CROSS LAYER ROUTING AND SCHEDULING FOR MULTI-CHANNEL WIMAX MESH NETWORKS

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To my family, especially my beloved parents

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ABSTRACT

Broadband wireless networks are becoming increasingly popular due to their fast and inexpensive deployment and their capabilities of providing flexible and ubiquitous Internet access. Due to the limitation of shared resources in wireless mesh network such as bandwidth, spatial reuse is introduced for concurrent transmissions. The simultaneous transmissions face many challenges regarding interference on the ongoing transmission. To maximize the network performance of mesh networks in terms of spatial reuse, it is essential to consider a cross-layer for resource allocation in different layers such as the routing network layer, the scheduling resource allocation Media Access Control (MAC) layer and physical layer. Therefore, this thesis focuses on improving the spatial reuse for resource allocation mechanism including routing tree construction by taking into consideration the reliable path, channel assignment and scheduling algorithms. Firstly, a Fuzzy based Constructed Routing Tree (FLCRT) is proposed to incorporate fuzzy logic with routing to enable cognitive capability in packet forwarding for uplink or downlink communication. Secondly, the link-aware routing path is proposed to satisfy the connection lifetime and better routing stability for successful requirements of transmission using multi sponsor node technique. Then, a better understanding of reliability analysis is pursued in the context of homogeneous wireless network. Ultimately, heuristic resource allocation including channel assignment and centralized scheduling algorithms are proposed based on the cellular learning automata to enhance the number of concurrent transmissions in the network by efficiently reusing the spectrum spatially. The attempt of heuristic resource allocation algorithms is to find the maximal number of nodes that could transmit data concurrently. The numerical and simulation results show that FLCRT, Learning Automata Heuristic Channel Assignment (LAHCA), and Learning Automata Heuristic Centralized Scheduling (LAHCS) perform better in terms of scheduling length, channel utilization ratio, and average transmission delay as compared with the existing approaches. The proposed FLCRT scheme with respect to the number of subscriber station (SS) nodes performs better in decreasing the scheduling length, average transmission delay, and channel utilization ratio by 38%, 19%, and 38% compared with Interference-Load-Aware routing. LAHCA algorithm improves the number of channels in comparison with random selection algorithm by 8%. LAHCS algorithm using multi channels proposed by LAHCA can reduce the scheduling time, average transmission delay as well as enhance channel utilization ratio versus number of SS nodes by 7%, 8%, and 6% respectively compared with Nearest algorithm in higher traffic demands.

ABSTRAK

Rangkaian jalur lebar wayarles menjadi semakin popular kerana penempatannya yang cepat dan murah dan keupayaannya menyediakan akses Internet yang fleksibel dan sepanjang masa. Dengan batasan sumber kongsi dalam rangkaian mesh wayarles seperti lebar jalur, guna semula ruang diperkenalkan untuk penghantaran serentak. Penghantaran serentak menghadapi pelbagai cabaran yang berkait dengan gangguan terhadap penghantaran berterusan. Untuk memaksimumkan prestasi rangkaian mesh dalam guna semula ruang, terdapat keperluan mempertimbangkan implementasi rentas-lapisan untuk peruntukan sumber yang melibatkan lapisan berbeza seperti lapisan penghalaan rangkaian, penjadualan peruntukan sumber bagi lapisan Kawalan Capaian Media (MAC) dan lapisan fizikal. Oleh itu, tesis ini memberi tumpuan kepada penambahbaikan guna semula ruang sebagai mekanisme peruntukan sumber termasuk pembinaan pepohon penghalaan dengan mengambil kira laluan yang boleh dipercayai, penguntukan saluran dan algoritma penjadualan. Pertama, Pepohon Penghalaan Terbina Logik Kabur (FLCRT) dicadangkan dengan gabungan logik kabur dan penghalaan yang membolehkan keupayaan kognitif dalam penghantaran paket komunikasi pautan atas atau pautan bawah. Kedua, laluan penghalaan sedar pautan dicadangkan untuk memenuhi tempoh hayat sambungan dan kestabilan laluan yang lebih baik untuk keperluan kejayaan penghantaran menggunakan pelbagai teknik nod penaja. Kemudian, pemahaman yang lebih baik bagi analisis kebolehpercayaan diteruskan dalam konteks rangkaian homogen wayarles. Akhirnya, peruntukan sumber heuristik termasuk penguntukan saluran dan algoritma penjadualan berpusat dicadangkan berdasarkan automata pembelajaran selular untuk meningkatkan bilangan penghantaran serentak dalam rangkaian dengan mengguna semula ruang spektrum secekapnya. Cubaan daripada algoritma peruntukan sumber heuristik adalah untuk mencari bilangan nod maksimum yang boleh menghantar data serentak. Keputusan berangka dan simulasi menunjukkan FLCRT, Penguntukan Saluran Heuristik Automata Pembelajaran (LAHCA), dan Penjadualan Berpusat Heuristik Automata Pembelajaran (LAHCS), lebih baik dari segi panjang penjadualan, nisbah penggunaan saluran, dan purata lengah penghantaran berbanding pendekatan sedia ada. Skim FLCRT yang dicadangkan berkaitan bilangan stesen pelanggan (SS) menunjukkan prestasi yang baik dalam mengurangkan panjang penjadualan, lengah penghantaran purata, dan nisbah penggunaan saluran sebanyak 38%, 19%, dan 38% berbanding dengan penghalaan Gangguan-Beban-Sedar. Algoritma LAHCA meningkatkan bilangan saluran berbanding dengan algoritma pemilihan rawak sebanyak 8%. Algoritma LAHCS yang dicadangkan yang menggunakan multi saluran LAHCA dapat mengurangkan panjang penjadualan, lengah penghantaran purata dan juga untuk meningkatkan nisbah penggunaan saluran berbanding bilangan nod SS sebanyak 7%, 8%, dan 6% setiap satunya berbanding algoritma Nearest untuk permintaan trafik lebih tinggi.

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LIST OF ABBREVIATIONS

2-D	–	2 Dimensional
3-D	–	3 Dimensional
ANN	–	Artificial Neural Network
BFS	–	Breadth First Search
BS	–	Base Station
BWA	–	Broadband Wireless Access
CA	–	Cellular Automata
CLA	–	Cellular Learning Automata
CTMC	–	Continuous Time Markov Chain
CUR	–	Channel Utilization Ratio
DCF	–	Distributed Coordination Function
DLA	–	Distributed Learning Automata
FDM	–	Frequency Division Multiplexing
FIE	–	Fuzzy Inference Engine
FLC	–	Fuzzy Logic Controller
FLCRT	–	Fuzzy Logic based Constructed Routing Tree
FLS	–	Fuzzy Logic System
IEEE	–	Institute of Electrical and Electronics Engineers
LA	–	Learning Automata
LAHCA	–	Learning Automata Heuristic Channel Assignment
LAHCS	–	Learning Automata Heuristic Centralized Scheduling
LAHRA	–	Learning Automata Heuristic Resource Allocation
LoS	–	Line of Sight
LP	–	Linear Programming
MAC	–	Medium Access Control
MAN	–	Metropolitan Area Network
MBS	–	Mesh Base Station
MSR	–	Maximum Spatial Reuse

MSS	–	Mesh Subscriber Station
NLoS	–	Non Line of Sight
OFDM	–	Orthogonal Frequency-Division Multiplexing
OFDMA	–	Orthogonal Frequency-Division Multiple Access
PHY	–	Physical
P2MP	–	Point-to-MultiPoint
QoS	–	Quaility of Service
RR	–	Round Robin
RRM	–	Radio Resource Management
SNIR	–	Signal to Noise Interference Ratio
SS	–	Subscriber Station
STDMA	–	Spatial Time Division Multiple Access
TDMA	–	Time Division Multiple Access
WFQ	–	Weighted Fair Queuing
WiMAX	–	Worldwide Interoperability for microwave Access
WMN	–	Wireless Mesh Network
	–	

LIST OF SYMBOLS

β	–	Fuzzy set
μ_β	–	Membership function
$\mu_\beta(x)$	–	Degree of membership of x
X	–	Universal set
$\int_X \mu_x/x$	–	Continuous fuzzy set
μ_i/x_i	–	Discrete fuzzy set
a	–	Reward parameter
b	–	Penalty parameter
r	–	the amplifier(reduction) of action probabilities
(L_{R-P})	–	linear reward-penalty algorithm
$(L_{R-\epsilon P})$	–	linear reward-ϵ penalty
(L_{R-I})	–	linear reward-Inaction
v_i	–	ith node of graph
R_{v_i}	–	Interference range of every terminal v_i
x_n	–	position of node n_i
L_p(i)	–	Traffic demand load of path
$I(i)$	–	Interference of node i
$L(i)$	–	Traffic demand load of node i
I_p	–	Interference of the path
n_t	–	Number of intermediate nodes
λ	–	The failure rate of primary sponsor node
δ	–	The failure rate of alternative nodes
T_1	–	The interval time that node n_1 is reliable and operational.
T_n	–	The life time of the existence of a sponsor nod
T_p	–	The life time of path including n_t intermediate SS nodes is operational
μ	–	The repairing rate
σ	–	The switching rate

R_t	–	The reliability of one mesh SS node
$R_P(t)$	–	The reliability of end to end communication path between SS node and BS node
$C_k^{(n-1)...(n-i)}$	–	The summation of all of permutations $(n-0)(n-1)...(n-k)$
$H = \{(i,j) \mid 1 \leq i \leq m, 1 \leq j \leq n\}$	–	Two dimension WiMAX mesh network
C_n	–	The number of disjoint clusters
C_{in}	–	The number of middle clusters between the source and destination clusters.
P_{BS}	–	The probability failure of BS node
R_{BS}	–	The probability of reliability among mesh BS nodes
R_p^{BS}	–	The probability of minimum reliability among mesh clusters in the communication path
R_{SN}	–	Reliability of source mesh SS node
R_{IN}	–	Reliability of intermediate mesh SS nodes
R_{DN}	–	Reliability of destination mesh SS node
R_{SS}	–	Reliability of mesh SS nodes
R_p	–	Reliability of communication path
$\underline{\alpha_i}$	–	Action of learning automaton
$\langle \underline{A}, \underline{\alpha} \rangle$	–	Network of Learning Automata
$\underline{A} = \{\underline{A_1}, \underline{A_2}, ..., \underline{A_m}\}$	–	The set of constant action-set learning automata
$\underline{\alpha} = \{\underline{\alpha_1}, \underline{\alpha_2}, ..., \underline{\alpha_n}\}$	–	The set of action-sets
$P_{i,j}^c$	–	Collision probability of i^{th} new channel request with j^{th} channel request
$P_{i,j}^a$	–	Probability of new channel request
λ_a	–	Arrival channel request
μ_c	–	Collision rate
(d_t, a_t)	–	Discrete-time Markov chain for Centralized Scheduling
a_t	–	Slot allocation time counter of a frame
d_t	–	Depth of tree
t and $t+1$	–	The beginning of two consecutive time slots
P_c	–	Collision probability in scheduling
P_T	–	Packet transmission probability to move to the next time slot.
	–	

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CHAPTER 1

INTRODUCTION

1.1 Overview

During the last decades, data communication is one of the essential factors for most of the social, scientific and business activities. As a result, multi-hop mesh wireless backhaul networks have emerged as a cost-effective and rapid deployment solution to enable ubiquitous and broadband multimedia applications while supporting quality of service. In this arena, a plethora of wireless access technologies have been developed, specifically Worldwide Interoperability for Microwave Access (WiMAX) and LTE (3GPP Long Term Evolution) as the latest and most promising ones. In this thesis, WiMAX is chosen as representative candidate for 4G technology due to much cheaper deployment than that of LTE network.

The main features of the adoption of WiMAX are mainly the advanced physical (PHY) layer technology with considering Scalable Orthogonal Frequency Division Multiple Access (OFDMA) to transmit data at the same time. In order to achieve the concurrent transmission, the limitation of resources such as bandwidth is the critical issue. As a matter of the fact, the transmission and reception of a signal on a wireless link is subject to the interference from other ongoing transmissions. Furthermore, due to existing interference, the utilization of shared resources is limited for data transmission in these networks. Therefore, resource allocation mechanisms and protocols have quickly emerged in order to encounter the effect of interference and to improve the achievable spatial reuse.

Although there are many non-cross-layer resource allocation algorithms based on only the physical (PHY) layer or medium access control (MAC) layer, they are not suitable methods due to channel-state-dependent scheduling where channel state information at the PHY layer are passed on to the packet scheduler at the MAC layer (Tse, 1999; Viswanath *et al.*, 2002). In wireless backhaul multi-hop networks, cross-layer design for optimizing network resource utilization is used (Bjrklund *et al.*, 2004; Capone and Carello, 2006; Capone *et al.*, 2008; Kompella *et al.*, 2008; Chen *et al.*, 2011; Gokturk *et al.*, 2013). In fact, the system throughput can be improved drastically if a cross-layer approach is applied to coordinate the network layer, MAC, and physical layer operations (Cao *et al.*, 2007). Because of the dependency of wireless links and changes in interference level (which directly affects the MAC scheduling decisions) originating from the selection of routing path, network layer routing and MAC/PHY layer scheduling become tightly coupled (Cao *et al.*, 2007). Indeed, a particular selection of routing paths at the network layer can provide a reduced level of cumulative interference at receiving nodes to activate the simultaneous transmissions at the MAC and PHY layers. Hence, the efficient utilization of the limited available resources leads to increase the spatial reuse.

From the given brief discussion, it is obvious that there is a definite need to develop cross layer for resource allocation including routing, channel assignment, and centralized scheduling with respect to spatial reuse. The spatial reuse results in utilizing the shared resources for efficient data transmission.

1.2 Problem Background

Cross layer design has been introduced to take the most benefits of the scarce radio resources available for wireless networks. Ad hoc networks and data packet transmission open the myriad of transmission possibilities, and motivate to break the barriers imposed by the layered transmissions (Corvino *et al.*, 2009a,b; Gokturk *et al.*, 2013). Cross layer design is defined by Su and Zhang (2009) as a protocol design that exploits the interaction between protocol layers to enhance the network performance gains. Bjrklund *et al.* (2004) and Capone and Carello (2006) show how cross-layer design can achieve a better network resource utilization and are being currently used as reference for several other researches presented by Capone *et al.* (2008) and Kompella *et al.* (2008).

As a result, spectral reuse enhancement is of the utmost importance in the WiMAX mesh network. Spatial reuse is performed through designing a cross layer for resource allocation mechanism. In fact, due to interference nature of wireless environment, firstly, efficient construction of routing tree is the important issue in order to achieve better spectral reuse. Since the improper routing path results in the degradation of network throughput and path corruption in data transmission, effective routing path construction for uplink or downlink communication should be addressed. Besides, link failures are the critical issues in routing of WiMAX mesh networks. Therefore, link failures due to interference nature affect on the communication path reliability. Furthermore, scheduling algorithm and channel assignment of WiMAX physical and MAC layer are the important challenges in WiMAX mesh networks for bandwidth allocation through routing transmission paths in order to tackle the interference (Mardini and Alfool, 2011; Calavia *et al.*, 2011).

To deal with cross-layer implementations, designing and solving the cross-layer of resource allocation including routing, channel assignment, and scheduling models is the important issue in WiMAX mesh networks. By exploiting the decomposition property of the resource allocation optimization problem into subproblems including routing, channel assignment and scheduling, the spatial reuse is optimized. Therefore, a mesh performance layer (mostly for scheduling) and a mesh connectivity layer (routing) are also required for building IEEE 802.16 mesh networks. The following sections elaborate the background of this thesis by delivering an overview on the problems and issues of routing construction which integrates with the long-term stability, channel assignment, and scheduling algorithms for WiMAX mesh network.

1.2.1 Routing in WiMAX Mesh Network

In WiMAX mesh network, base station (BS) serves as the gateway to the external network and all other nodes have to send their requests through the BS in multi hop transmission. For resource allocation, WiMAX IEEE 802.16 standard specifies that the assignment of link bandwidth is performed on a tree rooted at BS. The root node and relay nodes are BS and intermediate subscriber stations (SSs), respectively.

Routing in WiMAX mesh networks poses several design challenges. The issues that need to be addressed in the routing design include both short and long time scales. A good mesh routing scheme has to ensure both long-term route stability and achieve short-term opportunistic performance (Qassem *et al.*, 2009). For the short-term performance, the routing scheme has to take into consideration the interference and traffic load in the network. A routing scheme of less interference allows spatial reuse to increase the system performance. The routing problem is thus decisive in the system performance. In addition, the reliability of routing path should be ensured to achieve the long-term route stability. The following sections elaborate the background of the routing including short-term and long-term criteria.

1.2.1.1 The Short-Term Performance of Routing Path of WiMAX Mesh Network

Researchers face with designing efficient algorithms for routing and scheduling which are decisive in the system performance. Ensuring high system performance in mesh networks is a challenging task because of interference inherent in multi hop transmissions. In WiMAX mesh networks, the problem is even more complicated since stations have to be scheduled to transmit data in an interference-free manner. As a matter of the fact, the problem of routing and scheduling in WiMAX-based wireless mesh multi-hop network is the important issue, with the objective of determining a minimum schedule period that satisfies a given (uplink/downlink) end-to-end traffic demand. Minimizing the length of a schedule makes to maximize the spectrum spatial reuse by activating as many links on the same channel concurrently.

Previous researches concentrate on the effective criteria for routing in mobile ad-hoc networks, vehicular ad-hoc network and wireless sensor networks (Adya *et al.*, 2004; De Couto *et al.*, 2003; Koksal and Balakrishnan, 2006; Qassem *et al.*, 2009; Perkins and Bhagwat, 1994; Tarn and Tseng, 2007). These metrics can not be directly exploited in IEEE 802.16 owing to neglecting the quite sensitivity to the radio resource utilization and the differences between the MAC layer designs.

In addition, the standard of IEEE 802.16 provides specifications for centralized routing without giving any detailed routing algorithm except a random routing (IEEE, 2007). In the random routing, SSs randomly select their parents through building a tree. Furthermore, the random routing defines a routing tree mechanism rooted at BS to be established for the communication purpose between BS and SS. SSs send the request message including their link qualities and traffic demands to BS to ask for the bandwidth resources. Using the topology information along with SSs' requests, BS determines the routing tree to allocate and schedule the bandwidth requests and resources.

Centralized routing in mesh networks has attracted much attention from the research community. An excellent survey is provided on routing in mesh networks (Qassem *et al.*, 2009). Several researches aim to find the shortest routes using breadth first search (BFS) approach (Tang *et al.*, 2009; Du *et al.*, 2007; Xiao *et al.*, 2009; Wang *et al.*, 2008). Du *et al.* (2007) design a centralized scheduling for WiMAX mesh with multi-channel capabilities. Moreover, Narlikar *et al.* (2010, 2006) present a modified Dijkstra algorithm for the shortest path which is used for routing tree construction. The authors define $1/C(e)$ as the distance along an edge where $C(e)$ is the capacity of the edge. The drawback to the shortest path routing is that every node selects the shortest route and this may lead to bottlenecks in the network. Besides, the shortest path does not account for interference and traffic load which are essential metrics.

An interference aware routing scheme is proposed to reduce the level of interference and maximize concurrent transmissions (Wei *et al.*, 2005). When a node is considered to join the partially constructed routing tree, it selects the parent node with the least blocking metric. Although this work captures the interference in the network, it does not take into account the traffic load in the network. As a result, every node will choose the route with the least blocking metric and this will lead to congestion. Moreover, BellmanFord routing protocol like dijkestra algorithm is proposed to consider shortest path (Ning *et al.*, 2012). Furthermore, shortest path and blocking metric such as interference are considered in the optimized BellmanFord routing protocol.

To overcome neglecting load traffic, Fanchun *et al.* (2007) extends the research by (Wei *et al.*, 2005) to capture traffic load. In this work, the authors define blocking value as the degree of the node in the communication graph multiplied by the number of packets (traffic demand). This scheme takes into account traffic load in the network but can still lead to congestion. When an SS joins a parent node, the blocking metric of the parent node needs to be updated to reflect the increase in traffic load along that route else more SSs are likely to join the same parent node. The routing tree is constructed by having SSs choose parent nodes with the least neighbors along the path to the BS. When an SS joins the tree, it may affect the degrees of nodes in the tree which could cause some nodes to reselect their parent node. This may lead to an infinite looping.

Two routing construction algorithms are presented to provide a scalable routing between each mesh SS node and BS node in the presence of static node (Al-Hemyari, 2009; Al-Hemyari *et al.*, 2010). At first, five parameters including number of children per each node, node ID number, hop-count to the BS, the interference from the neighboring nodes (number of neighboring nodes), and number of packets for each node along the root to the BS are taken into consideration for routing. Secondly, the last four parameters are considered to select the best path with the least number of interfering neighbor nodes, minimum hop to BS and load balancing network. Furthermore, an efficient routing tree algorithm is proposed in uplink and downlink slot allocation on the centralized scheduling scheme to mitigate interferences in the network (Behfarnia and Tabataba Vakili, 2011). In the proposed algorithm, number of hop-count from the BS, node identification (i.e. ID node), number of interfering nodes and the number of uplink and downlink traffic per each node are considered one by one for routing construction. Although, these parameters are checked one by one to construct routing tree, the effect of jointly routing metrics is not considered for routing tree construction.

Chen *et al.* (2007, 2009) try to take both traffic load and hop count into account during the routing tree construction. The routing tree is constructed in a bottom-up approach where an SS with the highest degree is first attached to its neighbors with less or equal hop-count. The SS with the least traffic load is then chosen as the parent node. This scheme may lead to longer routes as SSs may choose neighbors with the same hop-count. Also, Cao *et al.* (2006) present a multi path routing scheme by multiplying interference, data traffic, and traffic class to obtain the best route.

Furthermore, since the quality of path often fluctuates due to interference from other communication and load demands, most of the mentioned researches are not suitable to guarantee the best path owing to considering one metric. Furthermore, Nsoh and Benkoczi (2012, 2013) present the multi path interference-load aware routing construction algorithm based on interference and load traffic to enhance the spatial reuse by simultaneous transmissions (Nsoh and Benkoczi, 2012, 2013). Besides, most of the mentioned researches did not take into consideration the inaccuracies of the important blocking metrics. Since the decision parameters are inaccurate for selecting the proper path, it is essential to address the inaccuracies as the important impact on the routing complexity.

1.2.1.2 The Long-Term Reliability of Routing Path of WiMAX Mesh Network

Transmissions of the WiMAX mesh network undergo in a multi hop manner with the aid of relaying technique by intermediate SS nodes for those SSs being far from the BS. Hence, one of the other important issues of WiMAX mesh network is the link failures which are unavoidable due to the hostile wireless environment. The link failures lead to excessive delay with great influence on the quality of service for delay sensitive applications and global performance of WiMAX network.

Reliability, availability and survivability are considered as three measuring ways of coping with failures which have been the main subjects of fault tolerant studies (Snow *et al.*, 2000). Reliability is defined in different concepts. For instance, it is defined as the probability that a given connection or application in a network is operational to provide the minimum requirement in order to achieve successful communication (Shooman, 1995). Reliability is also defined as the quantitative technique which is the need for a given system to perform its required functions under stated conditions for a specified period of time. Some authors define reliability as the probability of network performance maintaining in case of the equipment failures (Soni and Pirkul, 2002; Kerivin and Mahjoub, 2005).

Network reliability concerns with the capability of the underlying network to provide successful communication between set of nodes, i.e., sources and destinations, which is an issue of concern whenever there is a need of assurance of conveying critical data within the network.

Furthermore, designing a highly reliable transmission path is one of the other ultimate objects of this thesis. Due to the features and specifications of wireless environment, communication reliability of wireless networks is more complicated than wired networks. In reality, wireless environment faces many problems such as interference and disappearance of radio wave propagation especially low power in cluttered environments such as urban areas.

Although fault tolerant network has been extensively studied on ad hoc and interconnection networks, there are a few works on WiMAX mesh network. There are multi path algorithms which undergo faults in ad hoc networks and mesh networks such as multi path techniques. These routing methods have been proposed to reconnect between source and destination nodes in the failure situations (Pearlman *et al.*, 2000; Wang and Chao, 2006). Also, a path diversity method with the aim of path selection has been proposed to enhance reliability with consideration of the energy concept (Papapostolou *et al.*, 2013). In other words, analyzing the reliability of these networks presents that the mentioned approaches are based on making reconnection when failures occur through communication path.

Although some researchers have applied Markov chain based on multi path to measure the fault tolerance of ad hoc and interconnection network, few works used this model in WiMAX network. The Continuous Time Markov chain (CTMC) is used to represent a connection availability model for two hop ad hoc networks that incorporates the physical faults like node, power and link faults (Chen *et al.*, 2002). A generalized connectivity model is introduced with enlarged number of node failure types for static ad hoc networks (Koroma *et al.*, 2003). Furthermore, a connection availability and connection resilience of ad hoc networks are estimated using CTMC with taking special into consideration effective parameters like routing protocol and area size in which nodes are scattered (Dimitar *et al.*, 2004a,b).

In addition, network reliability analysis has been an important area of research in wired networks, but a little researches have been accomplished in wireless networks. Most of the existing works have considered networks as graphs with prefect nodes and edges of identical reliability, but wireless networks are quite different from wired networks because nodes are prone to failure and there is a large variance in the reliability of links. Wireless networks have several aspects that make them more susceptible to failures and loss of connectivity such as fluctuating medium characteristics and the properties of wireless devices. For instance, the broadcast nature of wireless communication links makes them unique in their vulnerability to loss of connectivity due to interference and limited transmission range. Because of these impediments, there is a paradigm shift from the traditional reliability analysis for wired network to wireless networks.

Previous research working on fault tolerant wireless and ad hoc networks are based on the graph model which is not realistic due to not considering stochastic and random distribution nodes (Cook Jason and Ramirez-Marquez, 2008, 2007; Khandani *et al.*, 2008; Moses E. Ekpenyong, 2009). Link reliability based on the stochastic model has been introduced among homogeneous networks with taking into consideration interference and signal to noise ratio (SNR) (Salami *et al.*, 2009, 2010, 2011).

However, the mentioned literature focus on the fault tolerance on ad hoc and wireless mesh networks, few of them work on the enhancement of reliability of WiMAX mesh networks and provide generic model to measure the reliability.

1.2.2 Channel Assignment in WiMAX Mesh Network

In addition to the specifications of MAC layer, the specification of PHY layer is used to subdivide the available frequency band into multiple non-overlapping frequency channels to be employed simultaneously in order to enhance the aggregated bandwidth available to the end users. However, in a multichannel system, multiple simultaneous transmissions in a neighborhood must operate on different channels in order to avoid the possible secondary interference (Du *et al.*, 2007; Han *et al.*, 2007). So, an efficient channel assignment strategy is required to assign channels to each link. Any such strategy should have the following two characteristics: (i) It must assign channels to each link in the network in such a way that secondary interference is eliminated completely from the network. (ii) It must minimize the total number of channels used for the mentioned purpose.

Some previous researches focus on the channel assignment in the PHY layer. Centralized scheduling and channel assignment algorithms have been proposed using the graph coloring approach for channel assignment to the links. In this approach, each link of the networks is to be colored with a different color from its interfering links (Jensen and Toft, 2005; Barrett *et al.*, 2006; Du *et al.*, 2007; Riihijarvi, 2005; Al-Hemyari, 2009; Al-Hemyari *et al.*, 2010). In this algorithm, an uncolored link is randomly selected to assign the minimum possible color which is different from the colors of the already colored links having secondary interference with the selected link. This random selection does not give the optimal result and uses more number of channels than the minimum number of required channels to avoid the secondary interference.

Some researchers translate the problem of channel assignment into a maximum clique problem defined by Ostergard (1999, 2001); Kim and Shi (2002), where the goal of these researches is to find the maximum number of concurrent interference-free transmissions (Liao *et al.*, 2012). The maximum clique problem is however non polynomial (NP) hard (Garey and Johnson, 1979). Hence, a quicker solution is more desirable.

1.2.3 Centralized Scheduling in WiMAX Mesh Network

The IEEE WiMAX/802.16 mesh mode of operation uses Time Division Multiple Access (TDMA) technology as a MAC layer access where each scheduling frame is divided into 256 time slots. The first 16 time slots form the control subframe and the others define the data subframe. Within a TDMA time slot, sub-channelization could be used where the available spectrum is subdivided into multiple orthogonal sub-carriers (WiMAX uses OFDM as a modulation method and supports subchannelization in units 1, 2, 4, 8, or 16 of OFDM sub-carriers) (Narlikar *et al.*, 2006).

As a result, packet scheduling remains an important research area in TDMA networks. The scheduling algorithm has to address issues such as throughput, delay, and channel utilization ratio among others. In addition, the goal of the scheduling algorithm is to find a minimum scheduling time for uplink traffic. Finding the minimum number of centralized scheduling transmission opportunities in the data sub-frame is an important area for 802.16 mesh networks (Du *et al.*, 2007).

There have been several approaches to address the centralized scheduling in WiMAX mesh networks to minimize the length of scheduling cycle in the MAC layer (Du *et al.*, 2007; Han *et al.*, 2007, 2006; Shetiya and Sharma, 2005; Jin *et al.*, 2007; Wei *et al.*, 2005; Wang *et al.*, 2008; Xiong *et al.*, 2007; Fu *et al.*, 2005; Chen *et al.*, 2007, 2009; Cao *et al.*, 2006; Akashdeep *et al.*, 2014).

Spectral reuse mechanism based on routing algorithm is proposed to achieve maximum spatial reuse and the overall network throughput with taking into account the interference in IEEE 802.16 based Wireles Mesh network (WMN) (Fu *et al.*, 2005). An efficient approach is proposed for increasing the utilization of WiMax mesh through appropriate design of multi-hop routing and scheduling (Wei *et al.*, 2005). Links are processed in the order of decreasing traffic demands in the research by Wei *et al.* (2005) while an optimal scheduling based on integer linear program is presented in the research by Fu and Cao (2006). However, they consider only the primary interference and does not consider the secondary interference.

A collision free centralized scheduling algorithm has been proposed based on Wireless Mesh Network (WMN) using relay strategy for the Mesh Subscriber Stations (MSSs) in a transmission tree. The objective of this algorithm is to provide high-quality wireless multimedia services by considering channel utilization and transmission delay with different effect of selection criteria including random, minimum interference, nearest to BS and farthest from BS. The simulation result shows that giving higher priority to the nodes nearer to the Mesh Base Station (MBS) when allocating time slots for uplinks will achieve higher spatial reuse and the best performance in terms of length of scheduling, channel utilization ratio and delay (Han *et al.*, 2006, 2007). Similar selection criteria are employed for centralized scheduling with the similar results (Wang *et al.*, 2008). Moreover, nearest node to BS node, maximum load, and minimum interference node are considered for centralized scheduling (Al-Hemyari, 2009; Al-Hemyari *et al.*, 2010). Simulation results show that nearest node to BS node algorithm performs better performance in terms of spatial reuse.

Furthermore, a uniform slot allocation algorithm is proposed for both uplink and downlink transmissions in order to achieve higher spatial reuse and network throughput (Liu *et al.*, 2009). In the proposed algorithm, smallest hop count first and hop by hop and largest hop count first and hop by hop link selection are selected as the important criteria for scheduling. These criteria are different with nearest or furthest methods in forwarding traffic generated by higher priority node itself not its children. Actually, the results of the proposed algorithm is similar to Nearest algorithm. Besides, how to exploit spectral reuse is studied in an IEEE 802.16 based on Wireless Mesh Network (WMN) through time slot allocation, bandwidth adaptation, hierarchical scheduling and routing (Chen *et al.*, 2007, 2009).

Actually, most of the mentioned literature give the higher priority to the nodes further from the Mesh Base Station (MBS) when allocating slots for Mesh Subscriber Stations (MSSs) (Fu *et al.*, 2005; Tao *et al.*, 2005; Kim and Ganz, 2005; Cao *et al.*, 2006; Chen *et al.*, 2007, 2009). Therefore, achieving the spatial reuse is limited.

Theory of artificial neural networks is used for bandwidth allocation and scheduling algorithm to predict traffic time series (Kumar *et al.*, 2011; Railean *et al.*, 2012; Daw *et al.*, 2014). The limitation of these studies is that the real world data should be taken (Kumar *et al.*, 2011) and the computation time is very high for training (Railean *et al.*, 2012).

In addition, since these scheduling algorithms are proposed based on the single channel, the efficient channel assignment has not been employed for scheduling.

The performance gains of jointly optimizing scheduling and routing is investigated in a multi-radio, multi-channel and multi-hop wireless mesh network (Ning *et al.*, 2012). In fact, a cross-layer algorithm is proposed by considering both MAC and network layers to address wireless media contention and spatial reuse. In this paper, multi radio increases cost and complexity. Also, the efficient channel assignment is not investigated.

Several studies focus on the multichannel single transceiver WiMAX centralized scheduling algorithm to maximize the number of concurrent transmission in the network (Du *et al.*, 2007; Tang *et al.*, 2009; Xiao *et al.*, 2009) . A nearest first scheme has been employed for uplink traffic to minimize the length of time needed for all bandwidth requests by considering multi-channel single-transceiver (Du *et al.*, 2007). (Tang *et al.*, 2009) present centralized scheduling and channel assignment algorithms designed using degree of saturation for link scheduling activation to reap the full performance potential of the multiple channel single transceiver system in the case of the insufficient channels. A group of maximal "active" links are identified to transmit concurrently meaning how to use fewer channels (Tang *et al.*, 2009). To do so, a channel assignment algorithm is used to find a group of links to transmit concurrently from the available links. Xiao *et al.* (2009) improve the research of Du *et al.* (2007) by equipping each node with two transceivers operating at different frequencies in order to ignore the primary interference. Although empowering nodes with multiple transceivers results in a short length of scheduling and high throughput, it causes to increase the cost of deployment and hardware complexity significantly. Since these algorithms choose the minimum index channel from the set of available channels, any efficient channel assignment is not employed.

The resource allocation problem in OFDMA based wireless networks is posed as an optimization problem with individual user constraints. The proposed method is based on standard graph theory and Lagrangian relaxation to enhance spatial reuse (Zaki and Fapojuwo, 2011). Besides, a realtime scheduling is presented in the uplink transmission for WiMAX mesh networks to maximize the number of data packets through an uplink subframe (Mohammadi *et al.*, 2009). The proposed method based on linear programming which is a heuristic algorithm results in higher computation.

A scheduling algorithm based on genetic algorithm is proposed with SS grouping resource allocation (GGRA) scheme for IEEE 802.16 uplink systems. The GGRA scheme uses a rate assignment strategy to formulate the resource allocation problem as an optimization equation subject to system constraints (Chang *et al.*, 2010;

Chiu *et al.*, 2010). Also, a dynamic programming algorithm is proposed based on genetic algorithm to find the conflict-free set of nodes that can be activated to achieve optimal solution for scheduling (Gunasekaran *et al.*, 2010). Next, a genetic algorithm is provided, which is more scalable than dynamic programming approach, but does not guarantee optimality. However, the proposed algorithm based on genetic algorithm is suffered from lots of comparisons and calculations and hence the process might be slow when the size of network is increased.

A maximum weight clique partitioning mechanism introduced by Ostergard (2001) and Kim and Shi (2002), has been presented to perform the centralized scheduling in an IEEE 802.16 WiMAX network operating as a mesh using multiple channels to transmit data (Liao *et al.*, 2012). In this method, throughput is optimized by minimizing the number of time slots used to transmit data. However, the maximum clique problem is NP hard (Garey and Johnson, 1979). So, a quicker solution is more desirable. Hence a sub-optimal heuristic should be proposed for the scheduling problem.

1.3 Problem statement

The mentioned open research problems in Section 1.2 lead to address the problem of achieving efficient performance of spectral reuse mechanism in WiMAX mesh network in different layers including routing, physical, MAC layers due to the problematic issues in interference.

Moreover, selecting the improper path leads to degrade the performance of resource allocation parameters including the number of consumed time slots, delay for granting bandwidth request demands. In fact, due to the nature of wireless environment including interference and load, spatial reuse is reduced during the communication path.

On the other hand, due to the failure prone in wireless environment, data communication path is corrupted. The link failures of communication path in error prone do not meet the requirement of successful transmission. To cope with the link failures during communication path bypassing the intermediate nodes, the enhancement of communication path reliability is of the utmost importance in the WiMAX mesh network.

Finally, the spatial reuse is reduced owing to interference in resource allocation in physical and MAC layers. In fact, activating multi nodes for spatial reuse enhancement is constrained by the interference nature of a wireless environment. Therefore, the improper scheduling algorithm without considering the multi channel specification of physical layer leads to reduce the number of concurrent transmission for traffic delivery.

1.4 Research Questions

The open issues described in this section and previous sections lead to mention some of the research questions addressed in this thesis as follows:

(i) How to construct routing tree for addressing the traffic load and interference of communication path for centralized scheduling?

(ii) How to address the link failures for the reliability enhancement of communication path with developing a realistic model for the reliability estimation of communication path from the source to destination mesh SS in homogeneous WiMAX mesh clusters?

(iii) How to provide the heuristic resource allocation in order to enhance spatial reuse in terms of less number of assigned channel, less scheduling time, less average transmission delay, and higher channel utilization ratio with taking into consideration interference at the MAC and physical layer?

1.5 Research Aim

The aim of this research is to enhance the spectral reuse of WiMAX mesh network in terms of routing, channel assignment and scheduling of transmission at different layers including routing layer with ensuring the reliability of transmission path of mesh WiMAX network, Physical (PhY) layer, and MAC layer to enhance spatial reuse.

1.6 Research Objectives

The specific objectives of this thesis are:

(i) To propose an intelligent fuzzy based constructed routing tree in order to elect the best path between each SS and BS for centralized scheduling to address load, and interference of communication path.

(ii) To enhance the reliability of communication path in one mesh cluster of WiMAX network in case of the link failures using multi sponsor node technique and to develop the analytical model in order to estimate the reliability of communication path of WiMAX mesh network between source and destination mesh SS in different mesh clusters using a realistic stochastic model.

(iii) To enhance the spatial reuse in terms of less number of assigned channels, less scheduling time, higher channel utilization ratio, and less average transmission delay using the finding maximal interference free set for channel assignment and time slot allocation based on cellular learning automata.

1.7 Significance of the Study

By increasing the ubiquitous access to Internet for urban and rural areas and to Broadband Wireless Access (BWA) for high data rates like media and video, ensuring packet delivery ratio at the minimum delay with taking benefits of channel utilization ratio is important in the WiMAX mesh network.

Since the wireless channel is a shared medium, transmissions with close proximity interfere each other. So, medium access in a multihop mesh network needs to be well coordinated to achieve good performance. In fact, the medium access requires an intelligent interference management mechanisms.

In addition, unlike in wired networks, merely providing connectivity at the routing layer is not sufficient for mesh networking in the wireless environments. The characteristics of the multihop wireless medium - namely, interference, fading, and broadcast - should be exploited to design wireless mesh networks with satisfactory performance. To achieve this goal, in addition to the mesh connectivity layer, a mesh performance layer should be implemented between the routing layer and the wireless interface. This layer should be responsible for providing a more reliable link layer over the wireless mesh medium with improved capacity and quality of service (QoS). Also, this layer should be able to interact favorably with the upper layers to achieve good overall system performance, in contrast to some undesirable interactions of IEEE 802.11 with higher layers, in multihop scenarios (Xu and Saadawi, 2001).

1.8 Scope of the Research

The scope of this thesis covers the following points:

(i) This thesis will focus on the fixed wireless aspects of the WiMAX mesh network and homogeneous mesh networks.

(ii) This thesis will focus on the protocol interference aspects of the WiMAX mesh network.

(iii) This thesis will focus on the channel aware aspects of scheduling algorithm without considering traffic class of WiMAX mesh network.

(iv) This thesis will focus on the centralized scheduling WiMAX network for time slot allocation.

1.9 Thesis Organization

The remaining of the thesis is organized as follows:

Chapter 2 provides the intensive literature review of cross layer resource allocation including routing, channel assignment, and scheduling algorithms. Then, the proposed solutions regarding routing, channel assignment and scheduling approaches are highlighted. Furthermore, it presents the main operation of different previous studies with emphasis on their advantages and disadvantages. It also presents a comprehensive literature review of reliability in different wireless network.

Chapter 3 describes the conducted research methodology in this thesis. The utilized methodology to formulate the research problems, protocol design, and simulation setup are explained in this chapter.

Chapter 4 outlines the design detail of the proposed routing tree construction algorithm in WiMAX mesh environments. The simulation result of designed routing tree shows that it can efficiently route data packets in high load and interference environment.

Chapter 5 presents an efficient technique based on multi sponsor node technique which can enhance the reliability of the multi hop communication path. Markov model is also applied to measure the reliability of the communication path based on the multi sponsor nodes when network faces with malfunctioning nodes. Ultimately, a generic model is developed to measure the reliability of the multi hop communication path based on the stochastic attribution of homogeneous mesh WiMAX network.

Chapter 6 presents the details of the proposed heuristic greedy resource allocation channel assignment and scheduling algorithms in WiMAX mesh network. The proposed channel assignment and scheduling algorithms are based on cellular learning automata to improve the performance of network in terms of number of assigned channels, scheduling time, delay, and channel utilization ratio.

Chapter 7 summarizes the thesis, restates the contributions, and suggests directions for future research.

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