxNum*.

Each node has the knowledge of the nodes within its interference range since it periodically exchanges "*HELLO*" messages with them. When a node collects sufficient broadcast messages from its neighboring nodes, it obtains the knowledge of the number of nodes within its interference range. This number (the number of nodes within the interference range of a node) becomes the weight of a node for electing itself as the group leader.

Each node broadcasts the weight within its interference range like broadcasting "*HELLO*" messages. The one with the highest weight will elect itself as a group leader and broadcast a "*GROUP LEADER*" message when it gathers sufficient broadcast messages within its interference range. Upon receiving the message, its neighbors of the group leader cannot elect themselves as group leaders. To resolve possible contention, if two or more nodes have the same highest weight, the one with the smallest ID will become the group leader. And other nodes with the same highest weight in the range will broadcast a "*NON GROUP LEADER*" message indicating that they will not elect themselves as group leaders.

When a node receives a "*GROUP LEADER*" message, it checks whether it has joined a group. If not, it will send out a "*JOIN*" message to the group leader, requesting to join the group. If the node has already joined a group but the weight of its group leader is lower than the new one, it will sends out a "*JOIN*" message to the new group leader; otherwise, its status will remain unchanged. Before a node leaves a group and joins a new group, it sends a "*QUIT*" message to the old group leader, who will remove it from the member list. When a group leader receives a "*JOIN*" message, it checks whether the number of its members exceeds *MaxNum*. If the number is less than *MaxNum*, the join request will be granted and the requesting node will be acknowledged with an "*ACCEPT*" message, otherwise, it simply rejects the request. The neighboring nodes of a group leader will have a higher priority to join the group than other nodes within the interference range of the group leader.

Once a group is formed, the group leader notifies all nodes within its interference range. Similar approach will be repeated for all remaining nodes in the range, that is, the node with the highest weight within its interference range elects itself as a group leader, and other nodes request to join the group and so on.

If all members leave the group, the group leader will reverse its role back to an ordinary node and can request to join other groups. On the other hand, if a group leader leaves the group instead, another election process will be triggered for all remaining nodes within its range and the one with the largest weight will become the new group leader. When confirmed, the nodes within its interference range will request to join the new group, whereas the rest of the nodes, which are outsides the interference range, will request to join other groups.

5.3 Load-Aware CAEPO-G Scheme

Like in the original CAEPO and Load-Aware CAEPO channel assignment scheme, we assume that each node in the network has two interfaces. Each node divides its two interfaces into two groups, fixed interface and switchable interface. The fixed interface is tuned on specified channels for longer intervals than the duration of a packet and responsible for receiving packets. The switchable interface can be frequently switched among the remaining non-fixed channels. When a node has no data to transmit, its switchable interface stays on a default channel. When the node has packets to send, the switchable interface switches to the receiver's fixed channel. The interference range of a node is set to two hops from it. The channel assignment scheme is comprised of two phases, the initial phase and the update phase. The grouping algorithm is first executed at the initial phase of channel assignment.

5.3.1 Cost Consideration in Load-Aware CAEPO-G

Load-Aware CAEPO-G uses the same metrics as the Load-Aware CAEPO to implement channel assignment. In the initial phase of the channel assignment scheme, the overlapping degree between channels defined in Table 3.1 is used as the only factor of the estimation of interference metric in Equation (3.1).

$$X[i][c] = \sum_{j\in I(i)} O[i_c][j], \tag{3.1}$$

where $X[i][c]$ is the total interference that node i suffers from the nodes in its interference range when any channel c is assigned to the node i. $I(i)$ is the set of the nodes within the interference range of node i and j is any node in the set $I(i)$. $O[i_c][j]$ is the channel overlapping degree between the channels used by node i and node j.

In the update phase, the overlapping degree between channels is not the only consideration in the estimation of interference. The interference metric is a combination of traffic load, self-interference factor and channel overlapping degree, as shown in Equation (4.1).

$$X[i][c] = \sum_{k\in N(i)} (B[i][k] \times X_{Self}[i_c][k]) + \sum_{j\in I(i)} \sum_{l\in N(j)} (B[j][l] \times O[i_c][l]), \tag{4.1}$$

where $X[i][c]$ is the total interference that node i suffers from the nodes within its interference range when channel c is assigned to node i. $I(i)$ is the set of nodes within the interference range of node i. $N(i)$ is the set of neighboring nodes of node i. j is any node in set $I(i)$. $N(j)$ is the set of neighboring nodes of node j. k is any node in $N(i)$, namely any node within one hop range of node i. l is any neighbor of node j. $B[i][k]$ is the traffic from the node i to its neighbor k and $B[j][l]$ is the traffic from node j to its neighbor node l. $X_{Self}[i_c][k]$ is the self-interference factor between channel c and the fixed channel of node k.

5.3.2 Load-Aware CAEPO-G Channel Assignment

Like Load-Aware CAEPO, Load-Aware CAEPO-G scheme uses two algorithms, the initialization algorithm and the update algorithm to implement channel assignment.

5.3.2.1 Initialization Algorithm of Load-Aware CAEPO-G

In Load-Aware CAEPO-G scheme, grouping algorithm is first executed at the beginning of the initialization algorithm. The elected group leaders will be responsible for selecting fixed channels for its members in the update phase. After groups are formed, any node i in the network uses $X[i][c]$, which is given by Equation (3.1), to calculate the interference it suffers given that any available channel c is assigned to node i like in Load-Aware CAEPO. The channel which makes node i suffer the least interference will be selected as the initial fixed channel for its fixed interface. Once determined, the node broadcasts the information to all nodes within its interference range like broadcasting "*HELLO*" messages in the initial phase.

5.3.2.2 Update Algorithm of Load-Aware CAEPO-G

In the update algorithm, $X[i][c]$, which is given by Equation (4.1), is used to calculate the interference that node i suffers within its interference range like in the update algorithm of Load-Aware CAEPO. After that, any node i calculates that interference metric to determine the three best candidate channels, i.e., those with the least interference weights for its fixed interface, which is denoted by x, y and z. Node i then informs its group leader of the three candidate channels and the interference caused by them. After the group leader has obtained the candidate channel information from all members, it broadcasts the information to its members. After receiving the message from the group leader, any other node q in the same group calculates $X[q][i_{candi}]$ for any candidate channel of any node i, which is the interference it suffers within its interference range given that any candidate channel is assigned to node i. Node q will then report the calculation result of $A[q][i_{candi}]$ for each candidate channel, as given by Equation (5.1), to the group leader.

$$A[q][i_{candi}] = \begin{cases} 1, & \dfrac{X[q][i_{candi}] - X_{current}[q]}{X_{current}[q]} \leq \alpha \\ 0, & \dfrac{X[q][i_{candi}] - X_{current}[q]}{X_{current}[q]} > \alpha \end{cases}, \qquad (5.1)$$

where $X_{current}[q]$ is the current interference that node q suffers and α is the pre-defined acceptance ratio parameter. $A[q][i_{candi}] = 1$ means that node q approves the candidate to be selected as the fixed channel of node i while $A[q][i_{candi}] = 0$ means that node q disapproves it.

When the group leader gathers the reports from all members, it uses Equation (5.2) to calculate the approval ratio of any candidate channel of any node i in its group.

$$R[i_{candi}] = \frac{\sum_{q \in G} A[q][i_{candi}]}{N_G - 1}, \tag{5.2}$$

where G is the set of the nodes excluding node i in the group and node p is any node in set G. N_G is the number of nodes in the group. $R[i_{candi}]$ is the approval ratio of any candidate channel of node i.

For any node i, the group leader will compare the approval ratios of its three candidates, $R[x]$, $R[y]$ and R $[z]$ and select the best channel, i.e., with the highest approval ratio, as the current fixed channel. If two or three candidate channels have the same approval ratio, then the channel which makes node i suffer the least interference will be chosen.

Once the group leader finishes selecting the fixed channel for each member, it broadcasts the results to all member nodes. Upon receiving the information from its group leader, each member node updates its fixed channel accordingly.

5.4 Routing Protocol for Load-Aware CAEPO-G

We employ Bandwidth-Aware AODV that was proposed in Chapter 4 as the routing protocol to facilitate the implementation of Load-Aware CAEPO-G scheme. The available bandwidth at nodes and the end-to-end delay are used as the routing metrics.

5.5 Performance Evaluation

In our simulations, the topology follows a 100-node square-grid network. A total of

10 traffic profiles are generated, each of which contains 20 pairs of randomly chosen (on the uniform distribution) source and destination nodes. For each profile, the data rate between each source-destination pair is randomly selected between 0 and 3 Mbps. The ratio between interference range and communication range is set to be 2. The simulation time is 300 seconds. We compare the performance (goodput and packet delivery ratio) of Load-Aware CAEPO-G with Load-Aware CAEPO, the original CAEPO, the load-aware centralized channel assignment [8] and Q-JOCAC [30].

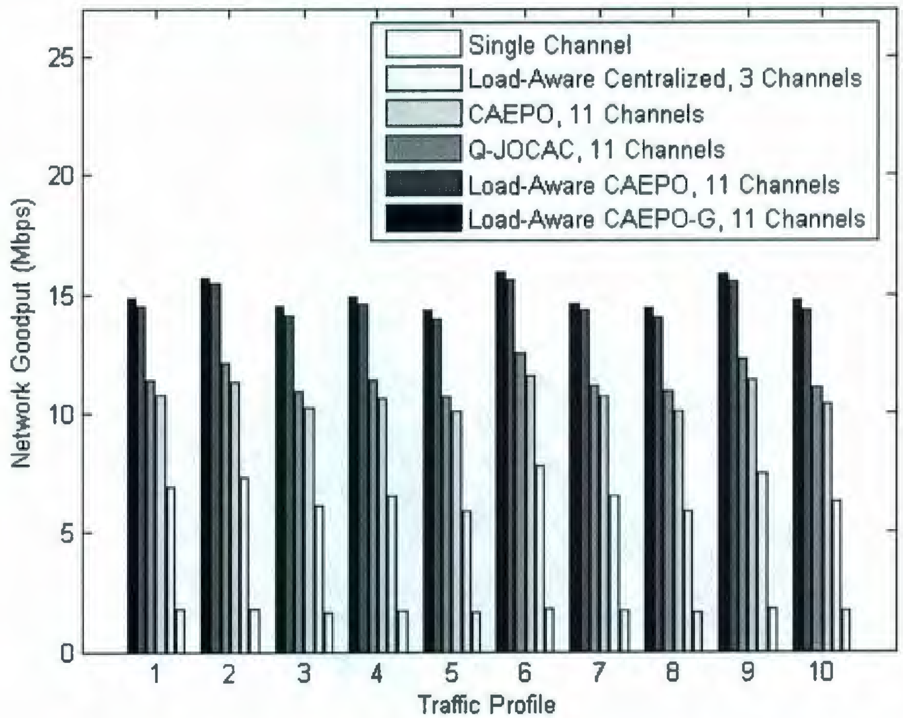

Figure 5.1: Network Goodput vs. Traffic Profile

In Figure 5.1, the aggregated network goodput of various schemes are compared. Compared to that from the single channel network and the load-aware centralized channel assignment, the load-aware CAEPO-G and the load-aware CAEPO achieve much higher aggregated network goodput. This is due to the better exploitation of partially overlapping channels; hence, more available bandwidth can be utilized, which leads to the significant improvement of network performance. In addition, by taking into account traffic load condition in the estimation of the interference metric, the load-aware CAEPO-G and the load-aware CAEPO can achieve better goodput than the original CAEPO scheme and Q-JOCAC using the same number of channels. Furthermore, the load-aware CAEPO-G scheme employs a node grouping algorithm prior to channel assignment, which requires each node to generate three candidate channels for the selection of the fixed channel. Therefore, compared to the load-aware CAEPO, the load-aware CAEPO-G scheme derives a fairer channel assignment and further enhances aggregated network goodput by 2%.

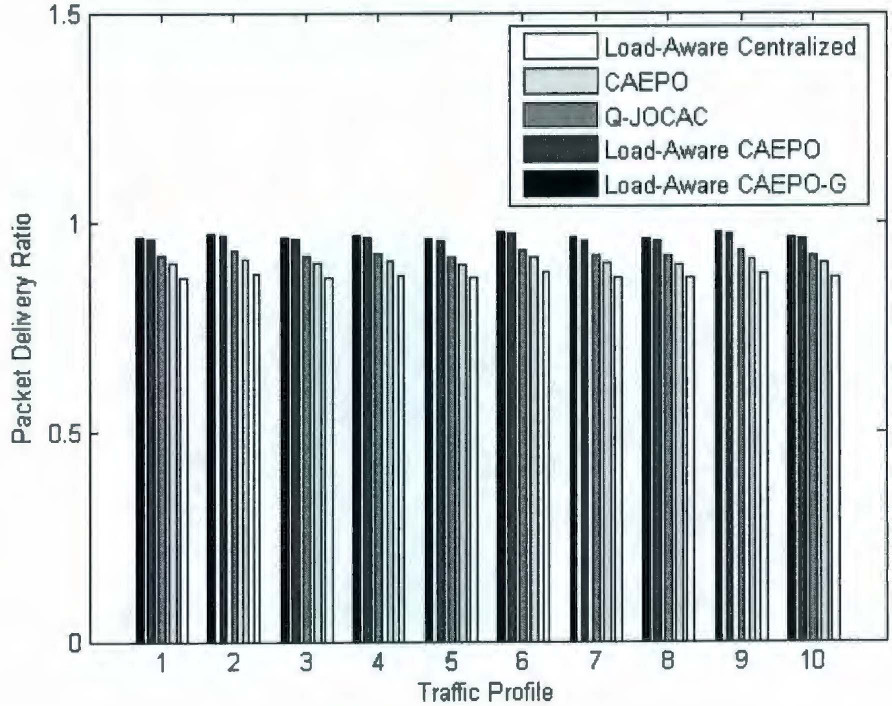

Figure 5.2: Packet Delivery Ratio vs. Traffic Profile

In Figure 5.2, the packet delivery ratio of various schemes is compared. From the figure, it is clear that the load-aware CAEPO-G scheme achieves a much higher packet delivery ratio than the load-aware centralized channel assignment using only three non-overlapped channels. With more precise channel estimation via load condition prediction and with the bandwidth-aware routing protocol, the load-aware

CAEPO-G scheme leads to a better packet delivery ratio than both the original CAEPO and Q-JOCAC scheme. Finally, when compared to the load-aware CAEPO, the load-aware CAEPO-G scheme not only achieves better network goodput but also improves packet delivery ratio by 4%.

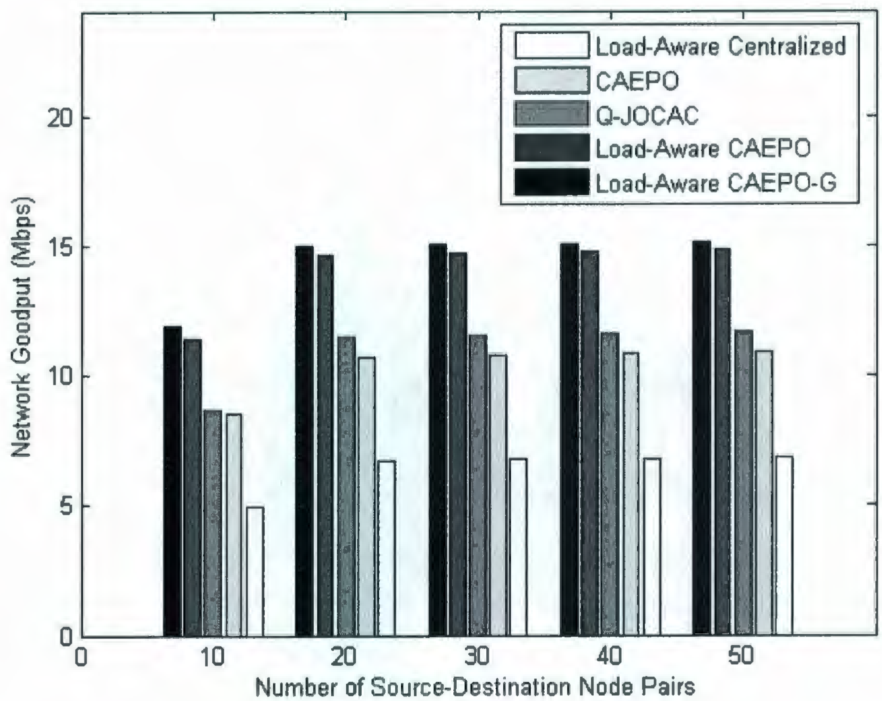

Figure 5.3: Network Goodput vs. Varying Traffic Load

In Figure 5.3, the aggregated network goodput versus the number of source-destination pairs, a.k.a., the number of flows, is studied. The number of flow varies from 10 to 50 source-destination pairs and 10 different traffic profiles are generated for each flow in the network. The average of the aggregated goodput of the 10 traffic profiles is denoted as the network goodput for a given number of source-destination pair case. From the figure, it can be observed that when more traffic load is introduced in the network, the load-aware CAEPO-G and the load-aware CAEPO achieve more improvement in the aggregated network goodput than the other three channel assignment schemes. This is because these two schemes consider the traffic load conditions in the estimation of channel assignment metric and the underlying bandwidth-aware routing protocol also takes into account the traffic load condition when updating routing information. Therefore, as the traffic load condition varies, the load-aware CAEPO-G and the load-aware CAEPO always demonstrate superiority over the other three channel assignment schemes. Compared to the load-aware CAEPO, the load-aware CAEPO-G scheme can achieve minor improvement of aggregated network performance because more nodes can obtain optimal channels so that better fairness can be achieved in channel assignment.

5.6 Conclusions

In this chapter, we propose a new channel assignment scheme, Load-Aware CAEPO with node grouping (Load-Aware CAEPO-G) by introducing the concept of node grouping in Load-Aware CAEPO scheme. At the beginning of the initial phase of channel assignment, a node grouping algorithm is executed and groups are formed in the network. In the update phase, each node generates three channels causing least interference in its interference range as the candidates of the fixed channel. The group leader selects a candidate as the fixed channel for each node according to the opinions of its members. Compared to Load-Aware CAEPO, Load-Aware CAEPO-G derives a fairer channel assignment, which leads to a minor improvement of both the aggregated network goodput and the packet delivery ratio.

Chapter 6

Case Study: Load-Aware CAEPO under Voice Applications over Wireless Mesh Networks

6.1 Introduction

In Chapter 4, we presented a load-aware channel assignment scheme, Load-Aware CAEPO. To facilitate the implementation of the channel assignment scheme, we extended the original AODV to be bandwidth-aware, where two quality-of-service elements, bandwidth and end-to-end delay were used as admission constraints. In this chapter, we study performance of the load-Aware CAEPO scheme under voice applications over wireless mesh networks. To address the two challenges in voice over packet (VOP) applications, end-to-end delay and delay jitter, we employ the end-to-end delay estimation approach and the distributed delay jitter control mechanism in the routing protocol based on the multi-radio, multi-channel extensions to AODV [39]. For end-to-end delay estimation, route request packet (RREQ) is used to estimate the end-to-end delay during the transmission of voice or data packets. End-to-end delay bound, which is a field of the RREQ packets, indicates the priority of packets. Voice packets normally have higher priority than data packets. In the distributed delay jitter control mechanism, end-to-end delay bound is distributed among all intermediate nodes along a path. The end-to-end delay and delay jitter are guaranteed by the control of local delay and delay jitter of each intermediate node.

6.2 Routing Protocol for VOP Applications

Table 6.1: Important Symbols in Routing Protocol for VOP Applications

Symbol	Definition
D_{bound}	End-to-end delay bound
J_{bound}	End-to-end delay jitter bound
n	Any intermediate node along a path
N	Destination node of a path
$d_{bound}[n]$	Local delay bound at any intermediate node n
$j_{bound}[n]$	Local delay jitter bound at any intermediate node n
$Delay$	Actual end-to-end delay
$delay[n]$	Actual local delay at any intermediate node n
$Delay_{RREQ}$	End-to-end delay of RREQ packet
$d_{RREQ}[n]$	Local delay of RREQ packet at node n

Voice over Packet applications face the combined challenges from telephone networks and data networks by allowing voice to be transported over the packet networks. In human conversation, an end-to-end delay of less than 300 *ms* is considered to be acceptable and 100 *ms* is recommended to obtain ensure an excellent interactivity. The goal in our case study is to control the end-to-end delay between 100 *ms* to 150 *ms* so as to achieve a medium audio interactivity and control the delay jitter under 0.5 *ms* to achieve a medium audio stability.

In our case study, we employ the end-to-end delay estimation approach and the distributed delay jitter control mechanism in the routing protocol based on the multi-radio, multi-channel extensions to AODV. The resulting routing protocol with delay and delay jitter control is named as VOP-AODV. The important symbols for the rest of this chapter are summarized in Table 6.1.

6.2.1 End-to-End Delay Estimation

In the original AODV, if a source node has data to send but no route is found toward the desired destination, it will broadcast RREQ packet through the network. The RREQ packet carries the source identifier, the destination identifier, the source sequence number, the destination sequence number and so forth. When an intermediate node receives the RREQ packet, if it has a route to the destination, it will send a route reply packet (RREP) to the source node, otherwise, it will forward the packet. When the destination node receives the RREQ packet, it will acknowledge with a RREP packet to the source node. Finally, the source node will find a route and start data transmission.

To enable end-to-end delay estimation, Benaissa *et al.* proposed a RREQ-AODV algorithm for voice applications over wireless ad hoc networks [41]. In RREQ-AODV, an intermediate node having a route to the destination does not send back an RREP to the source node, instead, it forwards the RREQ to its neighbors till the RREQ reaches the destination node. The end-to-end transmission time of the RREQ packet is used to estimate the end-to-end delay of voice or data packets.

Similar approach is used in our study for end-to-end delay estimation. When a source node has data to transmit, it sends an RREQ packet with an end-to-end delay bound attached, which indicates the priorities of packets. A packet with smaller end-to-end delay bound has higher priority. An intermediate node, even though it may already have a route to the destination, it will not acknowledge the RREQ packet, but instead forwarding the RREQ to its neighbors. Upon reaching the destination node, it will send out the RREP packet along the reverse path and use the round trip time of the RREQ packet to estimate the end-to-end delay of voice or data packets.

6.2.2 Distributed Delay and Delay Jitter Control

Delay jitter is the variance of end-to-end delay among successive packets. It is another important performance metric for real-time applications. Verma *et al.* proposed a delay jitter control mechanism for real-time communication [42], which will be used in our case study. The calculation of local delay jitter bound will be updated accordingly.

During the transmission of a packet, both local delay requirement in Equation (6.1) and the end-to-end delay requirement in Equation (6.2) need to be satisfied:

$$d_{bound}[n] - j_{bound}[n] \leq delay[n] \leq d_{bound}[n], \tag{6.1}$$

$$D_{bound} - J_{bound} \leq Delay \leq D_{bound}\ , \tag{6.2}$$

We set as a default $j_{bound}[n]$ equal to $d_{bound}[n]$ and a default J_{bound} equal to D_{bound} such that Equation (6.1) and Equation (6.2) are simplified to be Equation (6.3) and Equation (6.4).

$$0 \leq delay[n] \leq d_n\,, \tag{6.3}$$

$$0 \le Delay \le D_{bound} . \tag{6.4}$$

When the destination node N receives the first RREQ from a certain source node, it verifies whether the estimated end-to-end delay satisfies the requirement in Equation (6.5) first. If Equation (6.5) is not satisfied, the destination will discard the RREQ packet, which means that the route discovery fails. The source node needs to initiate a fresh route discovery. Otherwise, the destination uses Equation (6.6) to divide the end-to-end delay bound among intermediate nodes and attaches the local bounds in the route replay packet (RREP).

$$Delay_{RREQ} \le D_{bound} . \tag{6.5}$$

$$j_{bound}[n] = d_{bound}[n] = \frac{1}{N}(D_{bound} - Delay_{RREQ}) + d_{RREQ}[n] . \tag{6.6}$$

When an intermediate node receives the RREP packet, it knows its allowable local delay and delay jitter bound. The intermediate node will add a new route entry in its route table indicating the reception of RREP and is ready for forwarding packets from the source node. If a source node does not receive any RREP in $2D_{bound}$ after it issues a RREQ, it means that the route discovery fails and the source node will initiate a fresh route discovery by issuing another RREQ. If an intermediate node does not receive any packets from the source node in $2D_{bound}$ after it receives the RREP packet, it will delete the route entry from its route table.

When an intermediate node receives multiple packets from different source nodes, it will check the local delay jitter bounds of these packets in its route table and serve the packets according to their local delay jitter bounds, that is, the one with the lowest bound will be served first. Since typically voice packets will have much lower end-to-end delay and delay jitter bounds than the data packets, the voice packets usually have lower local delay jitter bounds. Therefore, the voice packets will be serviced prior to the data packets. In order to achieve better fairness among different types of packets, additional scheduling algorithms can be considered and implemented at each intermediate node. However, that is beyond the scope of this thesis and will not be further discussed.

6.3 Performance Evaluation

Similar to the previous performance study, we consider a grid network topology with 100 nodes in the field. We generate 10 traffic profiles with each containing 20 pairs of randomly chosen source-destination pairs. Among the 20 randomly chosen flows, we consider 5 pairs of audio traffic and the rest 15 pairs of data traffic. For each profile, the rate for data traffic between each source-destination pair is selected randomly between 0 and 3 *Mbps* and the rate for audio traffic is generated at 64 *kb/s* following the ON-OFF model. The active and idle periods both follow the exponential distribution with the average duration of 1.004 *s* and 1.587 *s*, respectively [43]. The ratio between the interference and transmission range is set to 2. We set the end-to-end delay bound for voice packets to be 130 *ms* and the end-to-end delay bound for data packets to be 1 *s*. We compare the performance (end-to-end delay and delay jitter) of the load-aware CAEPO with VOP AODV and the load-aware CAEPO with the bandwidth-aware AODV.

From Figure 6.1, we observe that compared to the load-aware CAEPO with the bandwidth-aware AODV, the load-aware CAEPO with VOP-AODV reduces the end-to-end delay. The reason is that VOP-AODV routing protocol incorporated end-to-end delay estimation and distributed delay jitter control mechanism when making routing decisions. In the distributed delay jitter control mechanism, end-to-end delay bound is distributed among all intermediate nodes along the path so that the end-to-end delay and delay jitter could be guaranteed by the control of local delay and delay jitter bound at each intermediate node. The voice packets which are assigned with lower local delay and delay jitter bounds have higher priority than the data packets. Hence, the voice packets are serviced prior to the data packets at each node, which leads to a lower end-to-end delay for voice packets.

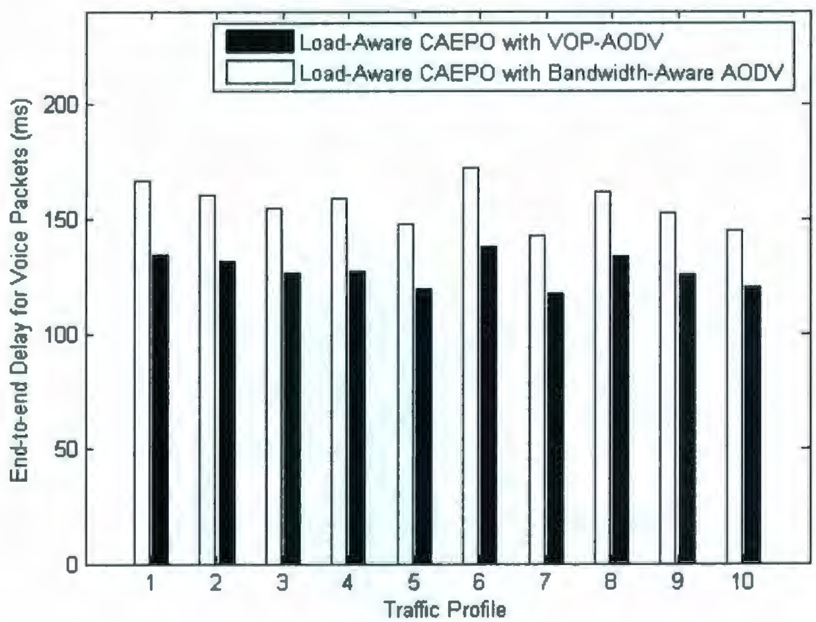

Figure 6.1: End-to-End Delay vs. Traffic Profile

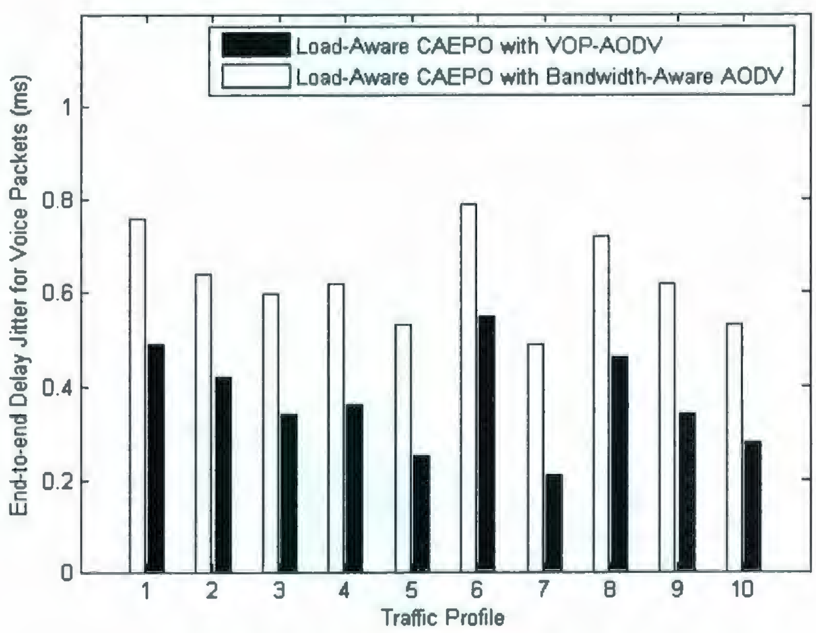

Figure 6.2: Delay Jitter vs. Traffic Profile

In Figure 6.2, the delay jitter performance is studied for different traffic profiles. From the figure, it is clear that the delay jitter of the load-aware CAEPO with VOP-AODV is much lower than that of the load-aware CAEPO with the bandwidth-aware AODV. Among the 10 different traffic profiles, 9 of them achieve medium audio stability with less than 0.5 *ms* delay jitter. Because of the use of distributed delay jitter control mechanism, packets with lower local delay jitter bounds are assigned with a higher priority and will be served first at each intermediate node, the end-to-end delay jitter for voice traffic could be more effectively decreased. Therefore, with the end-to-end delay estimation and the distributed delay jitter control, the load-aware CAEPO with VOP-AODV lowers not only end-to-end delay but also the delay jitter for voice packets over wireless mesh networks.

6.4 Conclusions

In this chapter, we study Load-Aware CAEPO for voice applications over wireless mesh networks. End-to-end delay and delay jitter are two challenges to overcome in voice over packet (VOP) applications. We employ end-to-end delay estimation approach and distributed delay jitter control mechanism based on the multi-radio, multi-channel extensions to AODV. In the end-to-end delay estimation approach, route request packet (RREQ) is used to estimate the end-to-end delay during the transmission of voice or data packets. In the distributed delay jitter control mechanism, delay bound is divided among all intermediate nodes along a path. By taking into account the end-to-end delay and delay jitter in VOP-AODV routing protocol, Load-aware CAEPO effectively decreases both the end-to-end delay and delay jitter for voice packets and achieves a medium audio interactivity.

Chapter 7

Conclusions and Future Work

In this thesis, we introduce the development, architectures, characteristics and applications of wireless mesh networks and present the existing channel assignments and routing protocols for wireless mesh networks.

To exploit partially overlapping channels under 802.11 b/g standards, in this thesis, we propose a channel assignment exploiting partially overlapping channels (CAEPO). In CAEPO, the interference a node suffers within its interference range is the main metric for channel assignment. It is defined to be a combination of the overlapping degree between channels and busy time proportion, i.e. channel utilization ratio of interfering nodes. In addition to that, packet loss ratio is another major consideration in the implementation of channel assignment.

Based on the original AODV, we propose Load-Aware CAEPO scheme based on the original CAEPO. In Load-Aware CAEPO, instead of using the busy time proportion of interfering nodes, we employ the traffic load as another main factor of the interference metric besides the channel overlapping degree. In addition, the concept of self-interference is introduced to estimate the interference metric. Moreover, to facilitate the implementation of the channel assignment scheme, we modify the original AODV to be bandwidth-aware, where the available bandwidth and end-to-end delay are both used as the routing constraints.

For large networks, we introduce a node grouping algorithm in Load-Aware

CAEPO and name the new channel assignment scheme Load-Aware CAEPO-G. Compared to Load-Aware CAEPO, Load-Aware CAEPO-G derives a fairer channel assignment and achieves a minor improvement of the aggregated network performance.

Finally, we study Load-Aware CAEPO scheme for voice applications over wireless mesh networks. To overcome two challenges in voice over packet (VOP) applications, end-to-end delay and delay jitter, we employ the end-to-end delay estimation approach and the distributed delay jitter control mechanism. In the end-to-end delay estimation approach, route request packet (RREQ) is used to expect the end-to-end delay during the transmission of voice or data packets. In the distributed delay jitter control mechanism, delay bound is divided among all intermediate nodes along a path. Along with VOP-AODV, Load-Aware CAEPO scheme effectively decreases the end-to-end delay and delay jitter for voice applications.

In the future, the proposed channel assignment schemes could be improved by taking into account the geographical distance between two interfering links with partially overlapping channels in the estimation of interference metric, which could better exploit the spatial utilization of partially overlapping channels.

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