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EFFICIENT FLOW-BASED CHANNEL ASSIGNMENT SCHEMES FOR CONGESTION AVOIDANCE IN WIRELESS MESH NETWORKS

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By

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The demand of fast and large bandwidth Wireless Mesh Network (WMN) to provide last mile Internet access has motivated high interest in enhancing WMN with multi-radio interfaces, where each radio is dedicated to a non-overlapping channel. However, as a result of contention-based nature of IEEE 802.11-based wireless mesh network, the node capacity is limited by the contention, interference caused by hidden nodes, data transmission over low rate links, and frequent interface switching. When a mesh node cannot win a sufficient number of transmission opportunities to satisfy its traffic load, it becomes saturated. In this case, more data packets are stored in the queue and congestion is occurred. Additionally, with the spanning tree structure of gateway traffic, where most of the traffic between gateway and mesh nodes, nodes near the gateway become congested.

This thesis presents efficient flow-based channel assignment schemes for congestion avoidance in WMN. The most significant contribution of this thesis is to design on-demand channel assignment that helps in avoiding node/link congestion by assigning non-overlapping channels having less interference to every link on the established path and avoiding the channel/link congestion at the critical links in WMN.

As a result, this thesis proposes a centralized on-demand channel reservation scheme (AODV-MRCR) that provides an efficient way of utilizing the multi-radio and multi-channel resources to establish high throughput path for the gateway traffic. To ensure high throughput path, AODV-MRCR uses path optimization as an intelligent mechanism to select a path with least interference and eliminate the intra-flow interference. In addition, the scheme develops multi-link routing discovery process to solve the problem of single routing entry of the

multi-source single destination flow traffic. In the proposed scheme, the channel-to-interface binding is integrated with reactive gateway discovery process and a hybrid cross-layer mechanism is developed for the channel negotiation and synchronization.

Next, AODV-MRCR is extended to address the problems of throughput limitation and reduction which are caused by channel assignment overhead, interference caused by hidden nodes, and link congestion at the critical links in WMN. The result is AODV-CSHDIA, distributed on-demand carrier sense and hidden node channel assignment scheme. Therefore, a channel selection metric is developed based on analytic throughput model with existing hidden nodes. This helps to avoid the collision caused by the on-going transmission of the hidden nodes. So, the network throughput will be improved. In addition, a hybrid interface assignment strategy is developed based on the spanning tree structure of the gateway traffic. This minimizes the interface switching and channel negotiation overhead of the hybrid channel assignment. The proposed channel assignment is integrated with the reactive and proactive discovery process to establish high throughput paths for local and gateway traffic. A receive-forward algorithm is developed to integrate the channel assignment with the proactive routing discovery process to assign channels for the links of the gateway traffic.

Finally, flow-based channel assignment is developed for rate separation in multi-rate, multichannel and multi-radio WMN. AODV-RDCA is introduced to avoid the capacity reduction of high data rate links caused by low rate links when they share the same channel. For this, a novel route metric is designed with the purpose of selecting a path with a minimum number of low rate links and less interfering with existing flows. The metric is developed based on the actual channel throughput. Also, two algorithms are developed to address the link sharing problem during the channel assignment stages; channel-to-interface and link-to-interface stages. To achieve that, system throughput channel selection metric is developed considering the effect of low rate link at both carrier sense and hidden ranges on the channel throughput. This metric is developed based on analytic throughput model taking into account the impact of low rate links and the hidden nodes on the channel throughput.

Several simulation scenarios and analytical model have been presented in order to evaluate and compare the proposed schemes with the existing channel assignment. The results demonstrate that the proposed schemes utilize WMN characteristics to use the spectrum of the resources efficiently and improve the WMN throughput significantly.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SKIM TUGASAN SALURAN YANG BERASASKAN PENGALIRAN YANG CEKAP UNTUK PENGELAKAN KESESAKAN DALAM RANGKAIAN JEJARING TANPA WAYAR

Oleh

HASSEN ABD-ALMOTALEB ABDULLA MOGAIBEL

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Permintaan jalur lebar yang cepat dan besar terhadap rangkaian jejaring tanpa wayar (WMN) bagi menyediakan akses Internet telah mendorong minat dalam meningkatkan WMN dengan antaramuka- antaramuka berbilang radio, di mana setiap radio didedikasikan kepada saluran tidak bertindih. Bagaimanapun , akibat daripada berbezaan IEEE 802.11 berasaskan rangkaian jejaring tanpa wayar, keupayaan nod dihadkan oleh pertelagahan, gangguan disebabkan oleh nod tersembunyi, penghantaran data atas pautan-pautan kadar rendah , dan kekerapan penukaran antara muka. Bila nod jejaring tidak boleh memenangi satu nombor yang mencukupi untuk peluang penghantaran bagi muatan trafiknya, ia menjadi tepu. Dalam kes ini, lebih banyak bingkisan data disimpan dalam giliran dan kesesakan berlaku. Tambahan pula, dengan struktur pepohon rentang trafik get laluan , di mana kebanyakan daripada trafik antara get laluan dan nod jejaring, nod berhampiran get laluan menjadi sesak.

Tesis ini membentangkan skim tugasan saluran yang berasaskan pengaliran yang cekap untuk pengelakan kesesakan dalam WMN. Sumbangan penting tesis ini ialah untuk mereka bentuk tugasan saluran atas permintaan yang membantu dalam mengelakkan nod/pautan kesesakan dengan menentukan saluran tidak bertindih yang mempunyai kurang gangguan kepada setiap pautan di laluan ditetapkan dan mengelakkan saluran/pautan kesesakan di pautan kritikal dalam WMN.

Hasilnya, tesis ini mencadangkan skim tempahan saluran atas permintaan berpusat (AODV-MRCR) yang memberikan satu jalan terbaik menggunakan berbilang radio dan sumber-sumber berbilang saluran untuk mewujudkan laluan daya pemprosesan yang tinggi untuk trafik get laluan. Untuk memas-

tikan laluan daya pemprosesan yang tinggi, AODV-MRCR menggunakan pengoptimuman laluan sebagai satu mekanisme pintar memilih satu tindakan dengan gangguan paling sedikit dan mengurangkan gangguan antara aliran. Sebagai tambahan, skim membangunkan proses penemuan penghalaan yang pelbagai bagi menyelesaikan masalah kemasukan penghalaan trafik aliran destinasi tunggal pelbagai sumber. Dalam skim dicadangan, saluran kepada antara muka ikatan disepadukan dengan proses penemuan get laluan yang reaktif dan mekanisme lapisan hibrid dibangunkan untuk saluran rundingan dan penyalarasan.

Berikutnya, AODV-MRCR diperluaskan bagi menangani masalah had daya pemprosesan dan pengurangan yang mana disebabkan oleh overhed tugasan saluran, gangguan disebabkan oleh nod tersembunyi , dan menghubungkan kesesakan di hubungan kritikal dalam WMN. Keputusannya ialah AODV-CSHDIA, mengedarkan deria pembawa atas permintaan dan skim tugasan saluran nod tersembunyi. Oleh yang demikian, satu pemilihan saluran metrik dibangunkan berdasarkan daya pemprosesan analitik dengan nodus tersembunyi sedia ada. Ini membantu untuk mengelak percanggahan disebabkan oleh penghantaran berterusan nod tersembunyi. Jadi, daya pemprosesan rangkaian akan diperbaiki.

Sebagai tambahan, strategi tugasan antara muka hibrid dibangunkan berdasarkan struktur pepohon rentang trafik get laluan. Ini mengurangkan penukaran antara muka dan rundingan saluran atas tugasan saluran hibrid. Cadangan tugasan saluran disepadukan dengan proses penemuan reaktif dan proaktif mewujudkan lorong-lorong daya pemprosesan yang tinggi untuk trafik setempat dan get laluan. Satu algoritma terima-hantar dibangunkan untuk menyepadukan tugasan saluran dengan proses penemuan penghalaan yang proaktif untuk menentukan terusan untuk pautan trafik get laluan.

Akhirnya, tugasan saluran yang berasaskan aliran dibangunkan untuk pemisahan kadar dalam WMN yang pelbagai kadar, berbilang saluran dan pelbagai radio. AODV-RDCA diperkenalkan untuk mengelak pengurangan kapasiti pautan-pautan kadar data tinggi disebabkan oleh pautan-pautan kadar rendah apabila mereka berkongsi saluran sama. Untuk ini, sebuah hala metrik direka bentuk dengan tujuan memilih satu tindakan dengan satu jumlah minimum pautan-pautan kadar rendah dan kurang ganguan dengan aliran sedia ada. Metrik itu dibangunkan berdasarkan daya pemprosesan saluran yang sebenar. Juga, dua algoritma dibangunkan bagi menangani masalah perkongsian pautan semasa peringkat-peringkat tugasan saluran; saluran untuk antara muka dan menghubungkan untuk antara muka peringkat. Untuk mencapainya, sistem pemprosesan pilihan saluran metric dibangunkan mempertimbangkan kesan kadar rendah menghubungkan di kedua-dua rasa pembawa dan julat tersembunyi pada saluran pemprosesan. Metrik ini dibangunkan berdasarkan daya pemprosesan analitik model dengan mengambil kira kesan pautan-pautan kadar rendah dan nod tersembunyi pada saluran pemprosesan.

Beberapa senario simulasi dan model analisis telah dibentangkan supaya dinilai dan dibandingkan dengan skim yang dicadangkan dan skim tugasan saluran sedia ada. Keputusan menunjukkan bahawa cadangan skim menggunakan ciri-ciri WMN untuk menggunakan spektrum sumber dengan cekap dan meningkatkan daya pemprosesan WMN dengan ketara.

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I certify that a Thesis Examination Committee has met on 12, August 2016 to conduct the final examination of **Hassen Abd-Almotaleb Abdulla Mogaibel** on his thesis entitled "**Efficient Flow-Based Channel Assignment Schemes for Congestion Avoidance in Wireless Mesh Networks** " in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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ACK	Acknowledgement
AODV	Ad hoc On-Demand Distance Vector Routing
AODV-ML	Multi-Link Ad-hoc On-demand Distance Vector routing protocol
AODV-MR	Multi-Radio Ad-hoc On-demand Distance Vector routing protocol
AODV-MRCR	On-demand Multi-Radio Channel Reservation
AODV-CSHDIA	On-demand Carrier Sense and Hidden Node Interference-Aware
AODV-RDCA	On-demand Rate Distribution Channel Assignment
AODV-ST	AODV-Spanning Tree
ARSCA	Autonomous network Reconfiguration System Channel Assignment
BFS-CA	Breadth First Search Channel Assignment
CA	Channel Assignment
CCA	Common Channel Assignment
CECU	Cumulative Estimated Channel Utilization
CIL	Channel Interference Index
CN	Central Node
COCA	COoperative Channel Assignment
CRB-CA	Centralized Rank-Based Channel Assignment
CSHDIA	Carrier Sense and Hidden Node Interference-Aware
CSMA/CA	Carrier Sense Medium Access control/Collision Avoidance
CTA	Centralized Tabu-search Approach
DCACA	Distributed Congestion-Aware Channel Assignment
Dflag	Decision flag
DNT	Direct Neighbors Table
DPSO-CA	Discrete Particle Swarm Optimization Channel Assignment
DR-CA	Distributed Rate Channel Assignment
ECU	Estimated Channel Utilization
ECATM	Equivalent Channel Air Time Metric
ETT	Expected Transmission Time
E2ed	End-to-end Delay
FB	Flow-Based
GL	Gateway Level nodes
GN	Gateway Node
GRREQ	Gateway Routing REQuest message
GRREP	Gateway Routing REPly message
GSO	Gravitational Search Optimization algorithm
GWADV	Gateway advertisement message
HDV	Hybrid Distance Vector
HQSPT	High Quality SPanning Tree
IACSM	Interference-Aware Channel Selection Metric
IEEE	Institute of Electrical and Electronic Engineers
ILP	Integral Linear Programming
ILS	Iterated Local Search

ISL	Interface Switching List
JCAR	Joint Channel Assignment and Routing protocol
JLREQ	Joint Link REQuest message
JLREP	Joint Link REPly message
JQRCA	Joint QoS Routing and Channel Assignment
JRCAR	Joint Routing, Channel Assignment and Rate allocation
JTCR	Joint Topology Control, Power and Routing
LA-CA	Load Aware Channel Assignment
LDR	Link Data Rate table
MAC	Medium Access Control
MCCA	Maxflow-based Centralized Channel Assignment
MCRP	Multi-Channel Routing Protocol
MLC	Multi-Link Connections
MRMC-WMN	Multi-Radio Multi-Channel WMN
MRCG	Multi-Radio Conflict Graph
MMAC	Multi-channel MAC protocol
MTH	Maximum Channel Throughput
NGL	Non-Gateway Level nodes
NIC	Network Interface Card
NS-2	Network Simulator
PNT	Power Neighbor Table
PC	Power Control
PCSACA	Probabilistic Channel Set Adaptation Channel Assignment
QoS	Quality of Services
RA	Rate Allocation
RB-CA	Rate Balance Channel Assignment
RCL	Reserved Channel List
RC-BFS	Reality Check BFS channel assignment
RFmon	Radio Frequency Monitoring mode
RREQ	Routing REQuest message
RREP	Routing REPly message
RTT	Round Trip Time
SCA	Sequence Channel Assignment
SINR	Signal-to-Interference-and-Noise-Ratio
SSCH	Slotted Seeded Channel Hopping
TCP	Transmission Control Protocol
TcL	Tool Command Language
TICA	Topology and Interference-aware Channel Assignment
TTL	Time To Live
UDP	User Datagram Protocol
VCA	Varying Channel Assignment
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network

CHAPTER 1

INTRODUCTION

1.1 Background

Channel assignment is the key enhancement of Wireless Mesh Network (WMN) to overcome the network throughput reduction. Establishing high throughput path in WMN varies based on different channel assignment schemes like centralized and distributed along with different channel interference avoidance indexes.

Joint routing protocol with channel assignment gains a significant network performance since it assigns channel with less interference to the active node involve in path establish process. Accordingly, the main concern of the joint solution is to reduce the packet loss and end-to-end packet delay due to multi-flow interference and to maximize the channel throughput in order to establish high throughput paths.

1.1.1 Wireless Mesh Network Architecture and Characteristics

Wireless Mesh Network (WMN) have been recently used by many wireless technologies, such as last-mile Internet access of application scenarios including public safety networks, campus networks, and broadband Internet access [1]. In [1], the authors classified the WMN architecture into three groups according to the mesh node functionality as infrastructure WMN, client WMN, and hybrid WMN.

The infrastructure mesh architecture is shown in Figure 1.1, where the networks are composed of mesh routers that collect and relay the traffic generated by mesh clients. The mesh routers are usually stationary and equipped with multiple radio interfaces. The mesh routers connect with each other to constitute a multi-hop wireless central network. The backhaul concept refers to the service of getting data from the mobile node and forwarding the data to the gateway node through which it is distributed over the Internet [1]. One or more mesh routers may have gateway functionality and provide connectivity to other networks, such as Internet access.

On the other hand, the mesh clients are typically mobile; and the data are relayed by mesh routers to the intended destination. The client nodes can communicate with each other or with wired resources through the mesh routers. Moreover, the mesh client usually has only one radio interface and so the hardware platform and software for mesh client can be much simpler. However, the client meshing network provides peer-to-peer networks among client devices. In this architecture, as explained in Figure 1.2, each node providing with routing func-

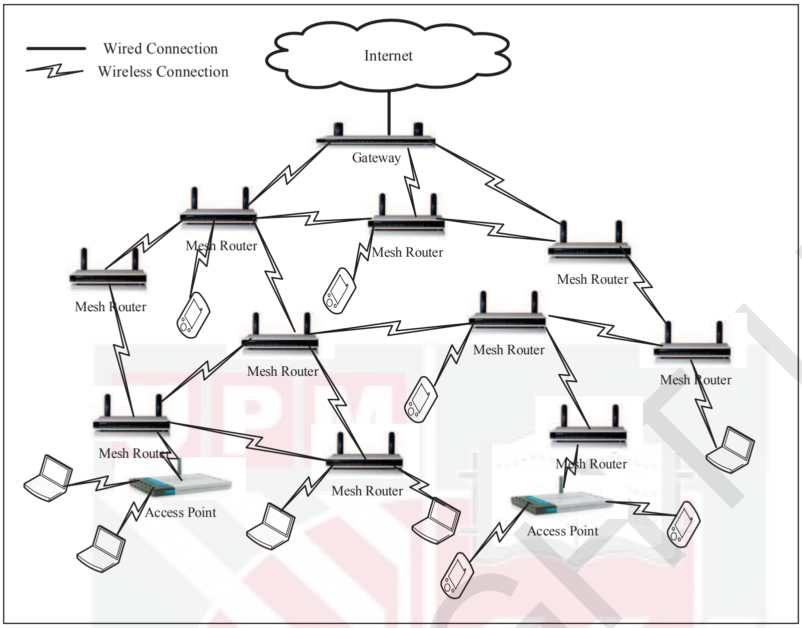

Figure 1.1: Infrastructure Mesh Architecture

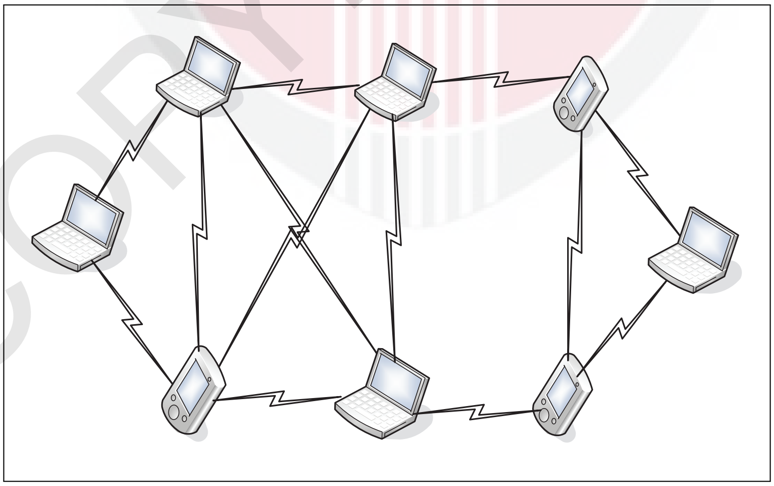

Figure 1.2: Client Mesh Architecture

tionalities, and thus, can route the received packet to the intended destination through multiple mesh client nodes.

Hybrid architecture represents the combination of infrastructure and client meshing. The hybrid mesh takes the advantage of both types of the WMN architecture, as illustrated in Figure 1.3. In the hybrid mesh, the client nodes have the ability to relay the data to the destination in order to extend the coverage area, and the backbone nodes provide more stable and high capacity paths. Hence, mesh clients can access the network through the mesh routers as well as through other mesh clients. The mesh clients improve the network connectivity and coverage inside the WMN [1].

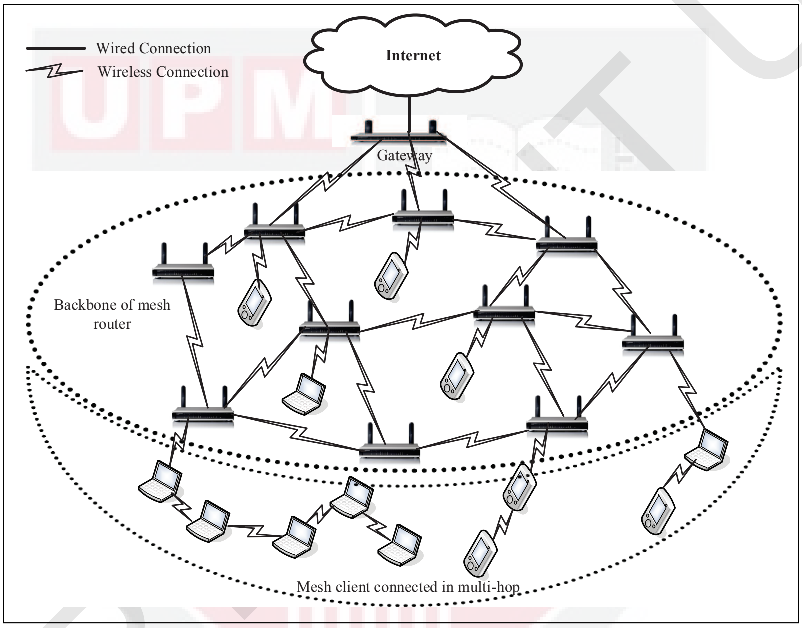

Figure 1.3: Hybrid Mesh Architecture

The infrastructure of WMN is a new broadband Internet access technology, and we will further research into the infrastructure WMN. Henceforth, the WMN refers to the infrastructure WMN without mentioning. The following important characteristics of the infrastructure WMN explain important points that we need to think and exploit in order to efficiently utilize the channel resources and reduce the channel assignment overhead.

- Multi-hop Wireless Network

  WMN network is considered as an ad hoc network because both of them use multi-hop fashion to deliver the data to intended destination. And this characteristic is the leading reason of lately attention as new broadband Internet access technology. Unlike the WLAN, the WMN extends the network coverage range without sacrificing the channel capacity. In order to meet these requirements, there is a need for multi-hop communication along with the mesh connectivity. This achieves more efficient frequency reuse, less interference between the nodes, and higher throughput. Since there are multiple intermediate links, these links can be short and transmissions can be at high data rates, resulting in increased the total network throughput compared to single hop communications.

- Traffic Pattern

  In WMN, the traffic can be classified as local traffic or gateway traffic. The local traffic refers to the traffic between mesh routers, such as peer-to-peer traffic while the gateway traffic is the traffic to/from the gateway. In WMN, most of the traffic is generated by the mesh client towards the gateway or from the gateway to the mesh client. Due to this traffic characteristic, which makes the WMN differs from the ad hoc network, WMN routing protocol should focus on the path from the gateway to each mesh nodes and Medium Access Control (MAC) protocol should also concentrate on next node along the established path, not all neighbor routers.

- Static Topology

  One of the unique characteristics that make the WMN differs from the ad hoc network is the immobile mesh router. This characteristic significantly increases the routing stability and reduces the complexity of the channel assignment compared to the ad hoc network i.e., dynamic topology. In addition, it enables the mesh router to be provided with unlimited power from electric outlets.

- Multi-radio Mesh Router

  Routers in infrastructure WMN are provided with half-duplex multi-radio interfaces turning on non-overlapping channels to effectively utilize the channel resources. These additional interfaces can create multi-link connections between neighbors which can be efficiently utilized to increase the channel diversity and support simultaneous multi-flow transmission for both kinds of the traffic. Moreover, the availability of the multi-link connection between nodes can provide an opportunity to improve the total network throughput by optimally distributed the network traffic among a set of available links, and separate the local traffic from the gateway traffic.

1.1.2 Channel Assignment in Multi-radio Multichannel Wireless Mesh Network

In traditional wireless networks, each wireless node is equipped with a single wireless network interface card which operates on a single wireless channel. Due to interference and packet collision in the single shared medium, the network capacity decreases as the number of wireless nodes increases [2]. The problem is more serious in the WMN due to interference caused by adjacent nodes on the same path as well as from neighboring routes. It has been shown that only 1/7 of the channel capacity can be used in a chain topology [2].

On the other hand, the IEEE 802.11 standards have uniqueness characteristic according to the carrier frequency and modulation technique used. The main important characteristic that helps to reduce the network interference is the number of non-overlapping channels. The frequency spectrum of IEEE 802.11b/g [3] is shown in Figure 1.4.

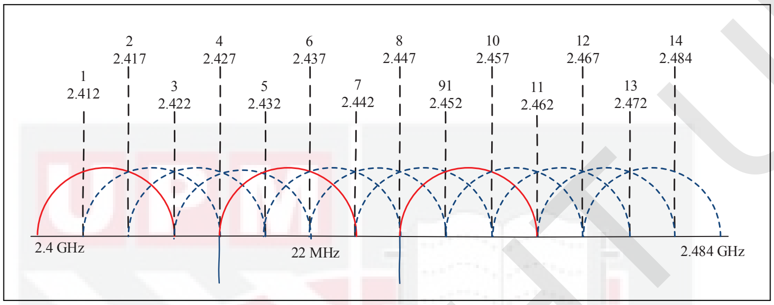

Figure 1.4: Frequency Spectrum of IEEE 802.11b/g in 2.4GHz Band

From the spectrum, we can see that the 2.4GHz band is divided into 14 channels, within which 3 non-overlapping channels (e.g. Channels 1, 6 and 11) are supported. There are even 12 non-overlapping channels supported by IEEE 802.11a in the 5GHz frequency band [4, 5].

Since the transmissions on different non-overlapping channels do not induce interference to each other, parallel transmissions, by nodes within interference range of each other, are made possible. By effectively utilizing multiple non-overlapping channels, the network capacity can be significantly enhanced. The Channel Assignment (CA) is an efficient tool to exploit multiple non-overlapping channels to minimize interference and enhance the capacity of WMN. It tries to find a feasible mapping between wireless channels and radio interfaces at each node with the aim of minimizing the interference and improving the capacity of WMN network. The CA can be classified into three categories according to the time period between consecutive runs of the CA approach [6, 7]. This classification is described as following:

1. Static Channel Assignment

   Most of proposed CAs in the literature fall into static category [4, 8]; where nodes tune their radios to certain channels permanently. Static CAs are easy to deploy but unsuccessful to cope with the changes in the wireless environment.

2. Dynamic Channel Assignment

   Dynamic channel assignments [5, 9, 10, 11, 12, 13, 14], on the other hand, enforce nodes to switch their interface dynamically from one channel to another between successive data transmissions. Therefore, they require tight synchronizations among nodes. However, they can not exploit the advantages of multi-radio networks, since they are only used for single radio working over multiple frequencies [15].

3. Hybrid Channel Assignment

   Hybrid CAs [3, 16, 17, 18] apply a semi-dynamic channel assignment to the fixed radio interface of each node while the other interface is controlled dynamically. Wireless nodes, which use hybrid CAs, do not share common channel with their neighbors, since the dynamic radio switches to the channel of the neighboring nodes to make the connection.

1.2 Research Problem

Wireless Mesh Network (WMN) has some unique characteristics that make it partly different from the existing 802.11-based wireless network such as ad hoc and sensor networks. For example, each mesh node is provided with multiple radio interfaces, as opposed to the ad hoc where each node is provided with a single radio interface. Also, the data flow in WMN is typically between the Internet gateway and the mesh nodes. Consequently, the gateway traffic is saturated on some critical links such as links around the gateway.

In addition to the numerous applications and services over WMN, the demands for faster and higher bandwidth WMN have been growing rapidly. One solution to enhance the node capacity is to provide each mesh node with multiple radio interfaces and dedicate each radio to a unique non-overlapping channel. However, although deploying multi-radio router enhances the WMN capacity, the node capacity is limited by contention, interference, and frequent interface switching [17, 18, 19, 20]. A node has to defer its transmission if there is an ongoing transmission from another mesh node. Besides, the interference caused by multi-flow transmission, such as intra-flow, inter-flow and data transmission over low rate links, causes capacity reduction which in turn increases the number of packet stored in the queue. If the node cannot get a sufficient number of transmission opportunities to satisfy its traffic load, it becomes saturated. In this case, more packets are stored in the queue and congestion is occurred. Therefore, load balancing and efficient utilization of available multi-radio interfaces and multiple non-overlapping channels are necessary to avoid link congestion and minimize the inter-flow interference.

Flow-based channel assignment in WMN has been used to establish a high throughput path for each established flow in the network [3, 21, 22, 23]. In general, the routing is used to discover an efficient path and determine the traffic load at each link, while the channel assignment is used to minimize the interference among the established paths. As a result, designing an efficient flow-based channel assignment in multi-radio multi-channel WMN network is a challenging problem due to the following three reasons:

1. The issues of high frequent interface switching and link congestion at critical links in WMN. Some of the researchers developed hybrid interface assignment to keep the node connected with its communication range nodes. However, their solutions suffer from high interface switching or need a synchronizing mechanism. In addition, one of the main characteristics of WMN which makes it different from the ad hoc network is the spanning tree structure of the gateway traffic. However, none of them has been considered the unique structure of the gateway traffic. Hence, by utilizing the multi-channel and multi-radio, the interface switching can be minimized and the congestion can be avoided at these critical links.

2. The existence of different types of network interference in WMN. Some flow-based channel assignment schemes have been developed to maximize the interference-free transmission. However, their solutions do not avoid the selection of a path with hidden nodes. The interference caused by the hidden nodes significantly degrades the network throughput.

3. The throughput reduction of high data rate links caused by low rate links when they share the same channel. In multi-rate WMN, when the number of low rate links share the same channel is increased, with regardless of whether the links are within carrier sense or hidden node range, the channel throughput is degraded. The flow-based channel assignment schemes developed channel selection metric based on the traffic load or the number of nodes shares the same channel. However, none of them have been addressed the impact of the low rate links on the total system throughput during the channel assignment stages and path discovery process.

1.3 Motivation

WMN, which employs the multi-hop technique to exchange traffic, has become more popular as a cost-effective broadband network. Such network improved people's lifestyle by maintaining their connectivity, entertainment, providing last-mile Internet access and affected their productivity. However, the broadband networks, starting from the cellular network for voice traffic to the WMN for data and online game traffic, suffer from capacity reduction due to multi-flow interference.

In addition, there are two models used to model the interference in multi-hop wireless mesh network, namely, protocol model and physical model. Because of the protocol mode is simple and easy to be applied to analyze the interference in density WMN, it has been widely used in the currently proposed channel assignment schemes [5, 6, 8, 16, 19, 24].

The protocol model assumes that two links interfere each other when they are located within the interference range. This assumption does not hold in reality. The channel throughput in a real network decreases dramatically with interference caused by channel reuse at the hidden node and over low rate links more than the channel reuse at carrier sense range and over high rate links.

Moreover, most of the interference avoidance channel assignment schemes are developed based on historical information or optimization techniques. However, the joint solution, routing and channel assignment, with aims to assign channel only to the active nodes was developed only to support peer-to-peer traffic in the ad hoc network. On the other hand, the WMN has unique characteristics that can be efficiently utilized to minimize the interference and increase the node capacity. For example, because the nodes locations are static, it's easy to determine the number of the conflict links at the carrier sense and hidden node. Moreover, the multi-radio per mesh router can be utilized to isolate the local traffic from gateway traffic and increase the node capacity. Therefore, the simplicity of the protocol model and the lack of on-demand channel assignment scheme in density WMN motivate us to exploit the WMN characteristics in order to develop on-demand channel assignment scheme and accurate channel interference index based on the protocol model.

1.4 Research Objectives

The main objective of this study is to exploit the characteristics of MR-WMN in order to establish high throughput path and avoid the link/channel congestion. The details of objective are as follows.

- To propose a centralized on-demand channel reservation scheme that effectively and efficiently utilizes the characteristics of MR-WMN to establish high throughput paths for the gateway traffic. The scheme aims to reduce the impact of local traffic on the gateway traffic by isolating the local traffic from the gateway traffic, support full duplex mesh routers, and eliminate the intra-flow interference. The scheme also aims to improve the network throughput by minimizing the channel assignment overhead such as node connectivity and channel assignment negation and synchronization.

- To propose on-demand carrier sense and hidden node channel assignment scheme in order to establish high throughput paths for both local and gateway traffic. The scheme aims to ensure the minimum number of competing nodes and minimize the packet collision caused by hidden nodes. The scheme also aims to avoid the link/channel congestion and minimize the interface switching overhead at the most critical link on WMN.

- To propose on-demand rate distribution channel assignment scheme in order to establish high throughput paths for 802.11-based multi-rate multi-radio WMN. The scheme aims to address the multi-rate link sharing and hidden node problems during the path established process and channel assignment stages, channel-to-interface and link-to-interface.

1.5 Research Contributions

In order to avoid channel/link congestion by selecting less interference and traffic load path, flow-based channel assignment schemes have been designed. These schemes efficiently utilize the characteristics of WMN to balance the traffic load and minimize the network interference. In particular, the schemes aim to avoid link congestion by minimizing the interference, avoiding the link congestion and balancing the traffic load among the non-overlapping channels. In addition, a hybrid interface assignment is presented in order to minimize the interface switching overhead at the critical links of the spanning tree structure. To sum up, the main contributions of this work as following:

- Designing flow-based channel assignment scheme to enhance the node capacity, minimize the channel assignment overhead and establish high throughput paths. The result is AODV-MRCR, which is interference-aware routing and channel assignment algorithm that aims to establish high throughput paths and avoid the intra-flow, inter-flow and local traffic interference. AODV-MRCR enables the usage of path optimization as an intelligent mechanism to select a path with least interference. In addition, the proposed scheme solves the problem of single routing entry of the multi-source single destination flow traffic.
- Designing flow-based channel assignment scheme to minimize the channel assignment overhead and capacity reduction caused by the hidden nodes interference for both local traffic and gateway traffic. Distributed on-demand carrier sense and hidden node channel assignment scheme (AODV-CSHDIA) is introduced. Therefore, a channel selection metric is developed to consider the influence of both carrier sense and hidden nodes on the channel throughput. The scheme allocates a channel to each link involved on the established path with the aim to minimize the hidden node interference. This helps to avoid the collision caused by the on-going transmission of hidden nodes which results in improving the network throughput. In addition, AODV-CSHDIA utilizes the structure of spanning tree topology to avoid the frequent interface switching and link congestion at the most critical links in the WMN. We come out with interface assignment and node connectivity strategies.
- Designing flow-based channel assignment for rate separation in multi-rate multichannel and multi-radio WMN. The scheme aims to establish high throughput path by avoiding the capacity reduction of high data rate links caused by low rate links when they share the same channel. Rate distribution channel assignment scheme (AODV-RDCA) is introduced. So, a novel route metric is designed with the purpose of selecting a path with a minimum number of low rate links and less interfering with existing flows. The metric is developed based on the actual channel throughput. In addition, two algorithms are developed to address the link sharing problem during the channel assignment stages. For this, system throughput channel selection metric is proposed to address the effect of low rate link at both carrier sense and hidden ranges on the channel throughput.

1.6 Research Scope

This research focuses on multi-radio multi-channel IEEE 802.11-based WMN as a key enhancement for providing last-mile Internet access. More focus is given on having flow-based channel assignment schemes that establish high throughput paths by interference avoidance, balance the traffic load among channel/paths and avoid the link congested. Thus, enhancing the throughput and reducing the delay via joint channel assignment with routing discovery process are the targets of this research. To simplify, we make some assumptions being as following: first, for constructive deployments, each node is provided with multiple 802.11a/b interfaces; two interfaces in minimum. Second, the link data rate is determined based on the distance between the link's endpoints [25]. Thrid, the schemes are tested under infrastructure and multi-hop WMN. Finally, the schemes in their current state and for the task of simplifying the channel assignment do not support multi-gateway WMN network.

1.7 Research Significance

The intra-flow and inter-flow interferences caused by carrier sense, hidden node and low rate links within the interference range have been proved to be major problems behind the inefficient throughput performance of multi-radio multi-channel WMN.

Several channel assignment schemes had already been developed by different researchers to efficiently utilize the multi-radio and multichannel in order to minimize the interference. The on-demand joint routing and channel assignment schemes have been proved to efficiently utilize the multi-radio and multichannel resources in order to reduce the interference and interface switching.

Despite the gain obtain by the on-demand channel assignment schemes, distributed channels among nodes are still challenging. The existing on-demand channel assignment used the protocol model to model the interference between links within the interference range. Due to the simplicity of this model, the network throughput of the on-demand channel assignment is limited by interference caused by multi-flow interference, interface switching, and channel negotiation. In addition, the current on-demand channel assignment does not exploit the WMN characteristics to proactively assign channels to the active nodes and efficiently utilize the multi-radio to overcome the link congestion and reduce the channel switching overhead and complexity of the on-demand channel assignment.

Thus, the significance of this research stems from the challenges in utilizing the multi-radio and multichannel which are provided by the WMN network to minimize the interference caused by intra-flow, inter-flow and low rate links as well as maximize the node capacity as efficiently as possible.

This work comes out with a new on-demand joint routing and channel assignment schemes that can be integrated to the existing router device with no hardware changes required. The schemes can enhance the backbone capacity by:

- Enhancing the capability of the node to receive and transmit concurrently (Full duplex).
- Efficiently utilizing the limited number of non-overlapping channels.
- Reducing the impact of the local traffic interference on the gateway traffic.
- Reducing the packet collision caused by the hidden node by minimizing the channel reuse at the hidden node range.
- Increasing the capacity of the low rate link as well as to minimize the impact of low rate link on the channel throughput.
- Reducing the channel assignment complexity.

1.8 Thesis Organization

The rest of the thesis is structured as follows. Chapter 2 reviews AODV routing protocol in multi-radio WMN and presents the channel assignment design issues as well as the interference models. It also shows the related works that address the channel assignment schemes based on our classification. Finally, a comparison of different channel assignment schemes and some channel assignment issues are also presented.

Chapter 3 identifies the definitions and conversions used throughout the thesis. It presents the framework of the thesis and explores the stages in detail. Experimental setup, as well as the performance metrics and their evaluation methods, are presented in this chapter.

Chapter 4 explores the design and evaluation of the AODV-MRCR scheme. It discusses the scheme architecture and algorithms. This is followed by the design analysis to study the impact of the local traffic and interface switching to maximize the throughput for the gateway traffic. Finally, this chapter finishes with the evaluation of the proposed scheme in term of aggregated goodput, packet delivery ratio and end-to-end delay.

Chapter 5 extends chapter 4 and presents AODV-CSHDIA architecture for multi-radio multichannel WMN. It starts with addressing the impact of channel reuse at the hidden node links on the channel throughput. Then, it describes the AODV-CSHDIA scheme architecture including the problem formulation, channel interference index, node connectivity and hybrid interface assignment strategy. Finally, it provides an extensive performance evaluation of AODV-CSHDIA comparing it with existing approaches and show its viability.

Chapter 6 presents a novel channel assignment scheme, namely on-demand rate distribution channel assignment (AODV-RDCA) considering the effect of the channel reuse over low rate link at the carrier sense and hidden node ranges on the system throughput during the channel assignment stages, and path established process. First, it describes the details of link-to-interface rebinding algorithms, followed by introducing the system interference index which developed based on throughput analytical model that taking into account the number of low and high rate links at the carrier sense and hidden node ranges. This followed by multi-rate path selection metric to avoid choosing a path suffers from interference caused by low link rate, hidden nodes and link congestion. Multi-rate channel throughput analytical model with existing hidden nodes is introduced. Finally, the AODV-RDCA scheme is evaluated through extensive simulations and demonstrate that the scheme improves network throughput by efficient utilization of the available spectrum. Chapter 7 concludes this thesis with some suggestions for future works.

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