INTERFERENCE AWARE CLUSTER-BASED JOINT CHANNEL ASSIGNMENT SCHEME IN MULTI-CHANNEL MULTI-RADIO WIRELESS MESH NETWORKS

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This thesis is dedicated to my beloved parents and family for their enduring love, motivation and support.

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ABSTRACT

Wireless Mesh Networks (WMNs) are emerging as a promising solution for robust and ubiquitous broadband Internet access in both urban and rural areas. WMNs extend the coverage and capacity of traditional Wi-Fi islands through multi-hop, multi-channel and multi-radio wireless connectivity. The foremost challenge, encountered in deploying a WMN, is the interference present between the co-located links, which limits the throughput of the network. Thus, the objective of this research is to improve the throughput, fairness and channel utilization of WMNs by mitigating the interference using optimized spatial re-usability of joint channels available in the 2.4 GHz Industrial, Scientific, and Medical (ISM) band. Interference is quantified depending on the relative location of the interfering links. Further, the Interference aware Non-Overlapping Channel assignment (I-NOC) model is developed to mitigate the interference by utilizing optimized spectral re-usability of Non-Overlapping Channels (NOCs). NOCs are limited in number. Therefore, I-NOC model is extended by using joint channels available in the free spectrum, and termed as Interference aware Joint Channel Assignment (I-JCA) model. Normally, joint channel assignment is considered harmful due to adjacent channel interference. However, by systematic optimization, the I-JCA model has utilized the spectral re-usability of joint channels. I-JCA model cannot be solved at the time of network initialization because it requires prior knowledge of the geometric locations of the nodes. Thus, Interference aware Cluster-based Joint Channel Assignment Scheme (I-CJCAS) is developed. I-CJCAS partitions the network topology into tangential non-overlapping clusters, with each cluster consisting of intra- and inter-cluster links. I-CJCAS mitigates the interference effect of a cluster's intra-cluster links by assigning a distinct common channel within its interference domain. On the other hand, the inter-cluster links are assigned to a channel based on the transmitter of the inter-cluster link. I-CJCAS is benchmarked with Hyacinth, Breadth-First Search Channel Assignment (BFS-CA) and Cluster-Based Channel Assignment Scheme (CCAS) in terms of throughput, fairness, channel utilization, and impact of traffic load in single-hop and multi-hop flows. Results show that I-CJCAS has outperformed the benchmark schemes at least by a factor of 15 percent. As a part of future work, I-CJCAS can be extended to incorporate dynamic traffic load, topology control, and external interference from co-located wireless network deployments.

ABSTRAK

Rangkaian Jejaring Wayarles (WMNs) muncul sebagai suatu penyelesaian yang dapat membantu mencapai jalur lebar Internet yang lasak dan merata di kedua-dua kawasan bandar dan luar bandar. WMNs meningkatkan liputan dan kapasiti kepulauan Wi-Fi tradisional melalui hop berbilang, saluran berbilang dan perhubungan wayarles berbilang radio. Cabaran utama yang dihadapi dalam membuat WMN adalah wujudnya interferens antara penghubung selokasi yang menghadkan truput rangkaian. Oleh itu, objektif penyelidikan ini adalah untuk memperbaiki truput, kesesuaian dan penggunaan saluran WMNs dengan mengurangkan interferens menggunakan penggunaan semula gabungan ruangan teroptimum yang wujud dalam 2.4 GHz jalur Industri, Saintifik dan Perubatan (ISM). Interferens dinilai bergantung kepada lokasi relatif terhadap penghubung-penghubung yang terganggu. Seterusnya, model *Interference aware Non-Overlapping Channel Assignment* (I-NOC) dibangunkan untuk mengurangkan interferens dengan mengaplikasikan penggunaan semula spektral yang dioptimumkan pada *Non-Overlapping Channels* (NOCs). NOCs mempunyai bilangan yang terhad. Oleh itu, model I-NOC dikembangkan menggunakan gabungan saluran-saluran yang terdapat dalam spektrum bebas yang dinamakan sebagai model *Interference aware Joint Channel Assignment* (I-JCA). Kebiasaannya, peruntukan saluran bergabung dianggap suatu keburukan disebabkan interferens saluran bersebelahan. Walau bagaimanapun, melalui kaedah pengoptimuman yang sistematik, model I-JCA telah dapat menafaatkan penggunaan semula spektral saluran-saluran gabungan. Model I-JCA tidak boleh diselesaikan pada peringkat awal jaringan kerana ia memerlukan pengetahuan awal mengenai lokasi geometrik nod-nod. Oleh itu, *Interference aware Cluster-based Joint Channel Assignment Scheme* (I-CJCAS) telah dibangunkan. I-CJCAS membahagikan topologi rangkaian kepada kluster tangen tidak bertindih dengan setiap kluster yang mengandungi hubungan-hubungan kluster intra dan inter. I-CJCAS mengurangkan kesan interferens sesuatu hubungan kluster intra dengan menetapkan saluran biasa yang berlainan di dalam kawasan interferensnya. Sebaliknya, hubungan-hubungan kluster inter diberikan kepada satu saluran mengikut alat pemancar hubungan kluster inter. I-CJCAS ditanda aras dengan Hyacinth, *Breadth-First Search Channel Assignment* (BFS-CA) dan *Cluster-Based Channel Assignment Scheme* (CCAS) dari segi truput, kesesuaian, penggunaan saluran, dan impak beban trafik dalam aliran-aliran hop tunggal dan hop berbilang. Keputusan menunjukkan bahawa I-CJCAS berjaya mengatasi skim-skim tanda aras ini sekurang-kurangnya dengan faktor sebanyak 15 peratus. Sebagai satu daripada kajian akan datang, I-CJCAS dapat diperkembangkan untuk merangkumi beban trafik dinamik, kawalan topologi, dan interferens luaran daripada penggunaan rangkaian wayarles selokasi.

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LIST OF ABBREVIATIONS

ACK	–	Acknowledgment
AIS	–	Asymmetric Incomplete State
AOMDV	–	Ad-hoc On demand Multi-path Distance Vector
BFS-CA	–	Breadth First Search Channel Assignment
BSS	–	Basic Service Set
CA	–	Channel Assignment
CAEPO	–	Channel Assignment Exploiting Partially Overlapping Channels
CAEPO-G	–	Load-Aware Channel Assignment Exploiting Partially Overlapping Channels
CAS	–	Channel Assignment Server
CBR	–	Constant Bit Rate
CCAS	–	Cluster based Channel Assignment Scheme
CG	–	Conflict Graph
CG-Model	–	Conflict Graph Model
CLICA	–	Connected Low Interference Channel Assignment
COASTS	–	Coalition Operating Area Surveillance and Targeting System
CO-Matrix	–	Channel Overlapping Matrix
CoMTaC	–	Cluster-based Multipath Topology control and Channel assignment
CSMA/CA	–	Carrier Sense Multiple Access with Collision Avoidance
CTA	–	Centralized Tabu-based Algorithm
CTS	–	Clear To Send
DCF	–	Distributed Coordination Function
DIFS	–	DCF Inter-Frame Space
ESS	–	Extended Service Set
ETT	–	Expected Transmission Time
FH	–	Far Hidden
FIFO	–	First In First Out

IBSS	–	Independent Basic Service Set
I-CJCAS	–	Interference aware Cluster-Based Joint Channel Assignment Scheme
IDIS	–	Interfering Destinations Incomplete State
IEEE	–	Institute of Electrical and Electronics Engineers
I-Factor	–	Interference Factor
I-JCA	–	Interference aware Joint Channel Assignment
I-Matrix	–	Interference Matrix
I-NOC	–	Interference aware Non-Overlapping Channel assignment
INSTC	–	Minimum Interference Survivable Topology Control
ISM	–	Industrial, Scientific and Medical
LP	–	Linear Programming
MAC	–	Medium Access Control
MANETs	–	Mobile Ad hoc Networks
Mbps	–	Megabits per second
MC	–	Multiple Channels
MCG	–	Multi Conflict Graph
MC-MR	–	Multi-channel Multi-radio
MICA	–	Minimum Interference for Channel Allocation
MILP	–	Mixed Integer Linear Programming
MIMO	–	Multiple Input, Multiple Output
MR	–	Multiple Radios
NAV	–	Network Allocation Vector
NOCs	–	Non-Overlapping Channels
NS	–	Network Simulator
OFDM	–	Orthogonal Frequency Division Multiplexing
OLPC	–	One Laptop per Child
PCF	–	Point Coordination Function
PCU-CA	–	Probabilistic Channel Usage based Channel Assignment
POCs	–	Partially Overlapping Channels
QoS	–	Quality of Service
RSSI	–	Received Signal Strength Intensity
RTS	–	Request To Send
SC	–	Sender Connected
SCAI	–	Senders Connected Asymmetric Interference

SCSI	–	Senders Connected Symmetric Interference
SC-SR	–	Single-Channel Single-Radio
SDP	–	Semi Definite Program
SINR	–	Signal to Interference and Noise Ratio
SIS	–	Symmetric Incomplete State
UDP	–	User Datagram Protocol
VANETs	–	Vehicular Ad-hoc Networks
VoIP	–	Voice over IP
Wi-Fi	–	Wireless Fidelity
WiMAX	–	Worldwide Interoperability for Microwave Access
WLAN	–	Wireless Local Area Network
WMNs	–	Wireless Mesh Networks
WSNs	–	Wireless Sensor Networks

LIST OF SYMBOLS

G	–	Directed network topology graph
N	–	Set of nodes
L	–	Set of edges or links
T	–	Time interval
$dist(i,j)$	–	Euclidean distance between node i and j
t_x	–	Transmission power of a node i
$l_{(i,j)}$	–	Link or edge between node i and j
R_t	–	Transmission range of a node
R_{cs}	–	Carrier sensing range of a node
K	–	Set of available channels
k	–	Channel number used by the link $l_{(i,j)}$
$\|k-k'\|$	–	Extent of channel overlap between the frequency channels k and k'
Γ_n	–	Total number of radio interface installed on a node n
τ_i	–	Set of links incident on a node i
C^k_{max}	–	Maximum capacity of channel k
$C^k_{l_{(i,j)}}$	–	Actual capacity of link $l_{(i,j)}$ while operating on channel k during a given time duration T
$U^k_{l_{(i,j)}}$	–	Total data traffic load that needs to be transmitted by the transmitter of a link $l_{(i,j)}$ when it operates on a channel k during a given time duration T
$\gamma_{l_{(i,j)}}$	–	Portion of the total traffic load actually transmitted by the link $l_{(i,j)}$ during time interval T
$Z^k_{l_{(i,j)}}$	–	Actual data traffic load transmitted by the link $l_{(i,j)}$ when it operates on a channel k during time interval T
$\Pi^k_{SC(l_{(i,j)})}$	–	Set of Sender Connected Interfering Links of a target link $l_{(i,j)}$ while operating on channel k
$\Pi^k_{AIS(l_{(i,j)})}$	–	Set of Asymmetric Incomplete State Interfering Links of a target link $l_{(i,j)}$ while operating on channel k

$\Pi^{k}_{SIS(l_{(i,j)})}$	–	Set of Symmetric Incomplete State Interfering Links of a target link $l_{(i,j)}$ while operating on channel k
$\Pi^{k}_{FH(l_{(i,j)})}$	–	Set of Far Hidden Interfering Links of a target link $l_{(i,j)}$ while operating on channel k
$\Pi^{(k,\lvert k-k'\rvert)}_{AIS(l_{(i,j)})}$	–	Asymmetric Incomplete State interfering links of a target link $l_{(i,j)}$ operating on channel k in interference range of $\lvert k-k'\rvert$
$\Pi^{(k,\lvert k-k'\rvert)}_{SIS(l_{(i,j)})}$	–	Symmetric Incomplete State interfering links of a target link $l_{(i,j)}$ operating on channel k in interference range of $\lvert k-k'\rvert$
$\Pi^{(k,\lvert k-k'\rvert)}_{FH(l_{(i,j)})}$	–	Far Hidden interfering links of a target link $l_{(i,j)}$ operating on channel k in interference range of $\lvert k-k'\rvert$

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CHAPTER 1

INTRODUCTION

1.1 Overview

Over the recent years, wireless nodes are popping up everywhere and are becoming more popular. Wireless mesh network is a cost effective, multi hop solution to provide the Internet connectivity to this large number of wireless nodes. Practical and extensive deployments of wireless mesh network are the target of several research studies. The motivation behind this research is to address this goal by developing a practical wireless solution to improve the performance of the network. The main focus of this research is to address the problems of interference and channel assignment which have a critical effect on the performance of the network. This research helps in the enhancement of network capacity by developing an interference aware cluster-based joint channel assignment scheme for wireless mesh networks.

1.2 Problem Background

Wireless Mesh Networks (WMNs) provide a promising solution for robust and ubiquitous broadband Internet access in urban and wilderness areas. WMNs extend the coverage and the capacity of traditional Wi-Fi islands through multi-hop wireless connectivity (Vural *et al.*, 2013). WMNs are co-operative multi-hop, self-organizing, and fault tolerant communication networks. The use of co-operative multi hopping technique helps the wireless nodes to route between node to node, node to multi-hop destination node, and node to the base station i.e., Internet back-haul (Akyildiz and Wang, 2008). Moreover, multi-casting feature of WMNs support Voice over IP (VoIP) and Video over IP services in community networks with a high level of quality of service (Ding *et al.*, 2012b).

1.2.1 Components of Wireless Mesh Networks

The components of WMNs consist of Mesh Gateway Routers, Mesh Routers and Mesh Clients (Carrano *et al.*, 2011). The components of wireless mesh networks are shown in Figure 1.1. Mesh gateway routers are outfitted with bridging and routing functionality. Thus, provide the Internet connectivity to the network and carry traffic in and out of the mesh network. Mesh routers are interconnected through multi-hop wireless links, and form the backbone of the network. Mesh routers are almost static in nature with no power constraints. Mesh routers are equipped with multiple radios. Each radio has its own MAC and Physical layer, which increases the throughput potentially by a factor equal to the number of radios on each node (Benyamina *et al.*, 2012). Non-Overlapping Channels (NOCs) present in a single radio are further used to increase the throughput of the network. For example, IEEE 802.11b standard splits the frequency into 11 channels, out of which 3 are NOCs as shown by the solid lines in Figure 1.2. Thus, multiple radios (MR) with multiple channels (MC) are available between the source and destination pairs, to increase throughput of the network (Avallone and Akyildiz, 2008; Li *et al.*, 2009).

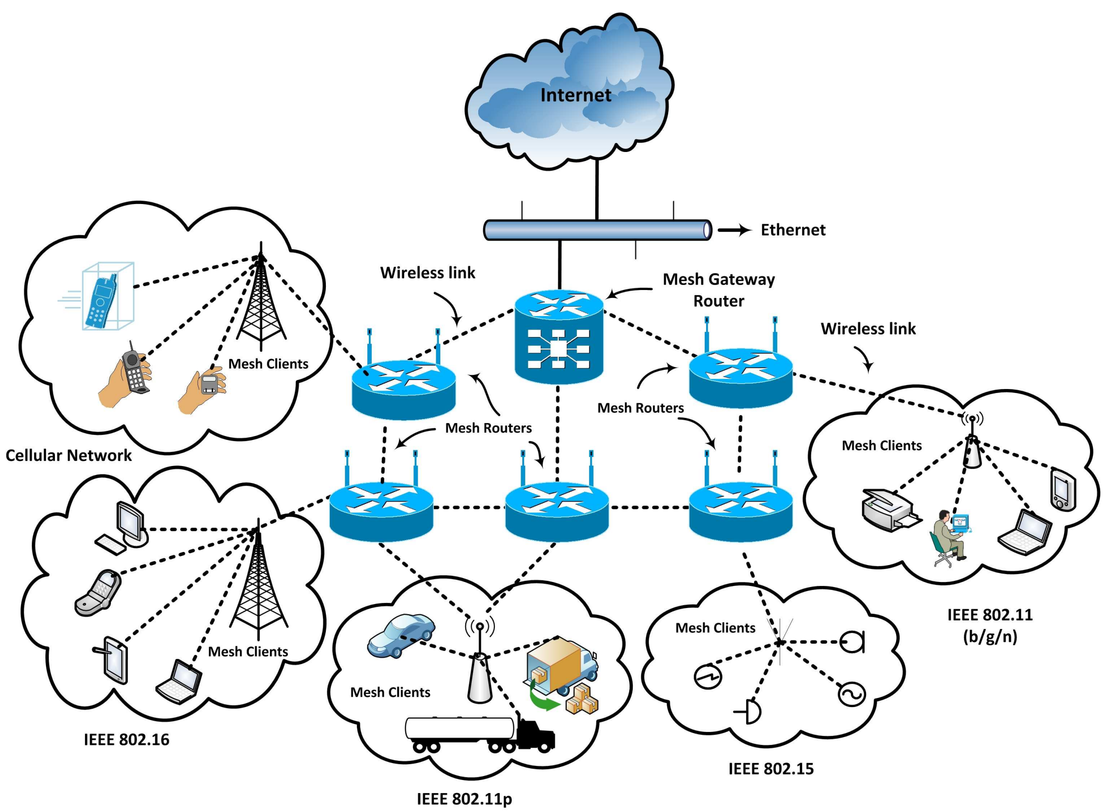

Figure 1.1: Components of wireless mesh network

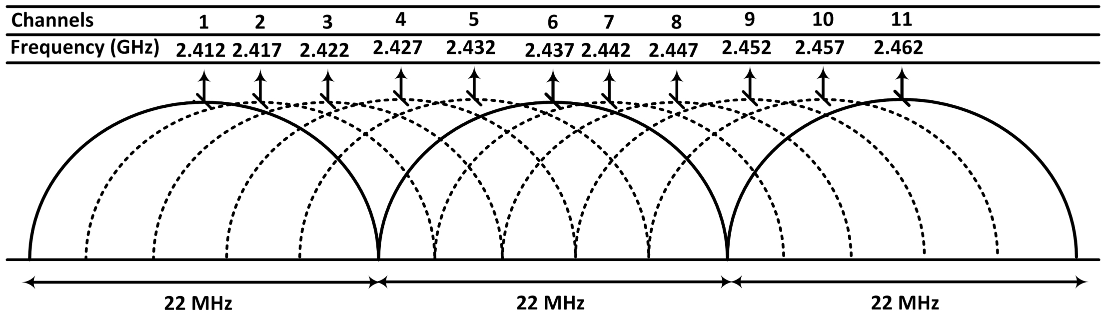

Figure 1.2: Channels available in IEEE 802.11b standard

The multi-channel multi-radio (MC-MR) architecture of wireless mesh network is defined by IEEE 802.11s standard (Wang and Lim, 2008). Figure 1.3 (a) indicates the protocol stack of mesh gateway router with bridging and router functionality which allow them to incorporate with different wired and wireless networks like Ethernet, Mobile Ad hoc Networks (MANETS), Wireless Sensor Networks (WSNs), Wireless-Fidelity (Wi-Fi), Vehicular Ad hoc Networks (VANETs), and Worldwide Interoperability for Microwave Access (WiMAX) (Hiertz *et al.*, 2010). The protocol stack of MC-MR mesh router is shown in Figure 1.3 (b). Each mesh router is equipped with two radios: Radio-1 and Radio-2. Each radio has its own MAC and Physical layer. The transmission is carried out by three NOCs (C1, C2 and C3) available in free spectrum. Consequently, MC-MR architecture of mesh router increases the overall performance of the network as compared to single-channel single-radio (SC-SR) architecture. Multi radios available in a mesh router also assist in the interoperability of WMNs with other networks like WSNs, VANETs, WiMAX, and cellular network as shown in Figure 1.1. Mesh clients are end user devices in the network i.e., laptops, tablet computers, IP and smart phones (Li *et al.*, 2010). The protocol stack of a single radio mesh client is shown in Figure 1.3 (c).

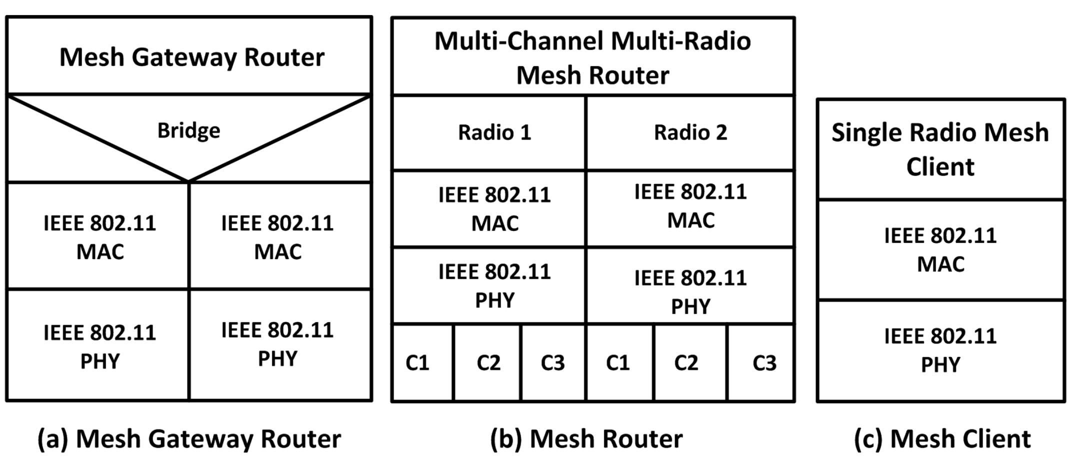

Figure 1.3: Protocol stack of IEEE 802.11s standard

The famous deployments of WMNs include One Laptop Per Child (OLPC) association (OLPC, 2012), National ICT Australia (NICTA) (NICTA, 2012), and Coalition Operating Area Surveillance and Targeting System (COASTS) by MESH Dynamics (MeshDynamics, 2012). Moreover, the search giant Google is deploying wireless mesh network in central cities of US with the help of a privately owned company Meraki (Meraki, 2013).

The foremost challenge encountered in deploying wireless mesh network is the interference present between the links which are in close proximity of each other's communication range. Such links are known as co-located interfering links, which limit the throughput performance of the network. As a result, scalability, capacity and QoS parameters are highly degraded in single frequency WMNs (Ashraf *et al.*, 2012). This is because wireless network used a shared medium for communication while communication in wired network took place through a dedicated medium. The shared nature of communication medium made the lower abstraction layers of wireless network extremely multifarious as compared to a wired network (Bouckaert *et al.*, 2010). The MC-MR communication architecture of WMNs has further increased the complexity of MAC and Physical layers. Moreover, the bandwidth and number of channels are limited in a wireless network; hence interference is unavoidable, resulting in the degradation of the throughput of the network (Ding *et al.*, 2012a, 2013).

1.2.2 Signal Propagation in Wireless Networks

In a wireless network, the signal propagation is Omni-directional. The rate of successful transmission of signals in wireless communication is highly dependent on the distance between the source node and the destination node of a link. The Received Signal Strength Intensity (*RSSI*) is directly proportional to $1/d^2$ whereas d is the distance between the source node and the destination node of a link in a given network topology (Schiller, 2003). On the basis of *RSSI*, the propagation behavior of the signal in wireless communication is classified as follows:

i. **Transmission Range**

The transmission range of a wireless node A is the distance from the node such that another wireless node B, within this distance can successfully receive and decode the radio signal from node A. In this case, a wireless link exists between the nodes A and B if the two nodes operate on a common channel. In Figure 1.4, the transmission range of wireless node *A* is encircled by the innermost solid circle. Any node located within this circle is considered within the transmission range of wireless node *A*. Hence, the packet sent by the source node *A* can be easily received at the destination node *B* with an error rate low enough to be able to communicate with each other (Lee *et al.*, 2009). Normally, the transmission range of a node is indicated by R_t.

ii. **Carrier Sensing Range**

The carrier sensing range of a wireless node *A* is the distance from the node such that another wireless node *C* within this distance can sense the radio activity (not necessarily correctly received the data) of node *A*. Thus, node *C* backs-off itself randomly, when the sender node *A* has a transmission of packets of its own (Garetto *et al.*, 2008). The carrier sensing range of a wireless node *A* is shown by the middle dash circle in Figure 1.4. The carrier sensing range of a node is denoted by R_{cs}.

iii. **Interference Range**

The nodes *A* and *D* are outside the carrier sensing range of one another can transmit packets simultaneously. Suppose node *A* is transmitting packets to node *B*. The interference range is defined by all possible locations of node *D* that discard some of packets transmitted by node *A* towards the node *B*. This is because the signal strength of a node *A* at node *B*, does not go beyond node *D's* signal strength at node *B* by some capture able threshold level. Therefore, node *A's* packets are lost at the node *B* (Alawieh *et al.*, 2009). The interference range R_i is shown by the dash dot circle in Figure 1.4.

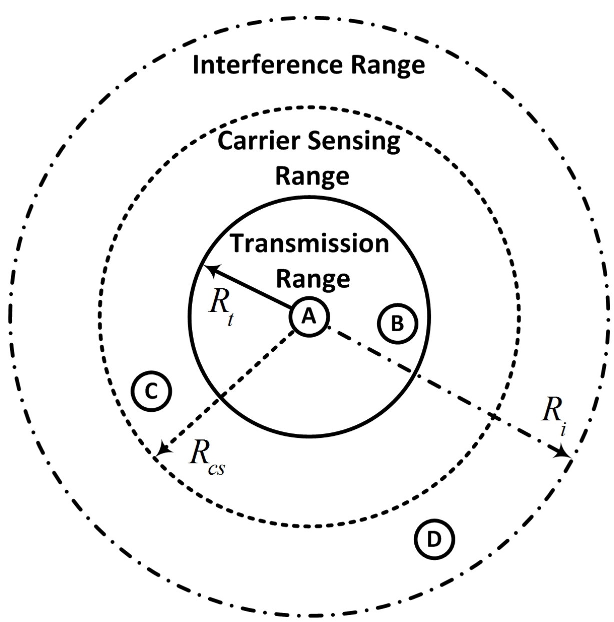

Figure 1.4: Propagation behavior of a wireless signal

Overall throughput of WMNs depends on the bandwidth or capacity of the links between the source and the destination pair, channel assignment techniques, and level of interference present between the channels. The interference is a critical restraining factor and is extraordinarily complicated to handle in WMNs. Therefore, the effect of interference on link throughput should be well thought-out for realistic routing models, channel assignment schemes, topology control, and network diagnosis in wireless mesh network (Naveed and Kanhere, 2009).

Interference affects both the sender and receiver node of a wireless link. On the sender or source side, the data sending rate decreases by Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) based Medium-Access Control (MAC) layer interaction. On the receiver or destination side, interference causes collisions which result in the degradation of overall throughput of the link (Alotaibi *et al.*, 2010). For example, consider a channel with capacity equal to X Mbps. If there are N interfering links present in the network then the capacity of the channel is distributed amongst the interfering links and each link can only achieve the bandwidth of $\approx \frac{X}{N}$ (assuming equal sharing of throughput among links). Moreover, when random access CSMA/CA MAC protocol is employed, the senders of more than one interfering links can start its transmission simultaneously. This will result in the collision of transmitted data, and the transmission opportunity is lost for the active links. Consequently, the achievable throughput of each link is further decreased.

The overall capacity of WMNs can be improved significantly by deploying MC-MR architecture as compared to SC-SR architecture. The use of multiple channels can decrease the effect of interference present between the communication links (Kyasanur and Vaidya, 2005). However, the channel assignment on the basis of interference present between multiple co-located channels becomes critical due to the following constraints:

i. **Limited Radio Interfaces per Node**

Only a limited number of radio interfaces can be installed on a single node. This is because multiple co-located radio interfaces installed on a node give rise to high level of interference in the network. The testbed results of Bahl *et al.* (2004) indicate that the maximum two-four radio interfaces per node are considered as a feasible solution. Therefore, limited number of interfaces acts as a constraint for assigning the channels to the co-located interfering links in wireless mesh network (Ku *et al.*, 2011).

ii. **Limited Frequency Channels**

Only limited numbers of channels are available in free ISM spectrum. This is because of technical facts or government regulations regarding the radio spectrum. For example in US, IEEE 802.11b radio spectrum is divided into 11 channels with 25 MHz frequency spacing (IEEE 802.11b standard, 1999). Only three channels 1, 6, and 11 are NOCs, which are used to overcome the interference present between the links. Thus, it is not possible to operate all interfering links on distinct NOCs. Consequently, the interference cannot be entirely eliminated from the wireless mesh network (Duarte *et al.*, 2012).

iii. **Network Connectivity**

The channel assignment schemes sometimes partitioned the network into disconnected Wi-Fi islands. A link is only possible between two nodes if nodes are physically placed within the transmission range of each other and are operating on a common channel. Otherwise, the logical topology of WMNs may differ from the physical topology. Therefore, the design of the channel assignment scheme is such that it ensures that there exist multiple paths between the nodes in the logical topology of the network. Further, the number of channels assigned to a node should be less than or equal to the number of radio interfaces installed on that node (Awwad *et al.*, 2012).

iv. **Fairness**

The fair distribution of the network capacity is the key feature of the channel assignment schemes in wireless mesh network. Otherwise, the channel assignment schemes cause bottleneck links in the network which degrade the overall performance of the network (Abouaissa *et al.*, 2013).

v. **Interference Model**

There are many interference aware channel assignment schemes, available in the wireless mesh network literature. As surveyed by Skalli *et al.* (2007), most of them are based on the Physical model of interference (Gupta, 2000), Protocol model of interference (Gupta, 2000), and Extended protocol model of interference (Tang *et al.*, 2005). However, Iyer *et al.* (2009) indicate that CSMA/CA MAC protocol of IEEE 802.11, behave contradictorily to these models. Therefore, accurate interference estimation in-accordance with CSMA/CA MAC protocol is pivotal for the performance of channel assignment schemes in a wireless mesh network.

1.2.3 Research Gap

Interference is mitigated by assigning distinct channels to the co-located interfering links in the network. Such channel assignment strategies are known as interference aware channel assignment schemes. As surveyed by Skalli *et al.* (2007), most of the interference aware channel assignment schemes available in the literature, are based on the Physical model of interference (Gupta, 2000), Protocol model of interference (Gupta, 2000), and Extended protocol model of interference (Tang *et al.*, 2005). However, Iyer *et al.* (2009) indicated that these models do not capture the effect of interference between the links precisely. This is because the behavior of CSMA/CA MAC protocol of IEEE 802.11 standard is not analyzed properly as mentioned by Bianchi (2000). Therefore, Garetto *et al.* (2005, 2008) based on the findings of Bianchi (2000), modeled the media access in embedded two-flow topologies of multi-hop wireless networks. Garetto's model of interfering links concluded that the impact of interference on the throughput of a link varies with the relative geometric location (relative physical position) of the sender and receiver of interfering links. Therefore, two links $l_1(i_1,j_1)$ and $l_2(i_2,j_2)$ act as an interfering links if any of the Euclidean distances $dist(i_1, i_2)$, $dist(i_1, j_2)$, $dist(i_2, j_1)$, and $dist(j_1, j_2) \leq R_{CS}$. The model classifies the interfering links into four different classes as shown in Figure 1.5. These classes are explained as follows:

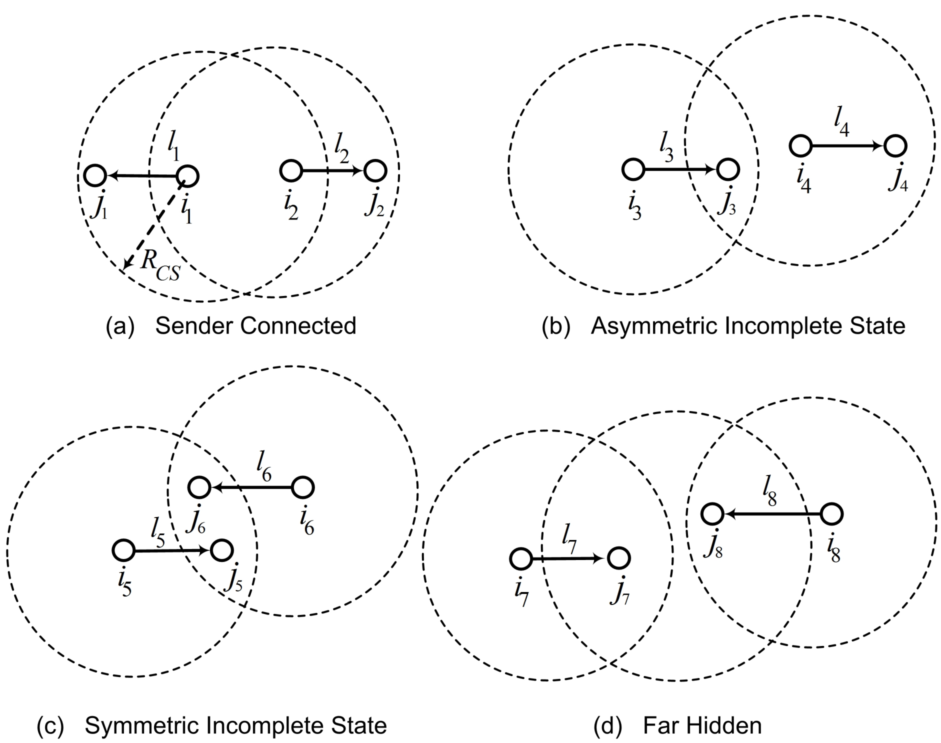

Figure 1.5: Garetto's model of interfering links

i. **Sender Connected (SC) Interfering Links**

Two links $l_1(i_1,j_1)$ and $l_2(i_2,j_2)$ are said to be SC interfering links if the Euclidean distance $dist(i_1, i_2) \leq R_{cs}$ as shown in Figure 1.5 (a). This means that the senders of the two links are within the carrier sensing range of each other, and can sense the transmission activity of each other. Hence, there is no problem of short term unfairness or long term unfairness in SC scenarios.

ii. **Asymmetric Incomplete State (AIS) Interfering Links**

Two links $l_3(i_3,j_3)$ and $l_4(i_4,j_4)$ are said to be AIS interfering links if the Euclidean distance $dist(i_3, i_4) > R_{cs}$ and $dist(j_3, i_4) \leq R_{cs}$ (the receiver of l_3 is within the carrier sensing range of the sender of l_4) and $dist(j_4, i_3) > R_{cs}$ (the receiver of l_4 is outside the carrier sensing range of the sender of l_3) as shown in Figure 1.5 (b). This means that only one of the sender i_3 or i_4 interferes with the other destination and only one of the flows experiences collisions.

iii. **Symmetric Incomplete State (SIS) Interfering Links**

Two links $l_5(i_5, j_5)$ and $l_6(i_6,j_6)$ are said to be SIS interfering links if the Euclidean distance $dist(i_5, i_6) > R_{cs}$ and $dist(j_5, i_6) \leq R_{cs}$ and $dist(j_6, i_5) \leq R_{cs}$ (the receivers of l_5 and l_6 are within the carrier sensing range of the sender of l_6 and l_5, respectively) as shown in Figure 1.5 (c). This means that the senders of the two target links are not connected, and either one or both of the senders can interfere with the other receivers. Therefore, SIS interfering scenarios are long term fair, but short term unfair.

iv. **Far Hidden (FH) Interfering Links**

Two links $l_7(i_7, j_7)$ and $l_8(i_8, j_8)$ are said to be Far Hidden Interfering Links (FH) if the Euclidean distance $dist(i_7, i_8) > R_{cs}$ (the senders of the two links are outside the carrier sensing range of each other), $dist(j_7, i_8) > R_{cs}$, $dist(j_8, i_7) > R_{cs}$, (the receivers of l_7 and l_8 are outside the carrier sensing range of senders of l_8 and l_7, respectively), and $dist(j_7, j_8) \leq R_{cs}$ (the two receivers are within the carrier sensing range of each other) as shown in Figure 1.5 (d).

The results of Garetto's model of interfering link indicate that this classification carefully capture the interference between the co-located links in a given network topology. Further, Shi *et al.* (2008) validate the Garetto's model of interfering links via testbed experiments in wireless mesh network. In another attempt, Naveed and Kanhere (2009) justify the Garetto's model of interfering links empirically and experimentally by developing a cluster based channel assignment scheme (CCAS) for MC-MR WMNs. The results indicate that model capture the interference between the links in-accordance with CSMA/CA MAC protocol. The CCAS, grouped the Garetto's classification into two classes i.e., coordinated and non-coordinated interfering links and mitigates the effect of interference by utilizing NOCs. The results conclude that the scheme gives a better picture of link quality in sparse topology. However, in dense topology, co-located links classified into two classes and operating on common NOCs again cause interference in the network. As a result, overall throughput of the network is degraded. Similarly, Alotaibi *et al*. (2010) classified the interfering links in two classes, based on the geometric position of the sender and receiver of a link. However, it experiences same limitations as mentioned in CCAS scheme.

The aim of this research is to overcome the limitations of existing channel assignment schemes based on the geometric location of the sender and receiver. Therefore, this work is based on the findings of Garetto *et al.* (2005, 2008) by classifying the co-located links exactly into SC, AIS, SIS and FH interfering links. Further, the clustering is used to identify the SC, AIS, SIS and FH interfering links in a given network topology (Naveed and Kanhere, 2009). This will escalate the correctness in capturing the interference present between the links. The effect of interference is mitigated by operating the interfering links on distinct channels. Unfortunately, NOCs are limited in nature. Therefore, the scarcity of NOCs is overcome by assigning joint channels (non-overlapping and partially overlapping channels) to co-located interfering links. However, joint channel assignment needs a systematic optimized approach for utilizing the spectral re-usability of all channels. Otherwise, it degrades the overall capacity of the network as indicated by the testbed results of Mishra *et al.* (2005a). Therefore, this research targets to design and develop an optimized structured approach for utilizing the joint channels available in a free spectrum, in mitigating the interference present between the co-located links of a wireless mesh network. It reduces the level of interference between the links, which in turn increases the spectral re-usability and parallel communication between the links. As a result, overall performance of the network increased.

1.2.4 Problem Statement

The above research gap leads this research to address the problem of utilizing the joint channels available in the free spectrum to mitigate the interference present between the co-located interference links classified on the basis of geometric location of the sender and receiver of the links in order to maximize the throughput of the network.

1.2.5 Hypothesis

The above problem statement leads to the following hypothesis:

The throughput of the mesh network can be increased significantly if the interfering links are classified on the basis of geometric location of the sender and receiver of links. Afterwards, joint channel assignment is used to mitigate the interference between the links while satisfying the capacity and connectivity constraints of the network.

1.2.6 Research Questions

The above research hypothesis leads to the following research questions:

i. How to design and develop an optimized interference aware non-overlapping channel assignment model in a wireless mesh network?

ii. How to design and develop an optimized interference aware joint channel assignment model in a wireless mesh network?

iii. How to design and develop an interference aware cluster-based joint channel assignment scheme in a wireless mesh network?

iv. How to test and validate the proposed models and joint channel assignment scheme with most widely used approaches in terms of throughput, fairness, channel utilization, and impact of traffic load?

1.3 Aim

The aim of this research is to maximize the throughput of the network by minimize the interference present between the links using optimized spectral re-usability of joint channels available in the free spectrum.

1.4 Objectives

The following objectives are in place to design and develop interference aware cluster-based joint channel assignment scheme in wireless mesh network.

i. To design and develop an optimized interference aware non-overlapping channel assignment model in a wireless mesh network.

ii. To design and develop an optimized interference aware joint channel assignment model in a wireless mesh network.

iii. To design and develop an interference aware cluster-based joint channel assignment scheme in a wireless mesh network.

iv. To test and evaluate the performance of proposed models and interference aware cluster-based joint channel assignment scheme with most widely used methods in terms of standard performance indicators such as throughput, fairness, channel utilization, and impact of traffic load.

1.5 Scope

The scope of this research covers the following points:

i. The proposed models and scheme are validated with the assumption that mesh routers are static in nature. Each mesh router is equipped with multiple radio interfaces. The R_t and R_{cs} of the radios are fixed, and R_{cs} is twice that of R_t of the radio interface.

ii. The external interference experienced by the links from co-located wireless network deployments is not under consideration.

iii. The position of cluster heads is known to the channel assignment server running parallel to mesh gateway router. The location of remaining nodes in the mesh network does not matter. Further, the positioning of the mesh gateway router is not under consideration.

iv. The proposed models and scheme are static in nature and are executed when the network is initialized. Once the channel assignment is complete, no further changes are made during the lifetime of the network. The dynamic channel assignment scheme is out of the scope of this research.

1.6 Significance of the Study

Interference is a key factor which degrades the overall capacity of wireless mesh network. The Physical and Protocol model of interference respond contradictory to CSMA/CA MAC protocol. Consequently, in the proposed scheme, interference is quantified on the basis of geometric location of the sender and receiver of a link. The existing channel assignment schemes used NOCs, to overcome the interference present between the links. Unfortunately, NOCs are limited in number, therefore, cannot handle the interference significantly. Therefore, spectral re-usability of joint channels is used to overcome the interference between the co-located links. It has increased the parallel communication between the interfering links. Thus, it increases the overall throughput of the network while satisfying the connectivity and fairness constraints of the network. The proposed scheme can serve as a benchmark in relay node placement, channel assignment, and topology control schemes in the wireless mesh network.

1.7 Thesis Organization

The remaining of the thesis is organized as follows: Chapter 2 provides the extensive literature review of interference modeling, and channels assignment schemes using non-overlapping and joint channels in MC-MR WMNs. Chapter 3 presents the research methodology, including the operational framework for the design and development of interference aware cluster-based joint channel assignment scheme in a wireless mesh network. Chapter 4 formally introduces the concept, formulation and implementation of an optimized interference aware non-overlapping channel assignment model. Chapter 5 explains the design and development of an optimized interference aware joint channel assignment model to maximize the network throughput by mitigation the interference present between the links. Chapter 6 is dedicated to the design and development of an interference aware cluster-based joint channel assignment scheme. The objective of the scheme is to maximize the throughput and fairness of the network while minimizing the interference between the co-located interfering links. Finally, Chapter 7 concludes the thesis and presents the possible future directions.

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