Thesis for the Degree of Doctor of Philosophy

Dynamic Traffic Engineering for High-Throughput Data Delivery in Wireless Mesh Networks

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As the candidate's supervisor, I have approved this dissertation for submission.

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Declaration of Authorship

We declare that this thesis titled "Dynamic Traffic Engineering for High-Throughput Data Delivery in Wireless Mesh Networks" and the works presented in it are our own. We confirm that:

- The full part of the work is done during PhD research study in University of Dhaka, Bangladesh.
- Any part of this thesis has not previously been submitted for a degree or any other qualification in this University or any other institution.
- We have consulted the published works of others with appropriate references.
- This thesis work is done entirely by us and our contributions and enhancements from other works are clearly stated.

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Candidate

Countersigned: ______________________________

Supervisor: Dr. Md. Abdur Razzaque

Co-supervisor: Dr. Md. Mamun-Or-Rashid

Abstract

Wireless Mesh Network (WMN) has recently been emerged as a promising technology for wireless Internet infrastructure development because of its low cost, ease of deployment and installation facilities. The increasing number of users and diversified application usages as well as the incorporation of sensors and Internet of Things (IoT) devices with the WMNs have caused exponential growth in traffic flows. This increased volume of traffic causes congestion in the network and degrades application throughput, reliability and delay performances. Therefore, providing satisfactory network performance using the limited bandwidth resources, has emerged as a challenging problem.

Our endeavour in this dissertation is to address high-throughput data delivery challenges in WMNs. Many state-of-the-art works address flow performance improvements in WMNs in many ways, ranging from routing, scheduling, channel allocation to rate control. However, none of these approaches merely addresses the instantaneous network conditions and sudden surge of huge data traffic from diverse user applications, that cause network to become congested. To optimize network performance, a dynamic traffic engineering mechanism requires to consider underlying network topology, available resources and traffic demand. Furthermore, traffic forwarding should act upon network dynamics, e.g., link error, link failure, neighborhood interference, path congestion, etc. Considering the aforementioned issues, in this thesis, we first develop an optimization framework for Dynamic Traffic Engineering, namely O-DTE, assuming that fixed channels are allocated to different links. O-DTE aims to minimize neighborhood interference and backlogged traffic, and explores the least congested next-hop nodes so that the overall throughput of the network is maximized. The O-DTE belongs to mixed integer nonlinear programming

(MINLP) problem and involves both combinatorial and continuous constraints, making it an NP-hard problem. A greedy heuristic alternate solution G-DTE is then developed that produces near-optimal results.

Motivated by the enhanced capacity offered by dynamic channel allocation in WMNs, the second part of our thesis focus on developing a joint link-channel selection and power allocation optimization framework (OLCP), which follows hop-by-hop traffic splitting approach and exploits single-hop information to forward traffic over least-congested and minimally-interfered link-channel pairs, which in turn improves spatial reuse and thus helps to improve overall network throughput. As finding a real-time solution of OLCP is intractable in a typical mesh router, we develop a greedy heuristic solution for the problem, GLCP, to achieve a sub-optimal solution.

Recently, cognitive radio (CR) enabled mesh routers have proven to mitigate spectrum scarcity by opportunistic licensed spectrum utilization. Thus, to boost up flow throughput in Cognitive Radio Wireless Mesh Network (CR-WMNs), we present a centralized optimization framework, called COTE, in the third part of this dissertation. The COTE aims at maximizing aggregated network throughput by selecting an optimal set of link-channel pairs, power allocation over those and fair traffic splitting after considering channel idle probability, link interference and path congestion. Further, a centralized Suboptimal Traffic Engineering (SOTE) solution is proposed by employing Lagrangian dual decomposition to the COTE problem, to ensure a resolution in polynomial time. Finally, a Distributed Greedy Traffic Engineering (DGTE) method is proposed to ensure fast convergence to the dynamic changing network behavior and to improve scalability.

The effectiveness of our proposed dynamic traffic engineering methods are evaluated via ns-3 simulations. The simulation results demonstrate that the proposed solutions outperform the state-of-the-art works in terms of throughput, delay, reliability, fairness and convergence cost.

Acknowledgment

In the vastness of space and immensity of time, it is with tremendous joy that I wish to express my gratitude to all those who helped and supported me on this long but fulfilling path in life. I would like to express my sincere thanks and gratitude to those who helped me throughout this research. I consider my PhD studies a great journey, full of lifetime experiences.

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Chapter 1

Introduction

1.1 Introduction

Wireless Mesh Networks (WMNs) typically consist of a large number of wireless mesh nodes, some of which are called gateways and are connected with public Internet using wired network [2]. The WMNs gained high popularity in the recent years since it facilitates easy deployment of wireless Internet infrastructure to a wide variety of devices and applications running on desktops, smartphones, tablets, sensor nodes, etc [2, 3]. The exponential growth of traffic volume, particularly from wireless devices, has imposed the need for greater capacity. However, improving network throughput has become a critical requirement in WMNs, due to limited resources, influence of interference, large number of users and emergence of real-time multimedia applications.

High-throughput data delivery challenges in WMNs have been addressed by different operation layer activities of communication architecture either independently or jointly [4, 5, 6, 7, 8, 9]. While forwarding traffic toward destinations, different routing solutions have been employed emphasizing on computing least interfered [10, 11] or high capacity [12, 13] or delay bound [10, 14] paths. Again, deployment of multi-radio routers in WMNs backbone [15], allows simultaneous parallel multi-path traffic transmission over orthogonal channels. Thus, higher incoming traffic can be apportioned over the multiple paths by minimizing inter-path interference [16] and extending path capacity [5, 6] to award higher reliability. Furthermore, dynamic channel allocations over concurrent transmitting links in a neighborhood focused on minimizing interference may harvest higher link capacities [17, 18] under channel and traffic dynamics. Nevertheless, due to wide range of variations in WMNs traffic, channels are eventually saturated and may bring up congestion due to contention caused by concurrent transmissions, buffer overflows and time varying wireless channel conditions. Addressing congestion, traffic engineering solution is required to adjust allowable rates over forwarding links dynamically by applying either end-to-end [19, 20] or hop-by-hop congestion control techniques [4, 21]. Rate adjustment through power control over transmitting links significantly improves spatial channel reuse and thus maximizes aggregated flow throughput [22, 23]. To satisfy the increasing demand for the bandwidth of the evolving network applications, cognitive radio enabled mesh routers are able to opportunistically share licensed channels to enhance spectrum resources [24, 25]. Here, dynamic selection of potential channels [24, 26] over high capacity paths along with pertinent rate, notably improves flow performances.

From the above discussion, it is apparent that ensuring high-throughput data delivery in WMNs is a great challenge of the underlying traffic forwarding mechanism. While computing the optimal resource allocation, the traffic forwarding mechanism should be able to measure the network dynamics in real-time and react instantly to satisfy flow demand. Thus, in order to enhance flow performances in a wireless multi-hop network, we need dynamic traffic engineering (DTE), that acts on instantaneous network condition by optimally splitting data over high throughput paths.

In this dissertation, we investigate the influence of random traffic arrivals, fluctuating link behavior, neighboring interference and path congestion, while securing higher throughput for traffic flows in multi-radio WMNs. To address aforementioned challenges, a distributed control agent is required at each forwarding mesh router to dynamically compute multiple forwarding links toward multiple gateways and distribute traffic over them in a way to maximally fulfill flow demand through minimizing the affects of interference and congestion. Here, we first propose an Optimal Dynamic Traffic Engineering (O-DTE) framework for routing and congestion control, that determines forwarding link qualities and split traffic over them in a way that can minimize backlogged traffic. Next, we develop a joint Optimal Link-Channel Selection and Power Allocation (OLCP) framework, which also follows hop-by-hop traffic splitting approach, exploits single-hop information to forward traffic over least-congested and minimally-interfered link-channel pairs, which in turn improves spatial reuse and thus helps to improve overall network throughput. Finally, a Centralized Optimal Traffic Engineering (COTE) mechanism is devised, that deploys Cognitive Enable (CR) routers targeting to opportunistically and dynamically utilize licensed channels to increase network bandwidth. Here, the proposed optimal traffic engineering problems belong to Mixed Integer Nonlinear Programming (MINLP) class and they involve both combinatorial and continuous constraints, making those NP-hard problems. Therefore, we develop alternate sub-optimal solutions employing greedy heuristic approaches.

1.2 Wireless Mesh Network

Wireless mesh networking has emerged as a promising design paradigm for next generation wireless networks due to its low cost, quick deployment, easy maintenance, installation facilities, high scalability and reliable services as well as enhanced network capacity, connectivity and resilience. Wireless mesh networks consist of mesh clients and mesh routers, where the mesh routers form a wireless infrastructure/backbone and interwork with the wired networks to provide multi-hop wireless Internet connectivity to the mesh clients [27, 28]. In addition, with the use of advanced radio technologies, e.g., multiple radio interfaces and smart antennas, network capacity in WMNs is increased significantly. Moreover, the gateway and bridge functionalities in mesh routers enable the integration of wireless mesh networks with various existing wireless networks, such as wireless sensor networks, Wi-Fi (wireless-fidelity), and WiMAX (Worldwide Inter-operability for Microwave Access) [28].

Some of the benefits and characteristics of wireless mesh networks are highlighted as follows,

- **Increased reliability:** In WMNs, multiple redundant paths exist between the sender-receiver pairs through the wireless mesh routers. Thus, the system offers higher capacity, eliminates single point failures and potential bottleneck links, ensuring reliability.

- **Low installation costs:** Mesh routers are able to provide extended communication range which reduces the network infrastructure cost. Here, few routers are required to fully cover a metro scale area. Moreover, WMNs require a few gateway routers to get connected with the wired network. Hence, WMNs can enable rapid implementation and possible modifications of the network at a reasonable cost.

- **Large coverage area:** Currently, wireless local area network (WLAN) standards offer higher data rates (e.g., 54 Mbps for 802.11a and 802.11g), by utilizing spectrally efficient modulation and coding schemes (MCS). Although the data rates of WLANs are increasing, for a specific transmission power, the coverage and connectivity of WLANs would decrease as the end-users reside farther from the access point. On the other hand, multi-hop and multi-channel communications among mesh routers in WMNs can enable long distance communication without any significant performance degradation.

- **Multiple types of network access:** In WMNs, both backhaul access to the Internet and peer-to-peer (P2P) communications are supported [29]. In addition, the integration of WMNs with other wireless networks and providing services to end-users of these networks can be accomplished through WMNs.

Wireless mesh networks (WMNs) are classified into three standard activities, namely IEEE 802.11, IEEE 802.15, and IEEE 802.16 mesh networks [28]. The working group within the IEEE 802.11, called IEEE 802.11s, has been formed to standardize the extended service set (ESS) [30]. The main objective is to define the Medium Access Control (MAC) and Physical (PHY) layers for mesh networks that extend coverage with no single point of failure. On the other hand, IEEE 802.15.5 working group has been established to investigate the necessary mechanisms in the PHY and MAC layers that can enable mesh networking in the wireless personal area networks (PANs) [31]. The IEEE 802.16 mesh networks working group aims at determining the possible mechanisms in the PHY

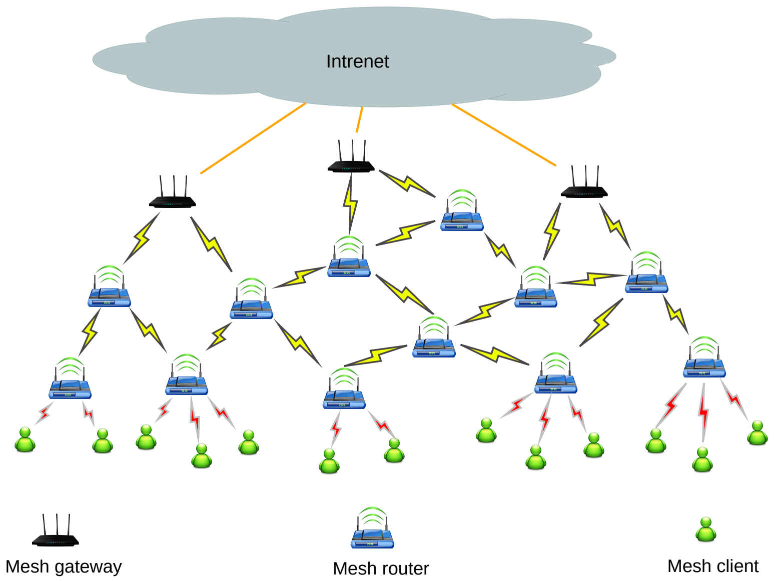


Figure 1.1: WMN architecture

and MAC layers which can serve the broadband wireless access in metropolitan area and support point to multi-point connection oriented Quality of Service (QoS) communications. However, the IEEE 802.16 mesh standard demonstrates several limitations such as lack of scalability, a connectionless MAC, etc. [32].

1.2.1 Wireless Mesh Network Architecture

A WMN is composed of static and mobile nodes interconnected via wireless links to form a multi-hop network. The static nodes known as wireless mesh routers (MRs) while mobile nodes are generally termed as wireless mesh clients (MCs), as shown in Fig. 1.1. Here, the static mesh routers form the wireless backbone and mesh clients access the network through mesh routers. In this integrated network architecture, some of the mesh routers are called gateways (GWs), which are special wireless routers with a high-bandwidth wired connection to the Internet [2]. In WMNs, each node operates not only as a host but also as a router, forwarding packets of data on behalf of other nodes that may not be within direct wireless transmission range of their destinations.

Moreover, the multi-hop packet transmission in an infrastructure WMN extends the area of wireless broadband coverage without wiring the network and therefore enables the integration of mesh networks with other existing wireless networks such as cellular and ad hoc networks (e.g. sensor, vehicular), 802.11 WLAN (Wi-Fi) and 802.16 based broadband wireless (WiMAX) [28].

Single-Radio Single-Channel Wireless Mesh Networks - The most basic type of wireless mesh network is a single-radio, single-channel (SRSC) network. Here, each node is equipped with a single radio interface, which is tuned to a fixed frequency channel. SRSC mesh network suffers from performance problems [33], due to the strong interference among communicating mesh routers on the same channel. As, there are a large number of nodes located in close proximity in WMN and each node employs IEEE 802.11 MAC (Medium Access Control) which works on the principle of CSMA (Carrier Sense Multiple Access); neighboring contention on the same channel increases collisions, retransmissions and packet drops that severely degrades the overall system performance.

Multi-Radio Multi-Channel Wireless Mesh Networks - Wireless mesh routers are inexpensive and due to the limited performance of single-radio mesh routers, each router in multi-radio multi-channel (MRMC) WMN is equipped with multiple radios so that a large number of concurrent connections can be maintained. The radio interfaces are typically tuned to non-overlapping channels to minimize interference [15]. There are different mechanisms available for channel allocations - static, dynamic or a combination of the two. In static channel assignment, the interfaces at all nodes are permanently tuned to a fixed channel using approaches such as graph-coloring to minimize interference between the routers. In contrast, dynamic channel assignment provides a mechanism for dynamically switching the interface to a different channel as the load conditions on the network vary. Dynamic channel assignment is more complex as it requires some underlying channel switching algorithm, a mechanism for synchronizing channel switch and a way to handle the channel switch latency [34]. A hybrid channel assignment can also be used which is a combination of static and dynamic channel assignment. In these solutions, some of the interfaces are permanently assigned to fixed channels (often referred to as a control channel) while other interfaces can dynamically switch channels.

1.2.2 Cognitive Radio Wireless Mesh Network

Though the WMNs are promising networking solutions for low cost, quick deployment, ease of maintenance, scalability and reliable services, the performance of a mesh network is still constrained by several limitations. The major hurdle for the network performance is the limited number of available orthogonal frequency channels. As the unlicensed ISM (Industrial, Scientific and Medical radio) bands are most commonly used for backbone communications in WMNs, it is largely affected by all other devices operating on the same ISM band, e.g., nearby WLANs and Bluetooth devices. Moreover, the limited bandwidth of the unlicensed channels cannot accommodate the increased demand of users and applications. However, obtaining additional bandwidth is very difficult. On the other hand, under the current system of licensed spectrum allocation, spectrum bands are assigned to some licensed users or services on a long term basis, which is under-utilized [1], as shown in Fig. 1.2. FCC (Federal Communications Commission) reports indicate that the utilization of assigned spectrum bands range from 15% to 85% [35] in metropolitan areas.

Cognitive radios are proposed as a feasible and promising solution to the frequency

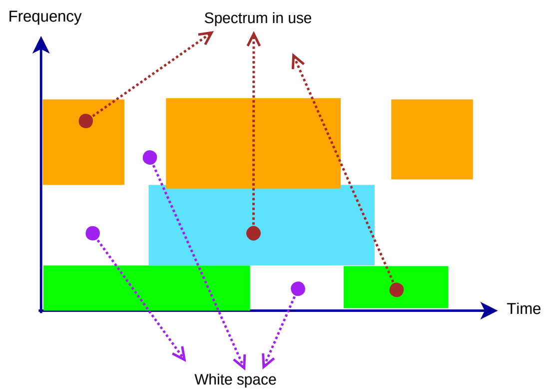


Figure 1.2: Example of spectrum availability [1]

reuse problem [25, 35] in wireless networks. The cognitive radio devices are capable of sensing the environment and opportunistically and dynamically access the licensed spectrum resources. In cognitive radio communication architecture, wireless users are classified into two categories based on whether they are licensed to use a particular spectrum band (primary users) or are unlicensed (secondary users) [25]. Secondary users (SU) employ opportunistic spectrum access (OSA), as long as they do not cause harmful interference to active primary users (PU). This is achievable if PU receivers are far enough from the SU transmitter (spatial channel availability), or no PU receivers are receiving while the SU transmitter is transmitting (temporal channel availability). When a PU occupies a channel, the SU using the same channel must vacate the channel immediately after sensing the arrival of PU. This opportunistic and dynamic communication allows SUs to utilize white spaces in licensed spectrum to retain higher delivery as well as allowing higher spectrum utilization. Thus, in cognitive radio networks, the key challenge is spectrum sharing, which defines the set of rules and strategies that regulate the behavior of SUs regarding spectrum mobility, allocation, and access. In general, the solution strategies for spectrum sharing are classified into two categories: centralized and distributed. For the centralized case, a spectrum management entity is responsible for both spectrum allocation and spectrum access. In a distributed approach, each SU is responsible for the channel allocation and access decisions. The SU may take its decisions based on its local observation of the network and spectrum status or by cooperating with other SUs to have a more global observation.

A cognitive radio wireless mesh network (CR-WMN) is a wireless mesh network (WMN) that deploys cognitive radios to its nodes, and relies on opportunistic and dynamic spectrum access for its operation [36]. The typical architecture of a CR-WMN is shown in Fig. 1.3, where the primary users are co-located with the cognitive mesh routers in the same region. Here, the available spectrum resources mitigate channel contention among the mesh nodes which helps to alleviate congestion by diverting traffic over the available licensed channels.

1.2.3 Applications of Wireless Mesh Networks

Continuous research and development of WMNs is motivated by many promising applications [2, 28, 27], those are discussed in this section.

- **Broadband wireless access:** To provide broadband access to residential users, the service providers use various technologies, such as optic fiber, twisted pairs, coaxial cables, Digital Subscriber Line (DSL), satellite communications, and wireless networks [37]. The used technology greatly depends on specific service provider and location of the users. In urban and sub-urban areas, cable and DSL appear as the most popular technology for broadband access. But, due to their very limited coverage, the service providers refrain from extending wired connections in rural areas. Again, rural areas have limited coverage using wireless technologies like satellite and cellular networks. On the other hand, IEEE 802.11 WLANs exhibit advantages in rural areas over wired counterpart, but one-hop communication results in costly solution. Thus, in order to provide a reliable broadband Internet access solution for rural areas, the deployment of a multi-hop WMN is a promising choice. Besides, because of the low cost deployment and operations of WMNs, free

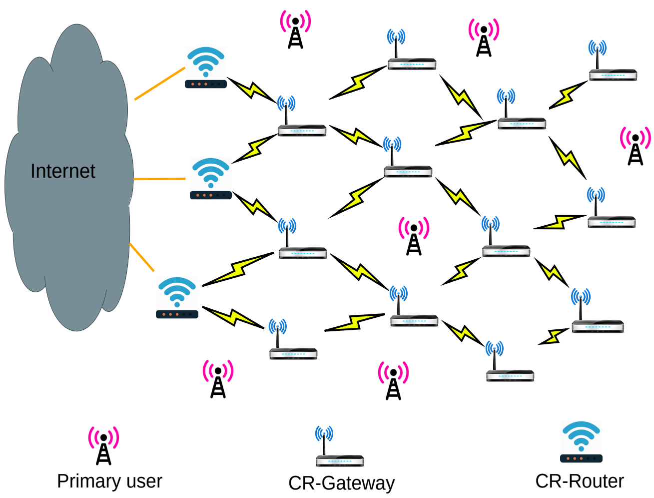


Figure 1.3: CR-WMN architecture

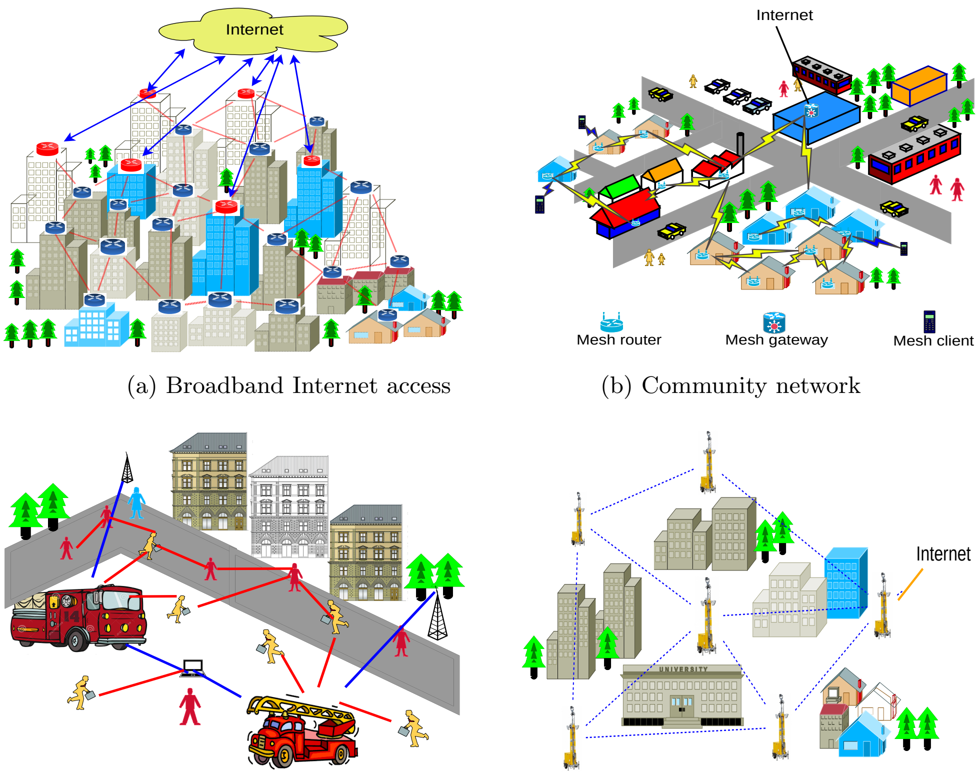
broadband access to city residents is also possible, as shown in Fig 1.4 (a).

- **Community and neighborhood networking:** In a community, the means for network access is based on cable or DSL connected to the Internet. Though a major portion of traffic in the community network remains confined within neighborhood, the use of conventional broadband connection forwards all traffic through the Internet. However, a WMN mitigates the above disadvantages through flexible mesh connectivity between community mesh routers, as shown in Fig 1.4 (b). Also, WMN covers the larger area in between houses through multi-hop communication. Moreover, WMN within a community can also provide many applications such as distributed file storage, distributed file access, and video streaming.

- **Building automation:** Now a days, building functions and applications are controlled electronically and wirelessly. In order to monitor and control electrical devices including power, light, air conditioner, elevator, etc.; the cost and complexity of deploying and maintaining a wired network in building automation is significant. Besides, Wi-Fi networks are another option, which is also unable to achieve satisfactory performance for expensive wiring of Ethernet. Thus, the use of WMNs offers distinctive advantages in the field of commercial and residential building automation [38]. Here, the deployment process is much simpler and installation cost is lower.

- **Health-care:** Monitoring and updating patients' information in a hospital or medical center requires to be online. Patient's history, diagnosis data etc. are needed to be processed and transmitted within the premise for various purposes. Since high resolution medical images and various periodical monitoring information produce a constant and large volume of data, deployment of wireless mesh network may provide higher bandwidth in low cost.

- **Transportation systems:** In order to extend Internet access into buses, plains, ferries, and trains, WMN technology can be used. WMNs also extend services



(a) Broadband Internet access

(b) Community network

(c) Emergency response

(d) Security surveillance system

Figure 1.4: Wireless Mesh Networks applications

toward remote monitoring of vehicles and drivers.

- **Emergency response:** Mesh networks connect nodes directly to each other without passing through any central controller, which can automatically reconfigure themselves according to the availability and proximity of resources. Thus, WMNs constructs promising platform for serving emergency phenomena and natural disaster. For example, wireless networks for an emergency response team and fire fighters do not have in advance knowledge of where the network should be deployed. By simply placing wireless mesh routers in desired locations, a WMN can be quickly established as shown in Fig. 1.4 (c).

- **Security surveillance systems:** As security is turning out to be a very high concern, security surveillance systems became a necessity for enterprise buildings, shopping malls, grocery stores, etc. Robust, high performance, low latency and multi-hop scalability of WMNs enable range, coverage and capacity in security surveillance system. Architecture of such a network is shown in Fig 1.4 (d).

In addition to the above applications, WMNs can also be applied to enterprise networking, metropolitan area networks, P2P communications, etc.

1.3 High Throughput Data Delivery in Mesh Networks

Conventional nodes, e.g., desktops, laptops, hand-held computers, PocketPCs, phones connected to wireless mesh routers [36] and their diversified application usages, has increased the traffic volume in WMNs exponentially [39]. Internet connectivity is now a core feature of those devices due to an increasing demand on any-time and any-where web access either for business or for entertainment and social networking purposes. Network and financial sectors forecast that, in the coming decade, average broadband applications will consume around 5 - 6 times more than what an average is consumed today [40, 41]. Unlike traditional applications, such as email and ftp, these new applications are much more sensitive to delay and loss of packets. Thus, ensuring reliable and timely data delivery in WMNs has emerged as a burning requirement.

1.3.1 Challenges of High-Throughput Data Delivery

Though, a WMN provides a cost effective way of deploying a network and providing broadband Internet access, it faces a number of challenges to ensure mesh clients' Internet access with sufficiently high coverage and throughput.

1.3.1.1 Interference

The main factor that limits data forwarding capacity in mesh networks is link interference, which is the consequence of using a shared communication medium. Also, the limited channel capacity, the large number of users and the emergence of real-time multimedia applications in conjunction with interference worsens network throughput. Using multiple channels instead of a single channel in multi-hop wireless networks has been shown to be able to improve the network throughput dramatically [22]. The IEEE 802.11b standard and IEEE 802.11a standard offer 3 and 12 non-overlapping channels respectively. However, channel assignment presents a challenge because co-located wireless networks are likely to be tuned to the same channels [42]. Again, the underlying CSMA/CA based MAC protocol in WMNs, performs poorly in high contention neighborhood. Besides, deploying multi-radio mesh routers, many approaches have been proposed to increase capacity and flexibility of wireless systems by using directional and smart antennas [2], and MIMO systems [43]. However, these advanced wireless radio technologies require a revolutionary design in higher layer protocols, especially in MAC and routing.

1.3.1.2 Congestion

The traffic in WMNs has a wide range of variations (i.e. bandwidth, jitter, delay jitter sensitive applications) due to its use as the backbone network for accessing Internet. Eventually, traffic variation contributes to channel saturation and may bring up congestion due to contention caused by concurrent transmissions, buffer overflows and time varying wireless channel conditions. As WMN is a multi-hop network, congestion taking place at a single node may diffuse to the whole network and degrade its performance drastically. Besides, since neighboring nodes share the wireless channel, the available transmission capacity at a node can depend on traffic between its neighbors. More precisely, congestion in wireless networks is defined not with respect to a node, but with respect to transmissions from a node to its neighbor [4]. Thus, to improve flow performance, congestion should be handled using mutual cooperation within the neighborhood of the congested link.

WMNs have a relatively stable topology where all the traffic flows either to or from a gateway. As the gateways are responsible for forwarding all the network traffic toward internet, they are likely to become potential bottlenecks in WMNs. The high concentration of traffic at a gateway leads to saturation which in turn can result in packet drops. Moreover, placing and connecting the gateways to the wired backbone affects the network throughput [44]. Thus, to mitigate congestion due to limited capacity of gateways, the traffic load has to be balanced over different gateways.

1.3.1.3 Traffic fluctuation

Recent studies of wireless network traces show that the traffic demand in WMNs, even being aggregated at access points, is highly dynamic and hard to estimate [36, 39]. Such observations have significantly challenged the practicability of the existing optimization-based routing solutions in wireless mesh networks. Traffic fluctuation is regulated by user demand, variation between inbound and outbound traffic and also time of the day/week. Again, the type of applications running over WMNs varies from movie or music file downloads or less-urgent email or file transfers to multimedia and p2p traffic. Also, the aggregated traffic load at each router may significantly deviate from others, due to the intensity of the connected users. The load variation at routers is also location dependent.

1.3.1.4 Dynamic link quality

Compared with the wired Internet, wireless mesh network has to cope with erroneous and dynamic wireless characteristics. The wireless channel is inherently error prone, and the loss rate can be quite high [45]. Wireless channel quality may vary instantly and greatly due to multi-path fading, obstacles, mobile objects, interferences and environmental noise. Therefore, the perceived signal-to-interference ratio (SINR) will change over time that impacts flow performances.

1.3.1.5 Scalability

Multi-hop communication is common in WMNs. In a multi-hop communication network, significant delay occurs at each hop due to queuing delay, contention for the wireless channel and channel error. The delay is therefore a function of the number of communication hops between the source and the gateway. As a typical example, current IEEE 802.11

MAC protocol and its derivatives cannot achieve a reasonable throughput as the number of hops increases to 4 or higher (for 802.11b, the TCP throughput is lower than 1.0 Mbps) [2]. The reason for low scalability is that the end-to-end reliability sharply drops as the scale of the network increases. Therefore, considering the above mentioned hardens, in order to improve flow performances is WMNs, efficient and fair resource allocation is required.

1.4 Traffic Engineering in Wireless Mesh Networks

As the amount of data and criticality of data being carried on WMNs grows, managing network resources to ensure reliable and acceptable performance becomes increasingly important. Furthermore, this should be accomplished while minimizing or deferring costly upgrades. One of the techniques that is being evaluated is Traffic Engineering (TE) [46, 47]. Traffic engineering uses information about the traffic entering and leaving the network to generate a routing scheme that optimizes network performance. Usually, the output of traffic engineering is an optimal set of paths and link loads that produce the best possible performance given the available resources. However, explicitly setting up such paths and (optimally) assigning traffic to them, typically calls for changes to both the routing protocols and the forwarding mechanism they rely on. Thus, the optimal TE solution, which ideally should be simple, fast, and distributed, is a prerequisite for resource and flow performance optimization in WMNs [9, 23].

1.4.1 Traffic Engineering Concerns in WMNs

Traffic engineering in WMNs, envisioned to optimize flow performances, requires to consider underlying network topology, available resources (e.g., radios, channels, node buffer, gateways) and traffic demand. Furthermore, traffic forwarding should act upon network dynamics, e.g., link error, link failure, neighborhood interference, path congestion etc. Thus, in order to design an effective, reliable and fair traffic forwarding mechanism in WMNs, the issues discussed in subsequent sections are required to be addressed.

1.4.1.1 Exploitation of multiple routing paths

In WMNs, mesh routers act as intermediate nodes and forward user traffic to mesh gateways (GWs) in a multi-hop fashion. A WMN with a single GW might create a bottleneck condition and a single point of failure for the network [29]. The use of multiple GWs in a WMN and multi-path data forwarding toward them have been proven to provide better throughput performance [48] since this strategy increases the aggregated bandwidth for certain traffic flow. Thus, the TE mechanism aiming at improving the flow performance in WMNs may exploit link-disjoint or edge-disjoint or mutually interference free or delay/bandwidth guaranteed multiple routes to split traffic.

1.4.1.2 Dynamic selection of link-channel pairs

The path capacity is determined by its constituent link qualities. Given the available resources (e.g. radio, channel, node buffer, gateways etc.), the link capacity is dependent on the contention and congestion present at its neighborhood. The number of concurrently transmitting links on the same channel within an interference range, as well as their traffic load, directly determines the rate achievable over a particular link-channel pair. Thus, flows forwarded over interfered links experience collisions, retransmissions and drops; greatly degrading delivery performance. However, switching links to least interfered and loaded channels helps to improve the attainable link bandwidth. Thus, selection of good quality channels along with the forwarding links, allows optimum traffic performance.

1.4.1.3 Congestion control over routing paths

Bandwidth scarcity is one of the major obstacles, limiting high-throughput data delivery in WMNs [4]. In order to allocate the limited bandwidth resource among the admitted traffic flows in the network fairly and efficiently, one of the primary goals of TE in WMNs is to limit the sustained congestion [2, 4]. A focused congestion may result from unbalanced mapping of traffic flows onto the forwarding paths. Then, means can be activated to distribute the traffic flow in a better way. While forwarding traffic over the selected paths, the rate allocation should be restricted by the bottleneck path capacity. Path capacity varies due to neighboring interference and traffic load, as well as fluctuating link condition [19, 49]. As follows, dynamic rate control mechanism is required at each router while splitting traffic over links [21, 50].

Concerning to mitigate the adverse effect of congestion, a simple and efficient technique is required to disseminate the forwarding capacity of each router (considering link and node congestion) throughout the network. Accordingly, based on the global information and local conditions, each router require an accurate link capacity measurement policy. Finally, the appropriate rates are required to be apportioned over the forwarding links by appropriate MCS [9] selection and power allocation. Here, optimum power allocation improves spatial channel reuse in neighborhood and allows more concurrent transmissions to improve the aggregated network throughput [22, 23].

1.4.1.4 Joint resolution

To maximize flow reliability, while accommodating varying traffic demand and instantaneous network conditions in WMNs, the traffic engineering mechanism is required to schedule link-channel pairs along with rate (or power) allocation over them accounting the neighboring interference and path congestion. Thus, an accurate measurement technique of network's link, channel and load condition; and real-time control mechanism, are the key factors that ensure high-throughput data delivery of an underlined TE mechanism in WMNs. Here, a centralized or distributed control mechanism can be realized [27, 28]. In the centralized schemes, the resource allocation is computed by a central controller, which can introduce a large overhead in the network in terms of both wireless resources consumed by the signaling messages and computational complexity of the centralized algorithms. Whereas in distributed schemes, each node computes traffic forwarding decisions in a less coordinated fashion, through communicating with the neighbors. Though distributed solutions offer sub-optimal resolutions, in large scale wireless mesh networks, they promise scalable solutions.

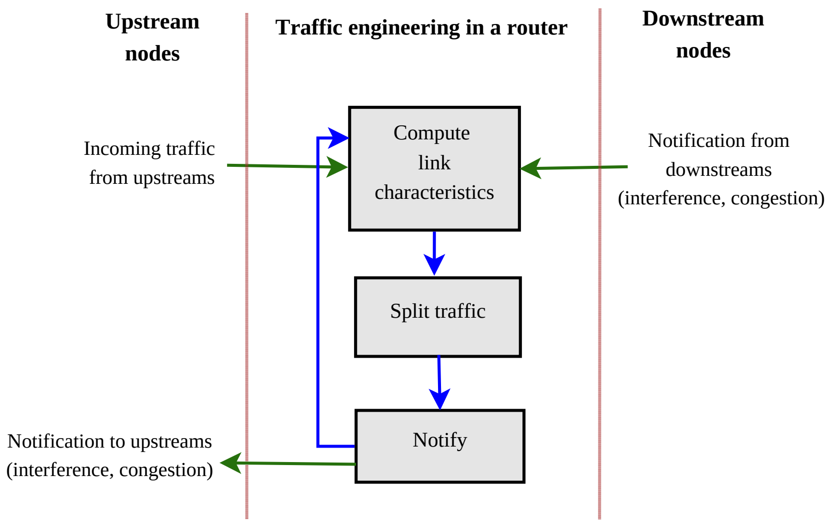


Figure 1.5: Overview of the developed TE mechanism.

1.4.2 Dissertation Problem and Solution Methodology

The problems addressed in this dissertation and their solution methodologies have been briefly introduced in this section.

1.4.2.1 Scope of the work

High-throughput data delivery is an emerging requirement of the many applications in the Internet. As a major portion of data forwarded over the WMN backbone is destined toward the Internet, ensuring stable performance of the exponentially growing application traffic is a great challenge of the underlying traffic forwarding mechanism [36, 39]. Furthermore, resource scarcity and varying changing network conditions pose additional difficulty to reliably transfer data over multi-hop wireless links toward gateways [2, 27]. To optimize flow performances in WMNs, a good number of efficient traffic engineering solutions are studied in the literature [5, 6, 7, 8, 9]. However, the problem of designing a high-throughput and scalable traffic forwarding mechanism to dynamically address network and flow variations while minimizing interference and congestion in large-scale mesh networks, draws little attention. In order to enhance flow performances in a wireless multi-hop network, we need a dynamic traffic engineering that acts on instantaneous network condition by optimally splitting data over high throughput paths. In this thesis, we develop a framework for dynamic traffic engineering in WMNs, with consideration of flow demand and network characteristics. More specifically, we investigate on routing, channel allocation and congestion control for traffic forwarding over multiple paths to distribute load and achieve higher throughput where the mitigation factors are link interference and path congestion. The developed framework employs hop-by-hop distributed traffic forwarding mechanism, where the upstream flow is split over the dynamically selected optimal set of downstreams that maximize flow throughput. Here, the forwarding routers exploit one-hop neighboring information to compute link interference and congestion, and controls the weighted-fair reception of data traffic from its upstream nodes to avoid congestion while maintaining flow fairness as shown in Fig. 1.5. The detail discussion on the development of dynamic traffic engineering solutions through routing and rate control are detailed in Chapter 3. To further enhance flow optimization through intelligent channel allocation, dynamic link-channel selection along with rate control solution is designed in Chapter 4 and an efficient TE mechanism exploiting white space is detailed in Chapter 5.

1.4.2.2 Design goals

The design goals of the proposed Dynamic Traffic Engineering (DTE) mechanism are as follows:

Distributed control. The flow throughput in WMNs greatly varies with network size, node density and network dynamics (i.e. link error, interference, load). Thus, traffic engineering mechanism driven by a centralized controller in a WMN, would increase scheduling delays, cause a single point of failure and might lead to wrong scheduling decisions due to obsolete information usage. To counteract the aforementioned deficiencies, a distributed control agent is required at each forwarding router to determine outgoing link qualities and split traffic over them in a way that can maximize network performance. Our proposed DTE solutions run autonomously at each forwarding router and exploit single-hop neighborhood information only to take traffic forwarding decisions and so make it scalable.

Hop-by-hop multi-path traffic forwarding. In WMNs, mesh routers act as intermediate nodes and forward user traffic to mesh gateways (GWs) in multi-hop fashion. A WMN with a single GW might create a bottleneck condition and a single point of failure for the network [29]. The use of multiple GWs in a WMN and multi-path data forwarding towards them have been proven to provide better throughput performance [48] since this strategy increases the aggregated bandwidth for certain traffic flow. Again, end-to-end traffic forwarding policy in a highly dynamic network environment can't often achieve good throughput. Hence, our proposed DTE mechanism follows hop-by-hop traffic splitting approach to forward its upstream traffic over least-congested and minimally-interfered link-channel pairs to improve overall network throughput.

Simple and efficient congestion and interference measurement techniques. The traffic in WMNs has a wide range of variations (i.e. bandwidth, jitter, delay jitter sensitive applications) due to its use as the backbone network for accessing Internet. Eventually, traffic variation contributes to channel saturation and may bring up congestion due to contention caused by concurrent transmission, buffer overflows and time varying wireless channel condition. As WMN is a multi-hop network, the impact of interference and congestion taking place at a single node may diffuse to the whole network and degrade its performance drastically. Thus, the accurate and timely measurement of interference and congestion is required to take optimal traffic forwarding decisions so as to achieve better network throughput. Hence, we devise a simple back-pressure based mechanism that transmits control message to one-hop neighbors periodically to diffuse node and link congestion status in the network. The DTE also learns neighborhood interference and channel quality through local monitoring and one-hop communication.

Congestion and interference aware traffic forwarding. To achieve high-throughput data delivery, traffic engineering in WMNs as required to act upon interference and congestion. Our proposed DTE enables routers, at each hop, to select outgoing links offering higher data rates and reduced interferences. While computing resource allocation for flows, priority is given to good quality forwarding links that require less power allocation to achieve the required rate, minimizing interference as well as congestion. Thus, the DTE emphasizes improving spatial reuse in neighborhood through reduced power allocation over each feasible outgoing links and hence it contributes to boosting the overall network throughput.

Weighted fair rate control To avoid congestion collapse in network due to exhaustive traffic demand, the proposed DTE policy necessitates dynamic adjustment of the data rates over the designated downstream links often taking into account the downstream nodes forwarding capabilities. Here, each router takes the responsibility of regulating upstream traffic rates in proportion to upstream's demand and its forwarding capacity.

1.4.2.3 Formulation of optimization framework

Traffic engineering in WMN poses challenges that necessitates novel modeling and optimization concepts to account for: (i) transmission scheduling on links realized by the MAC layer using CSMA, (ii) need of a dynamic channel assignment mechanism in multi-channel WMNs, (iii) transmission power control for interference mitigation, (iv) rate control on transmitting links considering the interference and load conditions, and (v) uncertain traffic demand to be routed between WMN routers and gateways. In this thesis, we propose mixed-integer non-linear programming (MINLP) optimization framework and algorithms for dynamic traffic engineering in WMNs with the aim to maximize flow throughput while minimizing congestion and interference in the network, taking into account routing, channel assignment, and rate (or power) control.

1.4.2.4 Development of scalable solutions

The traffic engineering optimization frameworks in WMNs are unable to provide an optimum solution within polynomial time due to the NP-hardness nature of the MINLP problems. Thus, to instantaneously and efficiently react on flow and network dynamics, we devised greedy heuristic suboptimal traffic engineering solutions that are practically employable in WMNs.

1.5 Thesis Contributions

In this thesis, we address the dynamic traffic engineering problems in WMNs, especially for large networks with multi radio and multi channel environment, for high-throughput data delivery under three different network architectures - with fixed channel assigned over radio interfaces, employing dynamic channel allocation over radio interfaces and finally, exploiting cognitive radio interfaces to opportunistically and dynamically utilize the licensed spectrum resources.

1.5.1 Routing and Rate Control in Fixed Channel Wireless Mesh Networks

The first contribution of this dissertation is to develop an optimization framework for Dynamic Traffic Engineering (O-DTE) in WMNs that aims to minimize the interference and congestion at each hop through joint power and rate control so as to achieve high-throughput data delivery. Due to NP-hardness of the O-DTE framework, we then develop a greedy heuristic alternate solution (G-DTE) that enables routers, at each hop, to select outgoing links offering higher data rates and reduced interferences. Thus, the proposed G-DTE produces near optimal results by taking multi-path data forwarding decisions in a distributed fashion; it exploits single-hop neighborhood information only and thus it is scalable. The simulation results, carried out in ns-3 [51], demonstrate that the proposed G-DTE significantly outperforms the state-of-the-art works in terms of throughput, delay, reliability and fairness performances.

1.5.2 Dynamic Link-Channel Selection and Rate Control

The key challenges of high-throughput data delivery in multi-radio multi-channel WMNs are fluctuating channel conditions, dynamic traffic flows, co-channel interferences and congestion. Thus, our second contribution of this dissertation is to formulate a MINLP optimization framework that chooses, at each router, a number of outgoing link-channel pairs and allocates power(s) on those so that the routers total outgoing flow rate is maximized while the interference and the congestion are kept at minimum level. Due to the NP-hardness of this optimal solution, we then develop a greedy heuristic method that separates the joint problem into two sub-problems, greedily chooses the high-performing link-channel pairs and heuristically goes either for increasing power levels on the best link-channel pairs or utilizing more pairs at minimum power. Finally, our simulation results show that the proposed system outperforms the state-of-the-art works in terms of throughput, delay fairness and convergence.

1.5.3 Dynamic Traffic Engineering in Cognitive Radio Mesh Networks

The third contribution is to investigate traffic engineering methods in CR-WMNs through joint selection of link-channel pairs at each forwarding router and allocating powers on those so as to boost up overall network throughput. We first present an optimization framework, Centralized Optimal Traffic Engineering (COTE), aiming at maximizing aggregated network throughput by selecting optimal set of link-channel pairs, power allocation over those and fair traffic splitting. Further, a centralized Suboptimal Traffic Engineering (SOTE) solution is proposed by employing Lagrangian dual decomposition on the COTE problem, to ensure a resolution in polynomial time. Finally, a Distributed Greedy Traffic Engineering (DGTE) method is proposed to ensure fast convergence to the dynamic changing network behavior and to improve scalability. Extensive simulation results are presented to demonstrate the effectiveness of our proposed TE mechanisms compared to the state-of-the-art works.

1.6 Thesis Organization

The outline of the thesis is as follows. In Chapter 2, we overview state-of-the-art traffic engineering solutions in wireless mesh networks and discuss on the motivation of this work. In Chapter 3, we develop a traffic engineering solution exploiting rate control over routing. The joint path selection, channel allocation and congestion control framework is presented in Chapter 4. Further, improvement in traffic throughput is explored through exploiting white space opportunistically in Chapter 5. Finally, we conclude the thesis in Chapter 6 by summarizing the findings in the thesis and describing avenues of possible extensions to this work.

Chapter 2

State-of-the-art Works

2.1 Introduction

Wireless Mesh Networks (WMNs) are envisaged to extend Internet access and other networking services in personal, home, local, campus, and metropolitan areas. Recently, there has been an explosion of wireless devices, and traffic volume has been grown exponentially due to the availability of high speed networks, more powerful mobile devices (smart phones, tablets), emerging applications and networks. The number of wireless devices and traffic is expected to keep growing rapidly in the coming years [3], imposing the need for greater capacity and throughput in the network. In order to ensure high throughput data delivery of WMN traffic, different strategies in the literature have emerged at different operational layers of the network architecture, ranging from channel assignment [15, 17, 52, 53] and congestion control [4, 19, 21, 54], to routing [10, 13, 48, 55].

The path selection in network layer is motivated to improve flow performance considering link/path quality [10, 14, 56], dynamic link conditions [10, 11, 57] and path capacity [12, 13]. To allow more concurrent flow transmissions over forwarding links, dynamic channel allocation strategies are employed to maximize network connectivity [58], minimize link/path interference [17, 18, 52] and enhance path throughput [15, 52, 59], being either traffic-independent [15, 58] or traffic-aware [60, 61]. Further, in order to maximize flow throughput over the forwarding paths, congestion is mitigated through incorporating many hop-by-hop [4, 21, 50] and end-to-end congestion control approaches [19, 20, 62], by measuring effective link/path bandwidth considering link quality, interference, load and traffic demand.

Next, considering the inter-dependency among routing, channel allocation and congestion control to enhance the flow performances in WMNs, researchers envisioned cross-layer solutions. As the characteristics of a wireless link greatly depends on the chosen transmission rate, routing and congestion control problems are solved jointly in literature [5, 6, 63]. However, despite of all these joint efforts, high-throughput data delivery is still a challenge in WMNs supporting large number of nodes in close proximity due to bandwidth scarcity. This problem can be alleviated by the cognitive radio paradigm that relies on opportunistic and dynamic access to frequencies other than those in the 2.4GHz ISM band [24, 25]. Many approaches in the state-of-the-art works put directions on efficient opportunistic spectrum allocation (OSA) techniques to minimize interference over licensed channels and ensure certain effective link capacity [64, 65, 66].

In this Chapter, the state-of-the-art works on flow performance improvement in WMNs have been scrutinized as being centralized or distributed, employing single-path or multi-path forwarding mechanism, applying end-to-end or hop-by-hop solution and incorporating dynamic flow behavior or not; and listed in Table 2.1, Table 2.2, Table 2.3 and Table 2.4.

The organization of the subsequent sections in this Chapter are organized as follows. In Section 2.2, we discuss on different routing algorithms. Section 2.3 examines state-of-the-art congestion control mechanisms to enhance network throughput under higher traffic demand. To fully capitalize the bandwidth offered by MRMC WMNs, a good number of dynamic channel allocation mechanisms are highlighted in Section 2.4. To optimize the flow performance through optimal resource allocations, cross-layer traffic forwarding solutions are brought into light in Section 2.5. Implementation of cognitive radios in mesh nodes provides the opportunity to attain higher bandwidth for application traffic in WMNs. Section 2.6 depicts the promising efforts that has been proposed in literature to utilize white space to boost up flow performances drastically in CR-WMNs. Finally, we summarize this Chapter in Section 2.7.

2.2 Routing in Wireless Mesh Networks

Given a wide range of scenarios where WMNs can be deployed, a lot of research contributions have been made to study and design efficient routing algorithms for WMNs.

There are several link-quality based routing metrics proposed in the state-of-the-art works. The metric Expected Transmission Count, ETX [56], computes the expected number of transmissions (including retransmissions) needed to send a packet over a link, by measuring the forward and reverse Packet Delivery Ratios (PDR) between a pair of neighboring nodes. The Expected Transmission Time metric, ETT [10], of a given link is defined as the expected time to send a 1500-byte packet at the rate that yields the highest throughput on that link. The metric Expected Number of Transmissions On a Path, ETOP [14], accounts for the finite number of retransmission attempts at the link layer.

2.2.1 Single-path Routing

A good routing metric should find paths constituting links that have low loss ratio, high data rate and experience least interference. Several research proposals incorporate varying interferences experienced by a link into the routing metric to find good quality paths. Authors in [10], propose a path metric, called Weighted Cumulative Expected Transmission Time (WCETT), which explicitly accounts for the interference among links using the same channel. The Metric of Interference and Channel switching, MIC [57], incorporates both interflow and intra-flow interferences in path metric.

Works on [13] and [12] focus on computing the achievable bandwidth when both inter and intra-flow interferences are present. Expected End-to-end Delay (EED) proposed in [13], monitors the transmission failure probability to estimate the transmission delay, and counts the number of packets waiting in the buffer to estimate the queuing delay. EED is then integrated with a path metric called Multi-radio Achievable Bandwidth (MRAB) to accurately capture the impact of inter and intra-flow interference along a path. [67] proposes a new routing metric EFT (Expected Forwarding time) for HWMP

(Hybrid Wireless Mesh Protocol)(IEEE 802.11s Task Group, 2008), where a forwarding node needs to estimate its queuing delay, number of retransmissions, expected duration of idle slots during backoff intervals, defer time due to contention with high priority traffic and neighboring conditions (e.g., density, loads, transmission rates and packet sizes of neighboring nodes).

2.2.2 Multi-path Routing

Limited and fluctuating bandwidth of wireless links, neighboring interference, congestion and reliability issues due to link error, are the key challenges a WMN faces while forwarding traffic. Multi-path routing can address these challenges and provide several benefits such as bandwidth aggregation, load balancing, optimal resource utilization and high fault-tolerance through forwarding traffic over parallel paths toward destinations. In this Section, we list the existing multi-path routing algorithms for WMNs.

In [48] and [55], traffic is forwarded over node or link disjoint multiple paths without considering path condition (interference, contention etc.) and path capacity (available bandwidth). Multi-path Refinement Algorithm, MRA [48], is a distributed approach that aims to find multiple mutually non interfering paths between each source destination pair exploiting single hop information. Here, a path graph, consisting of a set of available paths between each source-destination pair, is computed using any of the existing multi-path routing algorithms. From this graph, an interference graph is obtained that has an edge between nodes, where each node represents a path in the path graph, if they interfere with each other by sharing a common edge or an interfering edge. Finally, the maximum weighted independent sets from the interference graph is obtained which holds the desired set of least interfered paths between the source-destination pair. However, when number of nodes in a WMN increases, the number of multiple paths is also increased. So, finding maximum independent sets from interference graph becomes infeasible and thus increases computational overhead. Also, mutual non interfering paths do not necessarily lead to less interfered and congested paths. Again, traffic splitting over the computed paths do not react to dynamic congestion and condition of the network and thus degrading flow throughput.

2.3 Congestion Control in Wireless Mesh Networks

WMN is a promising wireless technology for numerous applications, e.g., broadband internet access, community and neighborhood networks, enterprise networking, building automation, etc [2]. The traffic in WMNs has a wide range of variations (i.e. bandwidth, jitter, delay jitter sensitive applications) due to its use as the backbone network for accessing Internet. Eventually, traffic variation contributes to channel saturation and may bring up congestion due to contention caused by concurrent transmission, buffer overflows and time varying wireless channel condition. As WMN is a multi-hop network, congestion taking place at a single node may diffuse to the whole network and degrade its performance drastically. Therefore, congestion control is a crucial issue for WMNs. Congestion control mechanism is responsible for preventing the occurrence of congestion, as well as for alleviating the impact of congestion on network if it occurs. Also, congestion control scheme should ensure a fair distribution of resources among contending nodes.

In the Internet, congestion has been resolved by applying end-to-end congestion control algorithm, i.e. Transmission Control Protocol (TCP). However, it has been reported that TCP does not perform well in a multi hop wireless environment [68], which usually results in inefficient and unfair bandwidth allocation among different flows. One of the well known reasons for TCP performance degradation is that traditional TCP assumes that the packet loss happens only due to the congestion in the network. However, this assumption may not be true in wireless networks, since the packet loss also happens due to erroneous wireless characteristics, MAC contentions, unstable network conditions and mobility of nodes. As TCP assumes all losses indicate congestion, when non congestion packet losses occur in wireless networks, besides retransmitting the lost packet, TCP also reduces its transmission rate as a result the network throughput drops quickly. Moreover once wireless channels are back to the normal operation, the classical TCP cannot be recovered quickly. Also an end-to-end congestion and rate control is inappropriate for wireless mesh networks, because it suffers from the adverse effects of multi-hop wireless environments, such as variable Round Trip Times (RTT), high Bit Error Rate (BER) and radio interferences. Here hop-by-hop schemes result in better performance than a corresponding end-to-end scheme by reacting to network congestion faster than end-to-end mechanisms. Besides TCP, many applications in internet such as audio and video streaming use User Datagram Protocol (UDP) as a transport protocol, since they require timely delivery of data rather than reliable transmission. As UDP protocol injects traffic into the network without seeking any feedback regarding the capacity of the network, more packets get collided and congestion situation gets worse. Coexistence of real time and non-real time traffic may direct the situation even worse. Therefore, to avoid congestion, WMN requires an effective congestion control protocol which is capable of avoiding/controlling congestion, while assigning rates to flows.

In recent publications, several approaches for congestion control in wireless multi-hop networks have been proposed. So far, there are two different types of approaches for congestion control in the existing literature: end-to-end congestion and hop-by-hop congestion control.

2.3.1 End-to-end Approach

A considerable amount of research has been performed on improving the throughput of TCP for wireless environment. These works attempt to improve wireless TCP throughput by distinguishing the packet loss due to congestion and link failure. We have articulated the pros and cons of the above mentioned technique in the following: A lot of work has been done focusing the area of TCP enhancement where TCP responds to special wireless characteristics. To discern between congestion and non congestion losses in multihop wireless networks several variants of TCP such as TCP ELFN (Explicit Link Failure Notification) [68], TCP Feedback [69] and TCP-Bus [70] were proposed. Upon detection of a route failure event by the network layer, these protocols ceases further packet transmission until the route recovery. In [62], a TCP enhancement called Congestion Coherence for WMN, has been proposed which distinguishes congestion losses from transmission errors and multi-path reordering based on ECN (Explicit Congestion Notification) marking by intermediate routers and thus reduces false retransmission, timeouts, unnecessary congestion window reductions, and thus provides improvements than existing wireless TCP enhancements.

A good number of end-to-end rate based congestion control protocols has been discussed in literature, where the rate of the source node is regulated by its destination. Here each intermediate node in the network estimates the available bandwidth at the node and attaches the information with all forwarding packets. Upon receiving these packets, the receiver calculates the allowable bandwidth on the path and notifies the source through acknowledgement. In Explicit Link Failure Notification, LRTP [20], each intermediate node measures the effective bandwidth of each of its wireless link, fairly allocates it among the flows going through it and the sender adjusts their sending rates based on the minimum allocation across all the hops. Since, WMN nodes in the proposed architecture run the LRTP protocol and the end user mobile nodes and the nodes in the wired network runs TCP, in LRTP each ingress/egress WMN node has to employ a TCP-LRTP proxy. LRTP protocol also suffers from unfair channel sharing problem as when an intermediate node allocates channel bandwidth among the input flows, it does not consider the interference relationship among the neighboring nodes and the number of flows going over them. WCP (Wireless Control Protocol) [19] is an AIMD (Additive Increase Multiplicative Decrease) based rate-control protocol which explicitly reacts to congestion within a neighborhood. On congestion at a link, WCP signals all flows traversing the neighborhood of that link, to multiplicatively reduce its rate by half. The main difference with TCP is that congestion is signaled to all flows traversing the neighborhood of a congested link. In EWCCP (Explicit Wireless Congestion Control Protocol) [49], the intermediate routers calculate the congestion feedback based on the size of the neighborhood queue on each wireless link and adds feedback in the congestion header of the packet. When the packet arrives at the receiver, the feedback field in the congestion header holds the sum of all feedbacks given by all wireless links along the path. The aggregated congestion feedback is echoed back to the sender with an acknowledgement from the receiver. [71] introduces Mesh Adaptive Pacing, MAP, which operates at the wireless TCP source as well as at the mesh gateway, and transmits TCP packets by adapting the transmission rate according to the current network state. MAP identifies the current load in the neighborhood by measuring the current level of contention by means of the coefficient of variation of recently measured round trip times and also accounts for the spatial reuse constraint of IEEE 802.11 mesh networks by measuring Out-of-Interference Delay (OID) as the time elapsed between transmitting a TCP packet by the TCP source node and receiving the packet at a hidden terminal. In [62], when a router's queue length exceeds a threshold, the router stamps every incoming packet with a ECN (Early Congestion Notification) bit set. With ECN, when a packet is dropped by a congested router, the ECN congestion signal carried by that packet is lost, but packets before and after the lost packet maintain coherent congestion information. A packet loss is considered as a congestion loss if any packet in its coherence context is marked. In this case, the receiver responds with duplicate ACKs to trigger an end-to-end retransmission and window reduction at the source. [72] devise a neural network based congestion control technique, where competing flows are treated independently and fairness is not addressed.

2.3.2 Hop-by-hop Approach

In hop-by-hop congestion control mechanism, local feedback on the sustainable capacity at each node is transmitted to the respective upstream node, in order to establish some kind of backpressure towards the source. Simple and Effective Congestion Control, SECC [50], uses local information available at nodes to detect congestion, computes target rate for the congested flows, notifies upstream nodes the target rates and finally upstream nodes modifies 802.11e channel access parameters to adjust the their MAC transmission rates. SECC outperforms TCP in wireless networks due to reacting to dynamic wireless conditions and neighborhood congestion instantly. However, congestion control in one part of the network may cause congestion in other parts of the network. Additionally, this approach uses explicit feedback to the upstream nodes that imposes feedback traffic on the network. In Adaptive and Responsive Transport Protocol, AR-TP [73], the router calculates the rates for the flows passing through it based on two different threshold levels of router buffer and employs a back-pressure mechanism to notify the upstreams regarding rate adaptation and also asks the downstreams to allow the congested node to increase the sending rate through a forward threshold adaptation technique. In order to mitigate congestion in one part of the network, AR-TP may introduce congestion on the other parts of the network. By using the forward threshold adaptation mechanism, a node may release its own congestion, but introduce congestion in its downstream nodes. Link Layer Adaptive Pacing scheme, LLAP [21], scheme tries to reduce the MAC contention in the network by properly scheduling the packets at the source node. In LLAP, the four hop transmission delay in a path is estimated by measuring the queuing and transmission delay incurred at the bottleneck node in a distributed manner and accordingly packets are paced for transmissions to reduce self contention. In Congestion Aware Fair Rate Control, CFRC [74], a link is considered to be congested when the average queue size of the link exceeda a predefined threshold. Links that route their traffic via the same bottleneck link synchronize their rate updates, which are enforced through rate-bounded backpressure sent by the bottleneck node to all links that use the bottleneck link to forward their packets. However, if the links obtain the rates based on their respective downstream bottleneck links, flows using different bottleneck regions might achieve different throughput. To avoid congestion, NICC (Neighborhood-Aware and Overhead-Free Congestion Control) [4] scheme addresses neighborhood congestion and proposes a overhead free congestion control mechanism that aims at realizing an efficient and fair bandwidth allocation in WMNs. NICC anticipated congestion by predicting the future queue length through analyzing its evolution using a fuzzy-based controller. The severity of congestion level is notified to the neighboring nodes by multi-bit congestion feedback using under-exploited fields in the 802.11 frames header. Finally, the rate control is performed at source nodes using an enhanced AIMD algorithm, where the degree of rate reduction is proportional to the congestion severity level reported by the congestion notification. [54] discusses the role of buffer sizes in reducing queueing delays in wireless mesh networks. The proposed work aims to distribute the neighborhood buffer among the bottleneck contention neighborhood to maximize bottleneck utilization. In [75], authors propose a gateway controlled centralized scheduling mechanism for managing flow rates to avoid congestion and improve fairness between network flows.

2.4 Dynamic Channel Allocation in Mesh Networks

At the early age, mesh nodes in WMNs followed conventional wireless network standards through being equipped with only one radio per node that operated over either a shared channel or a set of orthogonal channels. In this design, end-to-end data flow experiences substantial interference from ongoing transmission of both nearby simultaneous flows and nearby hops of the same flow. Therefore, a new architecture exploiting multiple radios on each node, having multiple available channels, has come to light. This architecture is commonly termed as multi-radio WMNs. It alleviates the interference problem, which exists in the single-radio architecture, to a great extent through the introduction of multiple channels over the radios available on a single mesh node. Moreover, it extends its usability by enabling simultaneous transmission and reception exploiting the multiple radios from a single mesh node. Therefore, the multi-radio architecture becomes a popular networking paradigm in recent times. However, the channel assignment techniques, which were originally proposed for single-radio WMNs, cannot be directly adopted in the multi-radio cases due to interference, channel diversity, channel switching etc. Therefore, a number of different channel assignment techniques for multi-radio WMNs have been proposed in the literature

There have been many studies on how to assign limited channels to network interfaces in a multi-radio multi-channel wireless mesh network so as to minimize interference and maximize throughput. Two basic channel allocation strategies have been studied: 1) static channel allocation, where interfaces are assigned channels permanently and 2) dynamic channel allocation, where interfaces are allowed to switch to different channels. Again, considering the diversified application running over WMNs, channel allocation over the forwarding links might be load independent or aware, which we investigate in following Sections.

2.4.1 Traffic-independent Allocation

In WMNs, each router is shown to contain a stable average traffic load over time [58]. So assuming known traffic profile in the network, authors in [58] proposes a centralized channel assignment strategy based on Tabu search technique that preserve the original network topology. They also proposed a distributed quasi static channel assignment technique based on the greedy approximation algorithm for the Max K-cut problem in graphs. The centralized and traffic-independent static channel assignment approach, Centralized Channel Assignment Algorithm, CLICA [17], greedily assigns channels to higher priority links aiming to form a connected topology following the protocol interference model that exhibits minimum neighborhood interference. However, CLICA has a limitation of only considering the probable interfering edges, not the actual interfering edges. Besides, it does not model all available radios altogether. In addition, its local greedy choice during the channel assignment may trap a local optima. Moreover, it totally ignores external interference, traffic load, queuing delay, and environmental effects.

NSGA-II (Non-dominated Sorting Genetic Algorithm) [18] is a centralized channel allocation algorithm, that attempts to maximize network connectivity while minimizing network interference. This technique adopts a genetic representation in which each gene represents a channel state. The proposed algorithm utilizes a ranking-based fitness function and uses a circular two-point crossover with a deletion operator as the recombination operator. For mutation, it exploits inversion variation based methods. NSGA-II based channel assignment techniques ensure connectivity while exhibiting very fast convergence rate. However, this technique ignore external interference, traffic load, and environmental effects.

Topology-controlled Interference-aware Channel-assignment Algorithm, TICA [52], is a centralized technique that builds a network connectivity graph by selecting the nearest neighbor for each node in the network, considering the notion of power control to minimize interference among mesh nodes. Next, a Shortest Path Tree (SPT) is built based on the connectivity graph, considering the minimum power to be the path selection metric. Next, the gateway calculates the rank of each link in the Minimum Power SPT (MP-SPT) based on the number of nodes that use a particular link to reach the gateway. In the second phase, TICA assigns a channel to each link of the MPSPT according to its rank. An improved version of TICA, Enhanced TICA (e-TICA) is also proposed here to encounter the hidden link problem, resulting in a more accurate and fair channel assignment. However, scalability remains a major issue as both the graph coloring and MST problems are NP-complete [52]. Besides, in both TICA and its improved versions, external interference, traffic load, queuing delay, and environmental effects are completely ignored.

2.4.2 Traffic-aware Allocation

Considering the elastic and bursty traffic nature of WMNs, several researchers opt to consider traffic-dependent channel reallocation. Studies in [15] assumed statistical traffic profile putting emphasize on flows originating from gateway to users. In their proposed technique, first a load-balanced routing tree is constructed from the original network architecture, and then a distributed load-aware algorithm assigns channels to the links on the tree. In [60], nodes organize their traffic transmission in different time slots through link layer synchronization which enables them to transmit without any contention. Here channels are reallocated and links are rescheduled according to changing traffic demand. In GNOC [53], a fuzzy control module monitors traffic load and interference on channels to deduce a dynamic threshold value for channel switching. The GNOC procedure is responsible for finding the appropriate channel to be switched to. The proposed balanced controlling model is used to make the decision of the switch and the enhanced routing agent is used for the channel switch scheduler. Authors in [61] proposed a heuristic Clustered Channel Assignment Scheme (CCAS) for fulfilling dynamically changing traffic demand while minimizing link/traffic disruption. Here, a centralized agent collects the traffic profiles from mesh nodes to compute the channel reassignment and link scheduling, which in turn incurs a great volume of control traffic in the network. Thus, the increased operational overhead of CCAS, limits the flow performances in WMNs.

A traffic-aware channel assignment approach proposed in [76], aims to re-configure the channels on a subset of radios to minimize the disruption in the network operations. In the first stage, a resource-minimized traffic-independent (TI) channel assignment provides basic network connectivity with limited interference by using minimum number of radios. In the second stage a traffic-driven (TD) assignment is devised, where the conserved radios are dynamically assigned in response to traffic demand to maximize flow rates. As traffic conditions change, the TD assignments are re-optimized for current traffic conditions while the TI component remaining unchanged. A static channel allocation technique proposed in MCCA (Multi-radio Centralized Channel Allocation) [59] attempts to increase network throughput by minimizing interference among links carrying higher traffic load. However, the channel assignment following the prioritization may adversely affect the network throughput. Besides, it does not consider external interference and environmental effects.

2.5 Cross Layer Design Optimization

To optimize the performances of a Wireless Mesh Network, MAC, routing, and transport protocols need to work collaboratively among themselves [2]. Such interactions demand a cross-layer design among different protocols.

2.5.1 Routing and Congestion Control

Recently WMNs have emerged as a promising networking solution mostly due to its low cost of deployment and maintenance. To provide a low cost solution, WMNs usually deploy routers based on the IEEE 802.11 standard. These devices allow multiple transmission rates, varying from 1 Mbps to 54 Mbps. Therefore, selecting the most suitable transmission rate over a link is essential, since there is a trade-off between link capacity and transmission rate. The achievable link capacity depends on the SINR (Signal to Interference and Noise Ratio) condition of a link. Again, considering the same link condition, Packet Error Rate (PER) increases with the transmission rate, as lower rates tend to use more robust modulations and code rates. Moreover, to avoid congestion, rate selection should also consider the forwarding capacities of the corresponding downstream nodes. Besides, to address network dynamics (e.g., link conditions, congestion), WMN nodes should implement a dynamic route selection mechanism. It is important to notice that these two problems - automatic rate adaptation and path selection, are strongly related. However, due to this strong dependency, mechanisms based on joint approach for solving these two important problems in WMNs, have been widely studied in the literature that we discuss next.

2.5.1.1 Single-path forwarding

The distributed cross layer approach, Metric Aware Rate Adaptation mechanism, MARA [77], has two major components: (i) routing - which evaluates and assign costs for network links, and (ii) rate adaptation - which chooses the most suitable transmission rate for each link. These two components share information and make coordinated decisions. MARA targets to compute the rate that minimizes the link transmission delay (ETX [56]), considering the average number of transmissions. To know the value of ETX for link in every available transmission rate, the average SNR of the link is estimated using the information provided by probe packets. Using the historical data, the estimated average SNR value is mapped into equivalent link success probability which in turn can compute ETX for each rate. Here, only considering link interference while computing link cost limits MARA to react to dynamic network congestion.

ETM (Expected Transmission cost in Multi-rate wireless networks) [11] routing metric captures hop count, link rates, success probability and link position along the routing path. Considering packet drops closer to the destination are expensive in terms of re-transmission cost, ETM-based rate adaptation algorithm tunes the rate dynamically that ensures less aggressive rate increase on those links.

2.5.1.2 Multi-path forwarding

In [63], a joint Routing and Admission Control Protocol (MRAC) distributively computes parallel, node-disjoint, high-capacity multiple paths towards destination. Here, each node computes link available bandwidth though measuring packet transmission delay, which accounts queue waiting time, MAC contention and channel error. Thus, sharing the link bandwidth information with 2-hop neighbors, allow each node to compute the effective link capacity considering the neighboring contention and congestion. While path computation, source node broadcasts a Route Request (RREQ) packet along with its traffic demand. Each node (except the destination) appends the current load and the bandwidth information to the partial path in the RREQ packet and rebroadcasts it. Finally, destination selects paths with higher capacities and notifies source using Route Reply (RREP) message. However, as MRAC considers flow demand to be stable and known, this assumption is unrealistic. Also, the aforementioned work does not react dynamically to any changes in network condition. Therefore, a control mechanism is required to adjust the traffic forwarding decisions following the dynamic behavior of the network.

The joint centralized Multi-path Routing and Rate Allocation, MRRA [78] uses two efficient heuristic path discovery algorithms - Iterative Path Discovery (IPD) and Parallel Path Discovery (PPD), to compute edge-disjoint parallel paths toward destination that experience minimum interference and WCETT [10]. Afterwards, a joint Max-Min Linear Programming (LP) problem is formulated to selects those paths that maximize the capacity of the bottleneck link (or minimize the network congestion). In order to obtain a solution in polynomial time, later it is transformed to a general LP problem which is approximated by a binary search technique. As the WMN has fixed architecture; router position, channel allocation etc. are known to all nodes in the network and periodic updates of available link bandwidth information helps each router to compute path bandwidth. However, due to arrivals of random traffic bursts, information regarding path bandwidth soon becomes obsolete, degrading congestion. Again, it causes excessive signalling overhead for disseminating link information and it does not respond to changes

Table 2.1: A comparison of routing and rate control techniques in WMNs.

Technique	Centralized	Distributed	Single Path	Multi Path	Hop-by-Hop	End-to-End	Fixed Traffic	Dynamic Traffic
MARA [77]	✗	✓	✓	✗	✓	✗	✓	✗
ETM [11]	✗	✓	✓	✗	✗	✓	✓	✗
MRAC [63]	✗	✓	✗	✓	✗	✓	✓	✗
MRRA [78]	✓	✗	✗	✓	✗	✓	✓	✗
MRT [5]	✓	✗	✗	✓	✗	✓	✗	✗
CLC_DGS [6]	✓	✗	✗	✓	✓	✗	✗	✓

in the network environment.

The centralized approach, Maximum Multi-path Routing Throughput, MRT [5], aims at maximizing the end-to-end throughput between source-destination pairs in WMNs by scheduling collision free transmission over multiple paths. To add multiple paths, MRT uses exhaustive search with intelligent pruning technique, as long as the aggregated path throughput is maximized. The data rate on each path is determined by the bottleneck link's effective capacity on the path. Here, static traffic splitting is unable to findoptimal resource scheduling under dynamic variations in traffic demand and path capacities. Again, MRT is highly unfair for newly admitted flows when the network is highly loaded.

In order to balance traffic toward multiple gateways, a joint traffic splitting, rate control, routing and scheduling algorithm (CLC_DGS) is developed in [6]. Here network utility is maximized while prioritizing delay sensitive traffic. Each router optimally apportions the traffic of a flow over multiple paths leading toward multiple least congested gateways. Here, a centralized controller schedules collision free transmissions for links having maximum differential backlogged traffic. The employment of a centralized controller can increase the scheduling delay and the decisions often may be taken based on obsolete data related to traffic flows and queue occupancy status.

2.5.2 Routing and Channel Allocation

With the development of advanced radio technologies, multi-radio multi-channel functionalities at each node is able to enhance network performance in WMNs. In MRMC WMNs, each node has multiple radio interfaces, where each radio interfaces on nodes may transmit simultaneously with other neighboring nodes, if they are allocated orthogonal frequency channels. In SRSC WMNs, channel assignment is simple and routing does not need to consider the channel state because all nodes use the same channel. However in MRMC WMNs, the channel assignment algorithm needs to allocate different channels to the radios at a node and additionally must select channel for each link in the path through the routing process. Therefore, the protocols in MRMC WMNs need more sophistication to regulate the spatial resources and optimize network performance. Otherwise, WMNs may perform poorly due to inefficient utilization of the multiple available channels. Many joint efforts on routing and channel assignment in MRMC WMNs have been reported in the literature, which we discuss in this Section in terms of the control strategy they employ - centralized or distributed.

2.5.2.1 Centralized control

Authors in [42] propose centralized Traffic-Independent Channel selection algorithm (TIC) to compute routes between the gateway and mesh routers and allocates channels to links on these routes. Here, a Channel Assignment Server (CAS) periodically determines the channel assignment over the transmission links in the network and informs all nodes. The CAS collects interference estimates from all mesh nodes and uses the protocol interference model to assign channels to radios. CAS generates a Multi-radio Conflict Graph (MCG) and uses a BFS-based channel assignment algorithm over the MCG. However, it TIC incurs transmission of huge beacon messages between CAS and the routers. Thus, the requirement of transmissions of the beacon messages limits the scalability of this technique.

The work in [79], proposes a divide and conquer approach to decompose the joint channel assignment and routing algorithm in a MRMC WMN into a number of local ILP (Integer Linear Programming) sub-problems, called G-PaMeLA (Generalized Partitioned Mesh network traffic and interference aware channeL Assignment). An optimal solution for each sub-problem is found by using a branch-and-cut method. Thus, the execution time of G-PaMeLA is relatively low, which makes it feasible for an operational WMN. On the other hand, assuming prior knowledge of traffic matrix and channel conditions, prevents this solution to catch up WMN's dynamics, which degrades the delivery and delay performances of traffic.

2.5.2.2 Distributed control

Routing over Multi-radio Access, ROMA [80], is a distributed channel assignment and routing protocol that targets to find paths between source and gateways that reduces intra-path interference by assigning orthogonal channels over individual paths. Each gateway associates a channel sequence with each of its radios. Every non-gateway node in the network participates in a distributed routing protocol to discover best gateway path that yields good throughput by assessing the proposed link metric. Here, the link metric incorporates the ETT [10] of a links which is computed considering link variation through measuring average and mean deviation of the link delivery ratio and external load. However, routing path selection here is load independent.

Authors in [81], proposes a distributed mechanism for Channel and Routing Assignment with Flow Traffic (CRAFT) that jointly optimizes routing and channel assignment to maximize flow throughput. While selecting link-channel pair, CRAFT prioritizes links having higher transmission success probability which is computed using the experienced SINR. The routing and channel allocation table of each node is broadcast periodically. Thus, the solution incurs higher overhead in large scale network.

[82] proposes a routing and channel allocation solution for a hybrid multi-channel multi-radio wireless mesh network architecture. Here, each mesh node has both static

and dynamic interfaces. While allocating channels over the static interfaces, a heuristic algorithm is employed that aims at maximizing the throughput from users to gateways. In the algorithm, a load balanced tree is constructed for each gateway to allocate bandwidth fairly to each user. After the topology has been constructed, each link is assigned channels where links closer to the gateways are given higher priority to be allocated with less congested channels. Further, an Adaptive Dynamic Channel Allocation protocol (ADCA) is used for assigning channels to dynamic interfaces. Here, all nodes negotiate on a default channel for the least congested data channel in the neighborhood. Next, to maximize the total throughput in the hybrid network with both static links and dynamic links, an Interference and Congestion Aware Routing protocol (ICAR) is employed. In order to find higher throughput paths, higher weighted links along each path are chosen, where the cost metric of each link incorporates link's ETX, load status and interference probability with the neighbors.

Interference Aware Routing metric, iAWARE [34], uses ETT [10] weighted with node interference ratio, which is the ratio of SINR and SNR at the receiver node. This metric aims to choose the route that uses the fewer co-channel links in the end-to-end path, which implies higher channel diversity and higher performance. However, higher channel diversity alone is unable to ensure performance improvements on distant routes.

In order to secure end-to-end throughput and minimize delay, Joint Optimization of Bandwidth and Delay, JOBD [83], computes two disjoint paths (delay minimized and bandwidth guaranteed) along with channel allocation between any source-destination pair. JOBD protocol offers enhancement over Ad hoc On-demand Multi-path Distance Vector (AOMDV) protocol [84] to discover bandwidth guaranteed path. AOMDV computes minimum hop-count based multiple loop-free and link-disjoint paths with flooding. Whereas, JODB employs link's effective bandwidth as routing metric considering inter-flow and intra-flow interference. Again, delay minimized path computation is determined through a path metric that incorporates MAC contention and queuing delay. Here, once paths are established, traffic is forwarded over them without considering the link and traffic dynamics. As a consequence, variation in channel conditions, interference and

Table 2.2: A comparison of routing and channel allocation techniques in WMNs.

Technique	Centralized	Distributed	Single Path	Multi Path	Hop-by-Hop	End-to-End	Fixed Traffic	Dynamic Traffic
TIC [42]	✓	✗	✓	✗	✗	✓	✓	✗
G-PaMeLA [79]	✓	✗	✓	✗	✗	✓	✓	✗
ROMA [80]	✗	✓	✓	✗	✗	✓	✗	✗
CRAFT [81]	✗	✓	✓	✗	✗	✓	✓	✗
ADCA, ICAR [82]	✗	✓	✗	✓	✗	✓	✓	✗
iAWARE [34]	✗	✓	✓	✗	✓	✗	✗	✗
JOBD [83]	✗	✓	✗	✓	✗	✓	✓	✗
RCL [85]	✓	✗	✓	✗	✗	✓	✓	✗

traffic matrix may refrain JOBD to attain the desired level of performance.

Joint Routing, Channel and Link scheduling (RCL) proposed in [85] utilizes a new representation of the network connectivity graph called a flow graph. A flow graph contains a universal source node and a universal sink node. The universal source node has directed edges to all nodes with outgoing flow. Each gateway node, which is used to communicate with a wired router, has an infinity capacity directed edge to the universal sink node. The flow graph is obtained after the routing decisions. Channel assignment takes a flow graph, interface constraint, and link capacity constraint as its inputs. Channel assignment techniques minimize the potential interference over the network, maintains the interface constraint and link capacity constraint, improves channel diversity by considering all of the available channels in the network. This technique ensures connectivity and considers the effective traffic load of each link while minimizing interference.

2.5.3 Channel Allocation and Congestion Control

Congestion control refers to the maximization of aggregated throughput across all nodes in the network subject to link capacity constraint. The channel assignment problem in turn refers to the maximization of the aggregated link capacities. In this sub section, we study the existing solutions in the literature focused on controlling traffic through dynamic channel allocation over transmitting links.

Minimum Variation Channel and Rate Reassignment Algorithm, MVCRA-R [86], is a centralized heuristic approach that takes the current channel assignment and the new set of flow rates into account and attempts to maximize throughput in each collision domain through optimal channel reallocation and rate adjustment. Here, collision domain of a transmitting link, consists of set of links that share bandwidth with the link; and the total utilization of a collision domain is defined as the sum of the flow to capacity ratios over the links on it. MVCRA-R prioritizes highly utilized links to switch to higher capacity channels and adjust rates so as to minimize interference in corresponding collision domains and to improve the overall network throughput. However, this approach incurs additional overhead as channel reallocation over a link may require other neighboring nodes to reassign channels in order to minimize interference.

Authors in [87], employ both centralized and distributed channel allocation strategy to minimize flow congestion in the network. In the distributed approach, each node selects channel allocation with the help of periodically broadcasted channel usage information among neighboring nodes. Here, the objective is to minimize interference through minimizing congestion. This technique considers the actually received power to capture interference in the network. However, this technique does not consider connectivity in its objective function. Therefore, connectivity is not guaranteed after the final channel assignment. Work in [88], decomposes the joint problem of congestion control and channel allocation into separate subproblems, which are solved sequentially and iteratively. Here, a centralized controller computes end-to-end paths for traffic flows, that may experience instantaneous congestion and interference degrading flow throughput performance.

Table 2.3: A comparison of routing, channel allocation and rate control techniques in WMNs.

Technique	Centralized	Distributed	Single Path	Multi Path	Hop-by-Hop	End-to-End	Fixed Traffic	Dynamic Traffic
JRCRA [89]	✓	✗	✓	✗	✗	✓	✓	✗
SCA [22]	✓	✗	✓	✗	✗	✓	✓	✗
JML [7]	✓	✗	✓	✗	✗	✓	✓	✗
ROPIM [8]	✓	✗	✗	✓	✗	✓	✓	✗
LBA [9]	✓	✗	✗	✓	✗	✓	✗	✓

2.5.4 Routing, Channel Allocation and Congestion Control

The key aspects influencing the performance of multi-radio multi-channel WMNs include routing, channel assignment (CA) and rate allocation (RA); and require finding the best route for each traffic flow, the best channel for transmission on each wireless link, and selecting the best rate for each traffic flow, respectively. These issues have been extensively studied in the past, but with least focus on instantaneous traffic conditions (i.e. current set of flows) and network dynamics. Another important issue is the need for highly responsive control of these aspects in real scenarios. Therefore, in this Section we analyze the state-of-the-art cross-layer frameworks that consider routing and channel allocation, along with congestion control in MRMC WMNs.

A a centralized MINLP based joint routing, channel and rate allocation approach proposed in [89] aims to optimize the performance of the traffic flows in terms of throughput and fairness. For a given set of flows, network constraints (i.e., topology, link interference, number of available channels and radios, effective link capacity etc.) are taken into account to find best route for each flow along with channel allocation and flow rate over the links, to balance the instantaneous traffic in the network. Due to the hardness of the joint problem, a fast heuristic solution, JRCRA (Joint Routing, Channel and Rate Allocation) is proposed that computes shortest route with maximum capacity. After determining the flow routes, channel assignment algorithm opts to adjust channels of those links first that carry more traffic. While looking for a better channel to replace the old channel without violating node interface constraints, the CA algorithm calculates reduction of interference with respect to links currently assigned to the same channel as the old channel and increase of interference with respect to links currently assigned to the new channel. From the candidate channels, the best one is selected and only if the reduction in interference is below a threshold value. Finally, when the flow routes and channel assignment are known and fixed, the dynamic rate control mechanism adjust the link rate. Here, the effective capacity computation of a link only considers the number of flows travelling the link while ignoring interflow interference, MAC contention, node congestion etc. Thus, JRCRA fails to capture the actual link-channel capacity. Again, flows are routed along paths that has minimum bottleneck load, whereas lightly loaded regions in a network may provide lower throughput due to poor channel quality and congested neighborhood.

Spatial-reusable Channel Allocation strategy, SCA [22], considers both channel diversity and spatial reusability to reduce co-channel interference by joint adjustment of channel, transmission power and routing. To mitigate the co-channel interference and improve capacity, transmission power is controlled over the transmitting links. The proposed heuristic, first computes routes for flows and then determines the load over each link on the path. Highly loaded links are assigned higher rates by intelligent power allocation. However, consideration of protocol model to find interference, limits the practical applicability of SCA.

In [7], the authors propose a joint channel assignment, routing and rate allocation, JML, based on the known traffic profile for multi-rate WMN. The JML consists of three stages - purge, search interference range (SIR) and routing and channel assignment. On purge stage, the JML optimizes the original network topology by removing the unwanted links from logical topology based on known traffic profile. On next stage, the interference range for each link is computed so that the capacity of individual link in the network is maximized. Then, it assigns the highest rate for each link in such a way that the links interference range does not exceed the desired range. Finally, JML solves the routing and channel assignment as MINPL problem based on the link rate allocation information computed in SIR stage.

Both the optimal and suboptimal solutions proposed in ROPIM (Robust Outage Probability based Interference Margin) [8], split traffic over multiple paths by selecting the channels over the links so that links experience minimum interference and corresponding link-rate in increased. Here, consideration of fixed end-to-end routing path along with known traffic demand limits the performance of the proposed solution in a dynamic environment. All the aforementioned joint solutions depend on a central controller, which require a complete view of the network dynamics in order to solve the joint problem. Thus, the required convergence time can make those solutions unsuitable for highly dynamic scenarios.

A generic MIP framework to characterize the capacity achievable over transmitting links in MRMC WMNs is proposed in [9], that allows multiple transmission powers and MCS over the links and accounts for link scheduling, channel assignment and rate control. At first, authors propose a Max-Min Flow (MMF) optimization problem realizing the proposed MIP framework. As the optimization problem is described by a large number of integer variables, it is hard to efficiently handle the computation of the solution. Therefore, a heuristic sub-optimal scheduling algorithm, referred to as LBA (Load Based Algorithm), is introduced for optimizing the MMF throughput in WMN. LBA is a two phase algorithm. In the first phase, LBA determines the link rates (corresponding MCS) over the links. Here link transmission powers are optimally allocated to enhance spatial channel reuse so as to increase simultaneous flow transmissions. The link data rates are then used in the second phase for calculating the achievable MMF solution over the given fixed routing paths. Here, the LBA solution is realized through a suitable scheduling algorithm. Though, the proposed solutions deal with instantaneous traffic demand, due to fixed path traffic forwarding, they are not able to divert the traffic load to an alternate least loaded area under exhaustive congestion in the network.

2.5.5 Discussion

The key characteristics of some of the traffic engineering mechanisms based on cross-layer solution are summarized in Table 2.1, 2.2 and 2.3. Note that both MRT [5] and CLC_DGS [6] support multi-path traffic splitting while mitigating congestion, but due to employment of central controller they are unable to address network dynamics instantaneously and are not scalable. Though, the work in [82] and JOBD [83] propose distributed multi-path computation and channel allocation to ensure high throughput data delivery, while forwarding traffic over pre-computed paths they do not incorporate traffic variations. Both ROPIM [8] and LBA [9] mechanism leverages neighboring interference through dynamic power control over scheduled link-channel pairs, but exhibit poor throughput performance in large scale WMNs due to employing central point of control. The dynamic traffic engineering mechanism developed in this thesis work, are aware of network dynamics and spontaneous flow demand, employ distritbuted hop-by-hop multi-path traffic forwarding toward multiple gateways to maximize flow throughput by minimizing interference and congestion.

2.6 White Space Utilization in Wireless Mesh Networks

The flow performance in WMNs is hindered due to the limited usable frequency resources. In current wireless mesh networks, the unlicensed ISM bands are most commonly adopted for backbone communications. Furthermore, the WMN is largely affected by the interference caused by all other devices in this ISM band, e.g., nearby WLANs and Bluetooth devices. Moreover, the limited bandwidth of the unlicensed band cannot satisfy the increasing demand for the bandwidth of the evolving network applications. On the other hand, as shown by a variety of empirical studies [25], the current allocated licensed spectrum is highly under utilized. As a consequence, the urge to explore the unused white space, which can significantly enhance the performance of the WMNs, attracts tremendous attention in the literature.

2.6.1 Opportunistic Spectrum Allocation

With emerging cognitive radios, unlicensed wireless users (secondary users) can access the under utilized licensed bands through Opportunistic Spectrum Allocation (OSA), as long as the licensed wireless users (primary users) in these spectrum bands are not disrupted [65, 90]. Cognitive radios are desirable for a WMN in which a large volume of traffic is expected to be delivered since they are able to utilize available spectrum resources more efficiently, thus significantly improving the network capacity. The state-of-the-art OSA techniques either centrally or distributively find good quality channels (i,e, least interfered, stable, high capacity) to be used by the SUs in a CR-WMN.

2.6.1.1 Distributed control

In [91], each node distributively allocates licensed channels over links, where the quality of a channel is determined by primary user's active period on that channel and channel error rate. Authors in [90] also employs distributed mechanism to select a channel for a node such that the interference temperature within its transmission range does not exceed a predefined threshold. Both the approaches are unable to optimize flow performance, as they do not consider flow demand and path congestion.

Work in [65], concentrates in the problem of resource allocation between Internet gateways and forwarding routers to maximize flow throughput. In the proposed approach, considering the high throughput data delivery requirement, devices operate on both unlicensed and licensed channels. This offers greater flexibility to meet flow requirements under unlicensed spectrum scarcity. Moreover, greater connectivity is ensured through control communication over unlicensed bands. Here, at first an optimization framework is developed to ensure a certain effective capacity for each link, independent of the channel conditions and the PUs activity. Next, a decentralized implementation of the algorithm is developed using dual decomposition of the optimization problem. Here, a cluster-based solution is proposed, where each cluster corresponds to a collision domain in the WMN. Each collision domain has a domain referent which is the head cluster in the proposed algorithm architecture. To find the collision domain, the conflict graph can either be pre-computed during the network design stage or a central entity may collect the interferant links' data by utilizing the sensing capabilities of the nodes. Next, to obtain the maximal cliques of the conflict graph, which correspond to the collision domains, BronKerbosch algorithm [92] is used. Each link in a cluster estimates local effective capacities and local PUs activity statistics and locally solves the spectrum allocation which is communicated to each domain referent. Upon receiving the pre-computed allocation for each link, each domain referent computes the allocation and broadcasts within the domain. Here, each link is assumed to have a priori traffic requirement that fails to portrait the real Internet traffic behavior in WMN.

[26] distributively assigns least interfered and congested channels over the radio interfaces. Here, each router measures the instantaneous collision probability and signal strength of each transmitting packet, which is used to estimate traffic load by using a fuzzy logic controller and a reinforcement learning algorithm. Finally, channels exhibiting greater capacity is selected for communication. Here, mapping between traffic demand and channel capacity is not considered, which fails to ensure fair bandwidth share among contending flows.

To alleviate traffic congestion due to bandwidth scarcity in CR-WMN, [24] proposes a novel spectrum sensing method that identifies primary user frequencies without additional transceivers and changing the de facto IEEE 802.11 standard for WMNs. Next, an analytical model is devised to estimate the amount of interference caused at any arbitrary location and channel due to the neighboring traffic. The channel assignment task is formulated as an optimization problem that is solved at each router in a decentralized manner. Authors do not consider the dynamic traffic demand which ensues congestion in the network.

2.6.1.2 Centralized control

To increase link reliability, maximize network coverage and alleviate the need for a common control channel (CCC), [66] proposes a centralized channel allocation strategy. While assigning channels to each mesh client and router, RBA (Receiver Based Channel Allocation) aims to establish maximum upstream and downstream paths between mesh clients and gateways so as to enhance traffic forwarding rate. The optimal RBA is formulated as a MILP problem, inappropriate for dynamic environment. Next, a polynomial-time complexity heuristic solution is devised that rolls over 3 phases - (i) assigning channel to routers to maximize their upstream and downstream connectivity, (ii) maximizing the number of high throughput upstream links from mesh clients to mesh routers, and (iii) finally, finding downstream links for those nodes that has already established uplinks. Here, channel allocations and path establishments are unaware of flow demand present at each node which fails to meet traffic dynamics and grant inter-flow fairness.

2.6.2 Routing, Congestion Control and Opportunistic Spectrum Allocation

The cognitive radio (CR) enabled mesh routers opportunistically share the licensed resources to mitigate the spectrum scarcity problem and it is of great importance to efficiently allocate the limited resources to all nodes in the network so that the performance is increased. Existing approaches in the literature explored OSA with routing and congestion control of data traffic over single or multiple paths so as to increase the resource utilization in CR-WMNs.

Aiming to improve the coexistence with primary users and other CR networks, joint routing and channel allocation strategy has been proposed in [93] and [94] considering the traffic demand. The optimization problem in Interference-Minimizing Routing and Scheduling, IRS [93], focuses to minimize the total interference from SUs toward PUs considering the flow control, scheduling, interference minimization and multi-hop routing in CR-WMNs. Further, a distributed algorithm is constructed based on the cost

Table 2.4: A comparison of routing, rate control and OSA techniques in CR-WMNs.

Technique	Centralized	Distributed	Single Path	Multi Path	Hop-by-Hop	End-to-End	Fixed Traffic	Dynamic Traffic
IRS [93]	✗	✓	✗	✗	✓	✗	✓	✗
JCAR-update [94]	✓	✗	✓	✗	✗	✓	✗	✓
MaxTh [95]	✗	✓	✓	✗	✓	✗	✗	✓
JRRA [96]	✓	✗	✗	✓	✗	✓	✓	✗
MMBA [97]	✓	✗	✓	✗	✗	✓	✓	✗
MRSA [98]	✓	✓	✗	✓	✗	✓	✓	✗
STE [99]	✗	✓	✗	✓	✗	✓	✓	✗
GA-CR [100]	✗	✓	✗	✓	✗	✓	✓	✗
Ga-CO [64]	✓	✗	✓	✗	✓	✗	✓	✗

considering interference to PUs and flow status in each link. Despite of minimizing interference toward the PUs, IRS fails to find a match between assigned channels and flow characteristics. JCAR-update (joint channel assignment and routing update) in [94] aims to minimize the number of operating channels for better coexistence with PUs and other CR networks while accommodating the total traffic demand of all routers.

A distributed resource allocation mechanism, proposed in MaxTh (Decentralized throughput maximization) [95], significantly improves service rate of each traffic flow with time varying demands over a pre-computed end-to-end path by maintaining flow conservation constraint at each router and minimizing the interferences amongst the contending neighboring links. Here, a optimum framework is proposed for link scheduling along with least busy PU channel allocations over them with an objective to maximize the end-to-end aggregated traffic throughput. Later, Lagrangian duality theory is employed to get a distributed solution of the problem. In this approach, each router distributively computes link-channel scheduling for upstream traffic; knowing next-hop path, channel allocation information from interfering neighbors, transmitting state of downstream node and maximum allowable rate considering the end-to-end minimum service rate. Here, end-to-end propagation of control information results in slow convergence of the solution which is unable to address network dynamics (varying link condition, bursty traffic demand. Also, the use of fixed-power transmission and single-path data delivery in MaxTh causes intra-flow contention and congestion along the path, which in turn degrades the network throughput performance.

A high throughput end-to-end path along with channel allocation over them considering intra and inter-flow interferences has been developed in JRCS (joint routing and channel selection) [101]. Furthermore, the algorithm only needs to propagate local information from the source to the destination and can be implemented in a distributed fashion. Again, single-path data forwarding approach proposed in JRRA (joint routing and resource allocation) [96] considering neighborhood interference (using protocol model), PU activity and node congestion is unable to fulfill the QoS requirement of delay sensitive traffic under random PU behavior. Here multi-path traffic splitting can guarantee packet delivery over alternate paths under sudden cease of channels over some forwarding paths. Here, the network is analyzed from a queuing theory perspective, and the joint routing and resource allocation problem is formulated as a Non-Linear Integer Programming (NLIP) problem. The objective is to optimize the overall packet dropping probability at node buffers. Therefore, as all the aforementioned works forward traffic over single path, they are prone to interference affects by both SUs and PUs and unable to meet flow demand under dynamic traffic condition.

[97] proposes an end-to-end bandwidth allocation mechanism in CR-WMNs with the objective to ensure fairness among forwarding nodes, which involves routing, scheduling, and spectrum allocation. The authors propose LP-based optimal and heuristic solution of Maxmin fair Maximum throughput Bandwidth Allocation (MMBA) and Lexicographical Maxmin fair Maximum Bandwidth allocation (LMMBA) problem. Here, a spectrum

management server is responsible to compute a feasible maxmin fair bandwidth-allocation vector for all nodes along with a corresponding link flow-allocation vector, a corresponding scheduling vector, and a set of transmission modes (subset of linkchannel pairs that can concurrently be active) such that the throughput of this bandwidth-allocation vector is maximum among all feasible maxmin fair bandwidth allocation vectors.

A genetic algorithm (GA) based nested optimization framework for channel and route scheduling, GA-CR, proposed in [100], to find a feasible channel allocation for each forwarding link while computing a least congested source-destination path. As the channel state is highly vulnerable in cognitive radio network due to PU's random behavior, an existing channel may become unavailable to a mesh node sporadically. Thus, finding a new allocation solution from a central entity leads to an unstable system condition.

Source to destination edge-disjoint multiple paths are computed in [98], where the channel allocations over the links ensure the bandwidth requirements of the traffic flows. As the cognitive wireless mesh network is intended to maximally fulfill user demand, the optimization goal of MRSA (Multi-path Routing and Spectrum Allocation) mechanism is to support maximum concurrent flows in the network. Here, both distributed and centralized heuristics are proposed to find minimum bandwidth paths while guaranteeing the independency between the multiple paths with regard to spectrum mobility.

A Stochastic Traffic Engineering approach, STE [99], distributively splits aggregated traffic over least interfered routes to address the QoS requirement of each traffic flow under the influence of random behaviors of PUs. The optimum STE is formulated to maximize flow utility from users' satisfaction perspective. Next, it derives a distributed solution via the stochastic primal-dual approach, for the cases where convexity holds. For the scenarios where convexity is not attainable, an alternative decentralized algorithmic solution based on the learning automata techniques is devised. As the route computation and traffic splitting is done by the source node, flow and path dynamics (i.e., interference, error, congestion) are ignored in STE.

Work in [64] proposes a GA based optimum channel and power allocation at link-physical layer, and a linear programming (LP) based source-destination route selection at network layer, GA-CO (Genetic algorithm based cross layer optimization), aiming to fairly allocate the capacity of the network among the set of contending flows, by maximally satisfying their demands. Here, power control over the links controls the size of the neighborhood collision domain, eventually minimizing interference to obtain the required rate over each link in the network. However, under dynamic varying flow demands, path and resource-allocation (channel and power) are recomputed, hindering the convergence time of the mechanism to trigger unstable state of the network. All the aforementioned works establish end-to-end paths among source-destination.

2.6.3 Discussion

The key working principles of OSA techniques in CR-WMNs, are compiled in Table 2.4. Centralized traffic engineering solutions in MMBA [97] and GA-CR [100] leads to an unstable system condition, as soon as an existing channel become unavailable to a mesh node considering the high vulnerable channel condition in cognitive radio network. On the other hand, MRSA [98] and Ga-CO [64] offer higher throughput and reliability through multi-path data delivery minimizing the effects of PU random PU arrival. Distributed traffic engineering solutions proposed in STE [99] and Max-Th [95], are suitable to optimize flow routing through promptly acting upon link and channel dynamics. However, the use of fixed-power transmission and single-path data delivery in MaxTh and end-to-end traffic splitting in STE causes intra-flow contention and congestion along the path, which in turn degrades the network throughput performance. The traffic engineering scheme designed in this thesis work to utilize the white space opportunistically, jointly investigates the problem of selecting good quality link-channel pairs and to allocate data rates on them (by selecting appropriate transmission powers) for each forwarding router so that the throughput of the network is maximized.

2.7 Summary

In this Chapter, we present a comprehensive analysis of existing traffic engineering solutions adopted in WMNs to enhance flow performances. In Chapter 1, we pointed the various design issues to be addressed by an effective traffic engineering solution. Based on that, we studied the state-of-the-art work, those attempted in differing aspects to provide a solution. We reviewed routing, congestion control and dynamic channel allocation solutions, respectively. Next, the cross-layer TE solutions are examined aiming at jointly optimizing flow performances. Finally, research on white space utilization are enclosed to further enhance the flow throughput under high interference and congestion in the network.

Chapter 3

Traffic Engineering in Wireless Mesh Networks with Static Channel Allocation

3.1 Introduction

Wireless Mesh Network (WMN) has been recently emerged as a promising technology for wireless Internet infrastructure development because of its low cost, ease of deployment and installation [2]. The increasing number of users and diversified application usages as well as the incorporation of sensors and Internet of Things (IoT) devices with the WMNs has caused exponential growth in traffic flows [39]. This increased traffic volume, however causes congestion in the network, degrading application throughput and reliability and delay performances. Therefore, how to provide satisfactory network performance, by utilizing the limited offered bandwidth, has emerged as a problem. In this Chapter, we explore traffic engineering policies that dynamically adjust transmission powers and data rates over outgoing links at each router so as to enhance the network throughput.

A good number of works in the relevant literature focus on the use of emerging wireless technologies including directional antennas [2], multiple-input-multiple-output (MIMO) [43] and multichannel and multiradio [15] solutions at lower layers for increasing data delivery throughput of a network. However, none of these approaches take into account the sudden surge of huge data traffic generated from diverse user (human or device) applications, that cause network to become congested. In WMNs, mesh routers act as intermediate nodes and forward user traffic to mesh gateways (GWs) in multi-hop fashion. A WMN with a single GW might create a bottleneck condition and a single point of failure for the network [29]. The use of multiple GWs in a WMN and multipath data forwarding towards them have been proven to provide better throughput performance [48] since this strategy increases the aggregated bandwidth for certain traffic flow.

There is a significant body of works that focus on multipath data forwarding to enhance flow performance in WMNs. Those studies include discovery of node-disjoint or link-disjoint multiple paths [55], optimal power allocation to mitigate interference [16, 102] and computing mutually interference-free multiple paths [48][78]. However, these end-to-end data delivery systems are less responsive to dynamic network conditions (link quality, interference, traffic demand, etc.) and thus they utilize instantaneous network capacity poorly. A central controller is deployed in [5] to find collision-free scheduling for all forwarding links using a backtracking algorithm. However, it does not consider rate adjustment in presence of varying link conditions and traffic demands. Authors in [6] propose a cross layer design approach to joint traffic splitting, rate control, routing and scheduling that splits traffic over multiple paths to enhance flow performance. The employment of a centralized controller would increase scheduling delays, cause a single point of failure and lead to wrong scheduling decisions due to obsolete information usage.

To counteract the aforementioned deficiencies, a distributed control agent is required at each forwarding router to determine outgoing link qualities and split traffic over them in a way that can maximize network performance. In this Chapter, we propose an optimization framework for Dynamic Traffic Engineering (O-DTE) in WMNs that aims to minimize interference and congestion and thus enhances throughput performance. The framework adopted belongs to a mixed integer nonlinear programming (MINLP) problem and involves both combinatorial and continuous constraints, making it an NP-hard problem. A greedy heuristic alternate solution G-DTE has also been developed that produces near-optimal results.

3.1.1 Contributions

The key contributions of this Chapter are summarized as follows:

- The traffic forwarding policies of the proposed O-DTE and G-DTE systems minimize neighborhood interference and backlogged traffic, and explore the least congested next-hop nodes so that the overall throughput of the network is maximized.

- We define a new weight function for each link based on its current achievable rate and the congestion level of the downstream. We allow a G-DTE router to prioritize the forwarding links based on their weights and to select less congestive and high-throughput links for traffic splitting.
- Each G-DTE downstream router controls the weighted-fair reception of data traffic from its upstream nodes and a high level of fairness is maintained.
- The proposed G-DTE routers exploit single-hop neighborhood information only to take traffic forwarding decisions distributedly and so make it scalable.
- Finally, the results of our simulation experiments, carried out in ns-3 [51], show that the proposed O-DTE and G-DTE systems offer significant performance improvements in terms of throughput, delay, reliability and flow fairness.

3.1.2 Organization

The rest of the Chapter is organized as follows. In Section 3.2, we explore the existing works in the relevant literature; while the system model is presented in Section 3.3. The objective function and constraints of the O-DTE framework are formulated in Section 3.4 and the G-DTE system is designed in Section 3.5. The performance evaluation results are presented in Section 3.6; while Section 3.7 summarizes the work.

3.2 Related Works

A good number of works in the literature is focused on throughput improvement of WMNs by exploiting diverse aspects of the network including congestion mitigation [4, 103], rate adaptation [77, 78], scheduling [5, 6], channel allocation [104] and routing [77]; either independently or jointly [77]. Based on the number of paths over which a source node delivers data to a targeted destination, traffic forwarding paradigm appears to be either single path or multipath. A significant number of works in the literature is based on single path data forwarding [23], which is unable to fulfill flow demands in presence of neighborhood interference, poor channel condition, limited bandwidth and network congestion [5]. A source node may utilize the aggregated bandwidth available over multiple alternate paths towards destinations using multi-path data forwarding approach [6, 78], which is expected to provide improved throughput and transmission reliability [5].

In [48] and [55], traffic is forwarded over node or link disjoint multiple paths without considering path condition (interference, contention etc.) and path capacity (available bandwidth). MRA [48] at each source node distributively computes multiple mutually non interfering paths toward destination exploiting single hop communications. Considering the initial knowledge regarding multiple paths toward destination, an interference graph is computed to find independence among the set of multiple paths. Finally, the maximum weighted independent sets from the interference graph is obtained which holds the desired set of least interfered paths between the source-destination pair. However, computation of maximal independent sets become an NP-hard problem, when the number of paths increase. Also, mutual non interfering paths do not necessarily lead to less interfered and congested paths. Furthermore, MRA is unable to exploit the capacity of the selected paths optimally, as it does not consider flow demand, path comgestion and network dynamics while traffic splitting. Proposals in [63], [83] and [104], also remain traffic agnostic, i.e., they consider flow demand to be stable and known. However, this assumption is unrealistic and the aforementioned works don't react dynamically to any changes in network condition. Therefore, a control mechanism is required to adjust the traffic forwarding decisions following the dynamic behavior of the network.

In [77], link success probability (computed from historical SNR values) is exploited to control data forwarding rates on the links. The authors in [9] applied max-min fairness based rate control for incoming traffic by jointly solving scheduling, channel assignment and rate control problems. In addition, [4] addresses neighborhood-congestion and path-congestion by controlling flow rates. Unlike controlling data rates over the pre-computed end-to-end paths in the aforementioned works, selecting the least congested alternate paths at each hop toward the destination would have been a better strategy to raise the data delivery performance.

In [78], each router floods its own capacity information throughout the network and then each node autonomously determines traffic distribution on multiple paths aiming to minimize congestion. However, it causes excessive signalling overhead for disseminating link information and it does not respond to changes in the network environment. MRT [5] exploits backtracking algorithm to add multiple paths between each source-destination pair in the network as long as the path throughput is maximized. The data rate on each path is determined by the bottleneck link's effective capacity of the path. MRT computes collision free scheduling (time slot allocation) over paths for multi rate link capacities, the duration of time slot allocated to each link is dictated by the bottleneck link. Here, static traffic splitting is employed without incorporating the dynamic variation in traffic demand and dynamic changing path capacity due to interference and congestion. Also highly unfair for newly admitted flows when network is highly loaded.

A joint traffic splitting, rate control, routing and scheduling algorithm is developed in [6], aiming to maximize network utility by distributing traffic of a flow into multiple gateways in an optimal way. The network utility maximization problem is formulated as a constrained optimization problem aiming to maximize the total average rates of all the network flows and ensure fairness among the flows under the fluid traffic model. Next, to solve the problem with a primaldual method, a novel Cross-Layer Control algorithm with Dynamic Gateway Selection (CLC_DGS) solution decomposes the problem into two sub-problems: (1) traffic splitting and rate control, and (2) routing and scheduling. At each forwarding router, rate controller injects traffic toward least congested gateway in an amount that limits queue congestion at forwarding nodes. Finally, the routing and scheduling component allows concurrent transmission over those links that has higher backlogged traffic, in order to alleviate congestion from the network. Based on CLC_DGS, authors also propose an enhanced Cross-Layer Control algorithm with Dynamic Gateway Selection and Delay Differentiation (CLC_DGS_DD) which considers different delay requirements for flows and provides a flexible framework for adjusting delays among different flows, and thereby can achieve low delays for preferential flows. However, the employment of a centralized controller can increase the scheduling delay and the decisions often may be taken based on obsolete data related to traffic flows and queue occupancy status.

Our proposed DTE solution at each forwarding node offers distinctive characteristics while aiming to fulfill upstream flow demand over multiple paths towards multiple GWs, compared to the leading works [48], [5] and [6]. Firstly, DTE dynamically determines a traffic allocation vector consisting of selected downstream links, along with appropriate power and rate allocations over them so as to maintain flow conservation constraints; it also takes into account link quality, neighborhood contention, node congestion and path congestion. Secondly, traffic is split over the designated multiple forwarding links to meet flow demand by exploiting the diversified path capacities. Finally, to avoid the adverse effect of congestion, each DTE node locally monitors its backlogged traffic intensity and forwarding capability to regulate upstream rates in a fair manner.

3.3 System Model and Assumptions

Let a graph $\Gamma = (\mathbb{V}, \mathbb{E})$ represent a typical wireless mesh network, where $\mathbb{V}$ is the set of mesh nodes and $\mathbb{E}$ is the set of links; and, $\mathbb{G} \subset \mathbb{V}$ is a set of mesh gateways. The clients are connected with edge routers and the core routers form a multi-hop network backbone that carries traffic mainly in between mesh clients and the Internet through gateways, as shown in Fig. 3.1. Each node $v \in \mathbb{V}$ has multiple radio interfaces, each operating on an orthogonal channel so as to facilitate enhanced network capacity by allowing more concurrent transmissions [89]. We assume that each radio on router $v \in \mathbb{V}$ is assigned a static channel, following a suitable channel assignment algorithm CLICA [17]. CLICA is a DFS-based channel assignment algorithm that uses a greedy heuristic to find a connected low interference topology in a multi-channel WMN. It starts by constructing a weighted conflict graph from the connectivity graph following the protocol interference

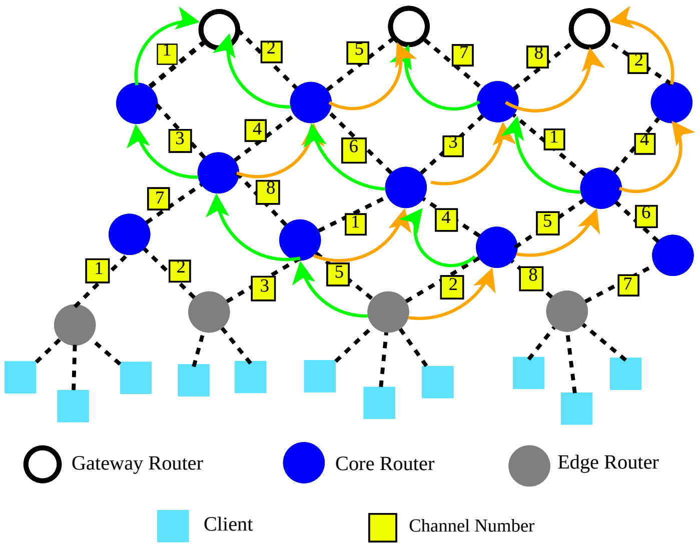


Figure 3.1: An example of multipath data forwarding in WMN

model. This graph contains node priorities and edge weights, which reflect the extent of interference between two links in the connectivity graph. CLICA assigns channels to the links based on the priorities following a greedy heuristic with the similar essence of graph coloring. The greedy heuristic minimizes either of two metrics - maximum link conflict weight or average link conflict weight over all interfering links. It uses an adaptive priority algorithm, which alters a nodes priority during the course of execution to ensure connectivity. Finally, it pairs unassigned radios either in the same greedy manner or based on the traffic load.

3.3.1 Wireless Interference Model

Signal interference plays an important role in wireless network transmission. When one node sends out packets, its signal may be heard not only by the receiver, but also by some of neighboring nodes. When two nodes are far enough away from each other, the signal from each node cannot be heard by the other and no direct transmission is possible between these two nodes. At the same time, there is no interference between those two nodes, which means one nodes communication will not affect the other. On the other hand, when two nodes are close enough, they can hear the signal clearly and communicate directly with each other. There is also an intermediate state, when two nodes may not be able to receive each others signal clearly, which means direct communication is not possible, but the signal can still be detected; this is usually called noise. The noise received at one node can affect its transmission with other nodes. Sometimes, the noise at the receiving node is so strong that it prevents the node from receiving packets from others. Several models have been proposed to describe this interference character. Two popular models, protocol model and physical model, define the condition for a successful wireless transmission and describe when two nodes are encountering interference [15, 17, 42]. The physical model is based on real scenarios and is much closer to actual networks. The protocol model, on the other hand, is a simplified, though popular, model favored in the research area.

Protocol Model: In the protocol model, each node, $u \in \mathbb{V}$, has a uniform Transmission Range (TR), defined as the maximum distance within which u's transmission can be successfully interpreted, and an uniform Interference Range (IR), defined as the maximum distance node u's transmission causes interference to over neighboring nodes. Thus, packet transmission from node u to node v is successful, if and only if (i) the distance between these two nodes, $d(u, v)$, satisfies $d(u, v) <$ TR , and (ii) any other node $w \in \mathbb{V}$ within the interference range of the receiving node v, i.e., $d(w, v) \leq$ IR, is not transmitting [15, 17]. The relationship between TR and IR can be expressed as IR $= (1 + \Delta)$ TR , where $\Delta \geq 0$ is a constant.

Physical Model: When a node is transmitting data to another node, its signal can be heard by neighboring nodes. The strength of the signal received at each node depends on the distance to transmitting nodes. Usually the farther it is away from transmitting nodes, the weaker the signal it receives. In the physical model, packet transmission from node v to w is successful if and only the signal-to-interference and noise ratio (SINR) at the receiver is sufficiently high to decode the signal [9, 34, 42]. The SINR at receiver w when a signal is transmitted by node v is defined follows:

$$\gamma^{p}_{(vw)} = \frac{p_{(vw)}\mathcal{G}_{(vw)}}{\eta_{(vw)}}, \tag{3.1}$$

where, transmitter v uses power p to transmit to node w, $\mathcal{G}_{(vw)}$ is channel gain function, computed by taking into consideration parameters such as path loss, fading and shadowing; $\eta_{(vw)}$ is the corresponding link interference plus Gaussian noise measure in the operating channel. The physical model's description of signal interference is close to that in actual networks, where it completely depends on the signal-to-noise ratio at the wireless card to determine whether a node can hear the signal clearly and decode it. One nodes signal may interfere with another node at one moment, but it may not interfere with that node at another moment. In the physical model, only the signal-to-noise ratio at the receiving node at a specific moment can determine whether it is disturbed by other nodes and whether it can receive the signal successfully. Thus, choice of physical interference model to capture the affect of dynamic channel condition, is justified in our thesis work.

3.3.2 Link Capacity Computation

A node can choose a discrete transmission power from a set $\mathbb{P}$, in the range $[p^{min}, \ldots, p^{max}]$ and we assume a wireless link, (vw), between nodes v and w, when the signal transmission from node v at a power $p \in \mathbb{P}$ is able to meet a minimum SINR threshold at w that corresponds to some achievable data rate $r \in \mathbb{R}$ in the range $[r^{min}, \ldots, r^{max}]$ using a specific modulation and coding scheme (MCS)[9]. In the IEEE 802.11a/g systems, the MCS defines finite and discrete transmission rates corresponding to minimum SINR values, shown in Table 3.1 [9]. A binary variable $x_{(vw)}$ contains 1 if the link (vw) is active (i.e., the node v is now transmitting data towards node w), and 0 otherwise.

Although intra-WMN communication is possible without loss of generality, we assume that most of the traffic is forwarded to the Internet. Users from random locations generate traffic flows at random time instants. Routers find multiple paths toward gateways using

Table 3.1: SINR vs link capacity in the IEEE 802.11a/g

SINR (dB)	6	7.8	9	10.8	17	18.8	24	24.6
Data Rate (Mbps)	6	9	12	18	24	36	48	54

a suitable routing algorithm [55] and forward data traffic over the paths. We let $\mathcal{L}_v^u$ and $\mathcal{L}_v^d$ denote the set of upstream and downstream links of a router v. The aggregated upstream traffic, $\sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)}$ at router v is split over each computed forwarding link $(vw) \in \mathcal{L}_v^d$ in a weighted fair proportion, denoted as $r_{(vw)}$. The value of $r_{(vw)}$ is limited to the achievable rate, $r_{(vw)}^p$, over the link (vw) for the SINR of $\gamma_{(vw)}^p$, when the transmission power is p. During the course of time, wireless links experience contention and congestion that restricts the rate achievable over the forwarding links. To combat the performance degradation due to poor link quality, dynamic rate splitting is invoked, as discussed in Section 3.5.1.

3.4 Optimization Framework for Dynamic Traffic Engineering

Our proposed optimal dynamic traffic engineering (O-DTE) at forwarding nodes aims to fulfill upstream flow demand while minimizing neighborhood interference and congestion. Let, for each link $(vw) \in \mathcal{L}_v^d$, the tuple $(x_{(vw)}, p_{(vw)})$ represents the activation status and power allocation over link (vw) at any given time, where $x_{(vw)} \in \{0,1\}$ and $p \in \mathbb{P}$. Let $\mathbb{Q}_{(vw)} = \{(x_{(vw)}, p_{(vw)})\}$, be the set of all possible allocation vectors over each link $(vw) \in \mathcal{L}_v^d$ and $\mathbb{S}_v = \prod_{(vw)\in\mathcal{L}_v^d} \mathbb{Q}_{(vw)}$ be the set of all possible allocations over set of downstreams of node v. Now, our problem boils down to finding a suitable allocation $s \in \mathbb{S}_v$, that achieves the aforementioned goal.

Links transmitting at higher powers may improve the SINR of its carried signal at their receivers, enabling higher flow throughput; but, it may cause excessive interference in the neighborhood [23, 102]. Our target is to find an optimal set of outgoing links for any node $v \in \mathbb{V}$ so that it can maintain flow conservation constraint by employing minimum power on the links. We implement this notion by assigning each forwarding link a weight, $\omega_{(vw)} = f(r^p_{(vw)}, r^o_{(vw)})$, where, $r^p_{(vw)}$ is the rate achievable over the link (vw) for a particular transmission power p under a given link SINR condition and $r^o_{(vw)}$ is the forwarding rate offered by the downstream node w. This offered rate $r^o_{(vw)}$ varies over time, following the congestion status of w, as detailed in Algorithm 2. We compute the weight of a forwarding link (vw) as follows,

$$\omega_{(vw)} = \left\{ \frac{p^{max} - p_{(vw)}}{p^{max}} \times r^p_{(vw)} \right\} \times \left\{ \frac{r^o_{(vw)}}{r^{max}} \right\} \times x_{(vw)}. \tag{3.2}$$

Note that the first part of the weight function exhibits higher values for the links providing higher rates using lower transmission powers; whereas, the second part produces higher values for the forwarding links having higher offered rates, i.e., a less congested downstream gets higher preference. Thus, our forwarding policy opts to minimize neighborhood interference and to explore the least congested paths by maximizing $\sum_{(vw)\in s} \omega_{(vw)}$, $\exists s \in \mathbb{S}_v$. Furthermore, the O-DTE traffic forwarding policy tries to minimize the backlogged traffic so as to better serve the upstream flow demand. That is, each forwarder node v tries to minimize backlogged traffic index, $\delta_v(s)$, over each allocation $s \in \mathbb{S}$, defined as follows,

$$\delta_v(s) = \frac{\sum_{(uv)\in\mathcal{L}^u_v} r_{(uv)} - \sum_{(vw)\in s} r_{(vw)}}{\sum_{(uv)\in\mathcal{L}^u_v} r_{(uv)}}. \tag{3.3}$$

Thus, $\delta_v(s)$ represents the node level congestion of a forwarder v under allocation s. Our proposed O-DTE framework is formulated as follows:

$$\underset{s\in\mathbb{S}_v}{\text{Maximize}} \quad \left\{ \frac{\sum_{(vw)\in s} \omega_{(vw)}}{\delta_v(s) + \epsilon} \right\} \tag{3.4}$$

s.t.

$$x_{(vw)} \in \{0, 1\}, \qquad \forall (vw) \in \mathbb{E} \tag{3.5}$$

$$0 \leq \delta_v(s) \leq 1, \qquad \forall v \in \mathbb{V} \tag{3.6}$$

$$p^{min} \leq p_{(vw)} \leq p^{max}, \qquad \forall (vw) \in \mathbb{E} \tag{3.7}$$

$$0 \leq r_{(vw)} \leq r^p_{(vw)} \leq r^o_{(vw)} \leq r^{max}, \qquad \forall (vw) \in \mathbb{E} \tag{3.8}$$

$$\sum_{(uv) \in \mathcal{L}^u_v} r_{(uv)} \geq \sum_{(vw) \in s} r_{(vw)}, \qquad \forall v \in \mathbb{V} \tag{3.9}$$

Constraint (3.5) depicts the activation status of link (vw) and the constraint (3.6) defines the boundary of backlogged traffic index. In the best case, total outgoing traffic of a node equals the total incoming traffic, the Eq. 3.3 produces 0 value for $\delta_v(s)$ and thus, we augment $\epsilon = 0.001$ with it in Eq. 3.4 so as to avoid the *division by zero* problem. The transmission power $p_{(vw)}$ allocated over a link (vw) is bounded by minimum (p^{min}) and maximum (p^{max}) values [23], depicted in constraint (3.7). Constraint (3.8) shows that the transmission rate $r_{(vw)}$ split over a link (vw) is limited either by an achievable rate $r^p_{(vw)}$ on the link (vw) for a given power p and link SINR condition, or by $r^o_{(vw)}$, or by r^{max}, whichever is smaller. Finally, constraint (3.9) states that the outbound traffic must not exceed the total inbound traffic at each $v \in \mathbb{V}$ [89].

Note that the objective function, formulated in Eq. 3.4, selects a set of forwarding links (with corresponding powers) $s \in \mathbb{S}_v$, that maximizes the aggregate forwarding rate, minimizes neighborhood interference, as well as node level congestion. Thus, it's a multi-objective optimization framework and the O-DTE component at each router implements optimal forwarding policy that dynamically adapts to changes in the network environment. The Eqs. 3.4 - 3.9 belong to a mixed-integer nonlinear programming (MINLP) problem that contains both combinatorial and continuous constraints. Thus, its real-time solution is intractable in a typical mesh router and the problem therefore becomes an NP-hard one [89]. Even in a server with 2 Intel Xeon E5-2698 @2.3GHz CPUs and 192GB RAM, it takes approximately 5 seconds using NEOS optimization tool [105] whenever $|P| = 10, |R| = 8$ and $|L^d_v| = 6$.

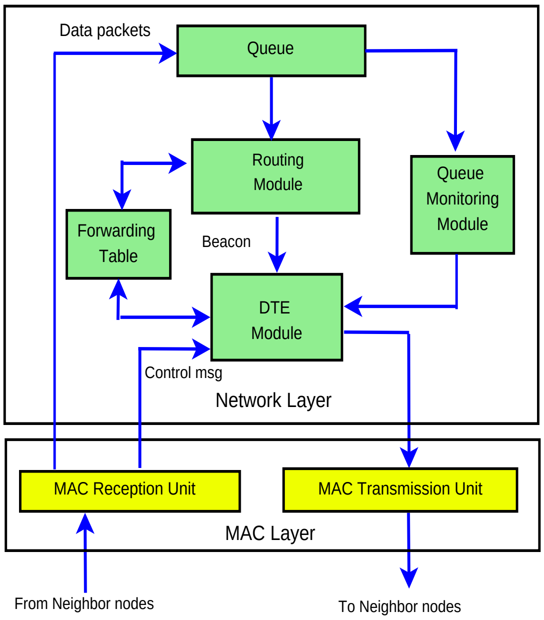


Figure 3.2: DTE component at each router $v \in \mathbb{V}$ in WMNs

3.5 Greedy Heuristic Dynamic Traffic Engineering

This section presents a greedy heuristic alternate solution G-DTE to the problem of DTE for high-throughput data forwarding problem that finds near optimal set of next-hop links and their power allocations so as to carry the aggregated upstream traffic flow by minimizing backlogged traffic.

3.5.1 Greedy Heuristic Traffic Splitting

The basis of the traffic splitting policy at each G-DTE router $v \in \mathbb{V}$ is to find a feasible traffic allocation vector (set of downstream links along with power allocation over them) $s \in \mathbb{S}_v$ so as to follow the flow conservation constraint (3.9). While computing s, priority is given to good quality forwarding links that require less power allocation to achieve the required rate, minimizing interference as well as congestion. As shown in Fig. 3.2, DTE component at each forwarding router, $v \in \mathbb{V}$, uses the control message feedbacks from neighboring nodes to compute the link quality. Thus, the G-DTE emphasizes improving spatial reuse in the neighborhood through reduced power allocation over each feasible outgoing link and hence it contributes to boosting the overall network throughput.

To rationalize a traffic splitting decision, each router $v \in \mathbb{V}$ evaluates the relative quality of each possible allocation vector $s \in \mathbb{S}_v$, by measuring its weight Ω_s as follows,

$$\Omega_s = \frac{\sum_{(vw)\in s} \omega_{(vw)}}{\delta_v(s) + \epsilon}. \tag{3.10}$$

Note that the higher value of Ω_s corresponds to a set of links that can achieve comparatively higher data rates while applying reduced power and vice-versa. A low-interfered and less-congested link contributes to achieving higher Ω_s value. In addition, allocation of lower powers on the good quality links to achieve the required rate in G-DTE helps it to improve the spatial reuse, increasing the network throughput.

In a G-DTE router $v \in \mathbb{V}$, the allocation vectors $s \in \mathbb{S}_v$ are sorted in descending order

Algorithm 1 G-DTE algorithm at each router $v \in \mathbb{V}$

Input: $\mathbb{S}_v$ and $\sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)}$

Output: $s \in \mathbb{S}_v$ and $r_{(vw)}$, $\forall (vw) \in s$

Compute Ω_s, $\forall s \in \mathbb{S}_v$ using Eq. 3.2
$\mathbb{S}_v = \{s_1, s_2, \dots, s_{|\mathbb{S}_v|} \mid \Omega_{s_1} \geq \Omega_{s_2} \geq \cdots \geq \Omega_{|\mathbb{S}_v|}\}$ \\Sorted in descending order
for $s' \in \mathbb{S}_v$ **do**
    if $\left(\sum_{(vw)\in s'} r^p_{(vw)} \geq \sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)}\right)$ **then**
        $s = s'$
        break
    end if
end for
if $\left(\sum_{(vw)\in s'} r^p_{(vw)} < \sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)}\right)$ **then**
    $s = s'$
end if
Compute $r_{(vw)}$, $\forall (vw) \in s$ using Eq.3.11

of their Ω_s values. In order to reconcile traffic splitting decision taken due to dynamically changing network conditions, a background agent continuously monitors and periodically updates sorting order of the elements in $\mathbb{S}_v$. The traffic splitting policy of a G-DTE router then sequentially checks the suitability of an allocation vector $s \in \mathbb{S}_v$ in a greedy way so that it meets the aggregated upstream flow demand, as shown in Algorithm 1. The execution of Algorithm 1 stops as soon as it finds a heuristically accepted solution; otherwise, it goes for the last allocation vector.

In order to distribute aggregated traffic load towards destinations through the set of selected forwarding links $(vw) \in s$ in proportion to their capacity in terms of congestion and contention, each G-DTE router $v \in \mathbb{V}$ splits traffic over the links with the designated power levels specified in the selected allocation vector $s \in \mathbb{S}$ as follows,

$$r_{(vw)} = min\left\{ r^p_{(vw)}, \sum_{(uv)\in\mathcal{L}^u_v} r_{(uv)} \times \frac{r^p_{(vw)}}{\sum_{(vw)\in s} r^p_{(vw)}} \right\}. \tag{3.11}$$

Thus, as the outcome of executing Algorithm 1 (in line 12), each G-DTE router $v \in \mathbb{V}$ finds the rate to be apportioned over the designated downstream links for the upcoming time interval. The computed forwarding rate $r_{(vw)}$ is then mapped to the closest possible discrete rate in $\mathbb{R}$. Note that the Algorithm 1 not only adjusts the traffic forwarding rates on the designated downstream links but also selects a set of good quality forwarders in a greedy heuristic way so that it can increase the throughput by means of minimizing interference as well as congestion.

3.5.2 Dynamic Traffic Engineering Control Knobs

Selecting of an allocation vector $s \in \mathbb{S}_v$ for a router $v \in \mathbb{V}$ is greatly influenced by the accurate and timely measurement of its Ω_s value. From Eq. 3.2, 3.3 and 3.10, it can be understood that the tuning control knobs for Ω_s are the achievable rate $r^p_{(vw)}$ at power level $p \in \mathbb{P}$ and offered rate $r^o_{(vw)}$ for each downstream link $(vw) \in s$ of a router $v \in \mathbb{V}$. The real-time measurement and update of these tuning parameters at router $v \in \mathbb{V}$ would ensure Algorithm 1 to take near-optimal traffic forwarding decisions so as to achieve better network throughput. Each downstream node w of a router v enables it to compute its $r^{p}_{(vw)}$ and $r^{o}_{(vw)}$ values through sending a periodic feedback message, called LIV (Link Information Vector). Next, we describe the dynamic measurement methods for these control knobs.

3.5.2.1 Achievable data rate of a link

Throughput of a forwarding link is significantly impacted by concurrent interfering neighboring links' transmission and amount of noise present on the link. Thus, as stated in section 3.5.1, each DTE router $v \in \mathbb{V}$ splits traffic over good quality downstream links, represented by their degree of interference and the noise present on forwarding links. Each upstream node v learns this as an average SINR value $\hat{\gamma}_{(vw)}$ of the link (vw) from its downstream node w in the LIV message. We allow each DTE downstream node w to compute $\hat{\gamma}_{(vw)}$ value for each link $(vw) \in \mathcal{L}^{u}_{w}$ by taking the weighted average of recent historical readings [106] as follows,

$$\hat{\gamma}_{(vw)} = \frac{\sum_{n=1}^{P} \gamma_{(vw)}(n) \times w_n}{\sum_{n=1}^{P} w_n}, \tag{3.12}$$

where,

$$w_n = \begin{cases} 1 - \frac{n-P/2}{P/2+1} & P/2 < n \leq P, \\ 1 & otherwise. \end{cases} \tag{3.13}$$

While finding the value of $\hat{\gamma}_{(vw)}$ over link (vw) from the received packets, we want to capture the real-time degree of interference as well as the variations over time. If we consider $P = 8$, four recent received packets are equally weighted at receiver and beyond that weights are gradually decreased. As soon as a router $v \in \mathbb{V}$ learns the recent value of $\hat{\gamma}_{(vw)}$, it is able to update the achievable rate over forwarding link (vw), $r^{p}_{(vw)}$, for a certain transmission power $p \in \mathbb{P}$, under the given $\hat{\gamma}_{(vw)}$, by consulting Eq. 3.1 and Table 3.1.

3.5.2.2 Offered data rate of a link

The proposed DTE policy necessitates dynamic adjustment of the data rates over the designated downstream links often taking into account the downstream nodes' forwarding capabilities. Here, each downstream router $w \in \mathbb{V}$ takes the responsibility of regulating its aggregated incoming traffic rate from the upstream. More specifically, each downstream node $w \in \mathbb{V}$ periodically signals its upsteam routers $v \in \mathbb{V}$ the rate adjustment factor β_w and queue congestion status ψ_w so that an upstream node v of w can calculate the offered data rate $r^o_{(vw)}$ for the link (vw), as described below.

First, we define and describe the computation processes of β_w and ψ_w values. The β_w of a router $w \in \mathbb{V}$ is the ratio of its aggregated offered rates towards all of its downstream links to its aggregated incoming traffic load, represented as follows,

$$\beta_w = \frac{\sum_{(wx)\in s,\ s\in \mathbb{S}_w} r^o_{(wx)}}{\sum_{(vw)\in \mathcal{L}^u_w} r_{(vw)}}, \tag{3.14}$$

where, $r^o_{(wx)}$ is the offered data rate over link $(wx) \in s$ for current allocation $s \in \mathbb{S}_w$, to be computed in Algorithm 2. Therefore, the value of rate adjustment factor β_w helps the G-DTE upstream routers to know about the forwarding capability of their downstream routers, which in turn facilitates adjustment of the forwarding rates dynamically over the next hop links (depicted in Algorithm 2). In other words, it helps in forwarding more data over good links and vice-versa. The queue congestion status, ψ_w, detects node level congestion by comparing the current queue occupancy, Φ_w, with predefined threshold levels Φ^{low}_w and Φ^{high}_w, and maximum queue size Φ^{max}_w; and, is computed as follows,

$$\psi_w = \begin{cases} 0 & \Phi_w \leq \Phi^{low}_w, \\ 1 & \Phi^{low}_w < \Phi_w < \Phi^{high}_w, \\ 2 & \Phi^{high}_w \leq \Phi_w \leq \Phi^{max}_w, \end{cases} \tag{3.15}$$

where, we set $\Phi^{low}_w = \frac{1}{\theta} \times \Phi^{max}_w$ and $\Phi^{high}_w = \Phi^{max}_w - \Phi^{low}_w$. Thus, the optimal values of Φ^{high}_w and Φ^{low}_w depend on the choice of θ, which in turn is controlled by desired queue occupancy and network utilization [107]. The queue of a forwarding router can be considered as an $M/M/1/K$ system and is found that the optimal values are $\Phi_w^{low} = 3$ packets and $\Phi_w^{high} = 9$ packets for $\Phi_w^{max} = 40$ and system utilization of 75% [107]. We set the value of ψ_w to 0 when the buffer in router w is under loaded, indicating no congestion. Future congestion is anticipated when ψ_w produces 1. Finally, the router w experiences congestion when traffic accumulating in the buffer exceeds high threshold Φ_w^{high} and we set $\psi_w = 2$.

Now, Algorithm 2 presents the computation process of offered data rate $r^o_{(vw)}$ of a link. In the initialization phase, it finds the current traffic rate $r_{(vw)}$ over each downstream link $(vw) \in \mathcal{L}_v^d$ under current allocation vector $s \in \mathbb{S}_v$, as computed by line 12 of Algorithm 1. Furthermore, node v exploits the wireless broadcast advantage (WBA) to learn the rates of the unexplored downstream links (downstream links that were absent in current $s \in \mathbb{S}_v$), i.e., the ψ_w and β_w values in LIV message carries this information. While finding the initial rate over an unexplored link (see lines 6 to 11 in Algorithm 2), a conservative choice is made for higher queue congestion status ($\psi_w = 1$ or $\psi_w = 2$) and $\beta_w \leq 1$. The computation of the offered rate, $r^o_{(vw)}$, is governed by the rate adjustment factor β_w. In such a case, a downstream router w offers $\beta_w > 1$ to its upstream node v, the proposed G-DTE increases the rate additively by a factor κ_1 and κ_2 of the increased amount of the allowable rate, following light and heavy congestion states of the downstream node respectively (see lines 16 to 18). On the other hand, if $\beta_w \leq 1$, the upstream node v decreases the forwarding rate proportionately, as shown in line 20. The κ_1 and κ_2 are the system design parameters and their values lie in the range $0 < \kappa_2 < \kappa_1 < 1$. For simulation experiments in this paper, we set $\kappa_1 = 0.5$ and $\kappa_2 = 0.25$ as depicted through numerous experiments.

The complexity of Algorithm 1 is quite straightforward. Firstly, in order to sort the set $\mathbb{S}_v$ in descendent order in line 2, we use quick sort algorithm which has the worst-case complexity of $O(|\mathbb{S}_v| \cdot \log |\mathbb{S}_v|)$. The statements in lines 4 to 7 are enclosed in a loop that iterates $|\mathbb{S}_v|$ times. The rest of the statements have constant unit time complexities. Therefore, the worst-case computational complexity of the algorithm is $O(|\mathbb{S}_v| \cdot \log |\mathbb{S}_v|)$. Algorithm 2 has the complexity of $O(|\mathcal{L}_v^d|)$ as it iterates over the list of downstream links

Algorithm 2 Computation of $r^o_{(vw)}$, $\forall(vw) \in \mathcal{L}^d_v$, at any node $v \in \mathbb{V}$

Input: β_w and ψ_w, $\forall(vw) \in \mathcal{L}^d_v$, $s \in \mathbb{S}_v$ and $r_{(vw)}$, $\forall(vw) \in s$

Output: $r^o_{(vw)}$, $\forall(vw) \in \mathcal{L}^d_v$

for $(vw) \in \mathcal{L}^d_v$ **do**
Initialization:
  if $(x_{(vw)} = 1) \in s$ **then**
    $r^{'}_{(vw)} = r_{(vw)}$
  else
    if $\big(\psi_w = 0 \text{ AND } \beta_w > 1\big)$ **then**
      $r^{'}_{(vw)} = max\Big\{r^{min} \times \beta_w, \frac{r^{min}+r^{max}}{2}\Big\}$
    else if $\big(\psi_w = 1 \text{ AND } \beta_w > 1\big)$ **then**
      $r^{'}_{(vw)} = min\Big\{r^{min} \times \beta_w, \frac{r^{min}+r^{max}}{2}\Big\}$
    else
      $r^{'}_{(vw)} = r^{min}$
    end if
  end if
Computation of $r^o_{(vw)}$**:**
  if $\big(\psi_w = 1 \text{ AND } \beta_w > 1\big)$ **then**
    $r^o_{(vw)} = r^{'}_{(vw)} + \kappa_1 \times (r^{'}_{(vw)} \times \beta_w - r^{'}_{(vw)})$
  else if $\big(\psi_w = 2 \text{ AND } \beta_w > 1\big)$ **then**
    $r^o_{(vw)} = r^{'}_{(vw)} + \kappa_2 \times (r^{'}_{(vw)} \times \beta_w - r^{'}_{(vw)})$
  else
    $r^o_{(vw)} = r^{'}_{(vw)} \times \beta_w$
  end if
  $r^o_{(vw)} = min\big\{r^{max}, r^o_{(vw)}\big\}$
end for

$\mathcal{L}^d_v$ of node $v \in \mathbb{V}$.

3.6 Performance Evaluation

In this section, we implement O-DTE, G-DTE, MRA [48], MRT [5] and CLC_DGS [6] in a discrete-event network simulator, ns-3 [51] and present the comparative performance results. In implementation of O-DTE, we have explored all possible assignments of power and data rates on all downstream links to find out the optimal allocation using the objective function of Eq. 3.4. However, for G-DTE implementation, we look for the first feasible set of links that satisfies the demand constraint from the list of descending order sorted allocation vectors, as described in Algorithm 1. The MRA is a refinement over existing multi-path routing algorithms that provide a distributed solution to compute multiple mutually interference-free minimum hop-count based paths toward destination. Governed by centralized controller, the MRT and the CLC_DGS are operational under collision-free scheduling. Note that there is no consideration of employing multiple gateways in MRA and MRT. For fairness of the comparison, we let MRA and MRT algorithms randomly choose a gateway for traffic forwarding. In MRT, multiple paths between source-destination pairs are added to enhance throughput. The CLC_DGS focuses on balancing traffic load toward multiple gateways which incorporates an optimal traffic splitting strategy with rate control, routing and scheduling.

3.6.1 Simulation Environment

To evaluate the effectiveness of our proposed DTE approach, in all simulation experiments, we use IEEE 802.11 DCF with RTS/CTS as MAC layer protocol. We consider a static WMN with 50 nodes (46 mesh routers and 4 gateways), with uniform random distribution in an area of $1000 \times 1000\ m^2$ area. Each node is equipped with at most four IEEE 802.11a interfaces and communicates over fixed allotted channel chosen among 8 available orthogonal channels. Each link is allowed to pick up a transmission rate among eight feasible data rates: 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. We use the channel assignment algorithm proposed in [17] to statically assign channel to each interface, minimizing interference in the network. Each node can transmit at maximum power $p^{max} = 100mW$

Table 3.2: Simulation parameters

Parameter	Value
Total area	1000m × 1000m
Number of nodes, GWs	50, 4
Wifi standard	IEEE 802.11a
Path loss model	FrissPathLossModel
RTS/CTS	Enabled
Transmit power	10mW - 100mW
Noise density	-174 dBm/Hz
Number of radios/node, orthogonal channels	4, 8
Traffic type, packet size	UDP, 1000 Bytes
Simulation time	500s

and minimum power $p^{min} = 10mW$ and is allowed to choose from 10 different discrete power levels $[10mW, 20mW, \ldots, 100mW]$.

In our simulation, we use the constant bit rate (CBR) traffic model under UDP for data transmission with a packet size of 1000 bytes. The sources are selected independently at random for each simulation run and kept fixed during the simulation period. All flows are generated from the edge routers towards the gateways. Each node computes the set of next hops towards destinations using MP-OLSR [55] algorithm. The simulation parameter settings are listed in Table 5.1.

3.6.2 Performance Metrics

We have used the following metrics for the comparative performance analysis.

- *Aggregated flow throughput* ($\mathcal{F}^t$): Network aggregated flow throughput is the total amount of data bytes received at destinations in unit time.

- *Average end-to-end delay* ($\mathcal{F}^d$): It is defined as the average of latency for all received packets at destinations to measure the timeliness of packet transmission.

- *Packet delivery ratio* ($\mathcal{F}^r$): In order to measure the reliability of transmission, packet delivery ratio is measured as the ratio of the number of packets received at all destinations and the number of packets that have been sent from all sources.

- *Flow fairness* ($\mathcal{F}^f$): To investigate the fairness ability of the considered approaches, we use Jain's fairness index [108]. The fairness index could vary between 0 and 1. The closer the fairness index is to 1, the fairer is the bandwidth allocation.

- *Operation overhead* ($\mathcal{F}^o$): The amount of control bytes exchanged per successful data byte transmission constitutes the operation overhead, *i.e.*, we are measuring the portion of cost each mechanism pays for each byte of successful data transmission.

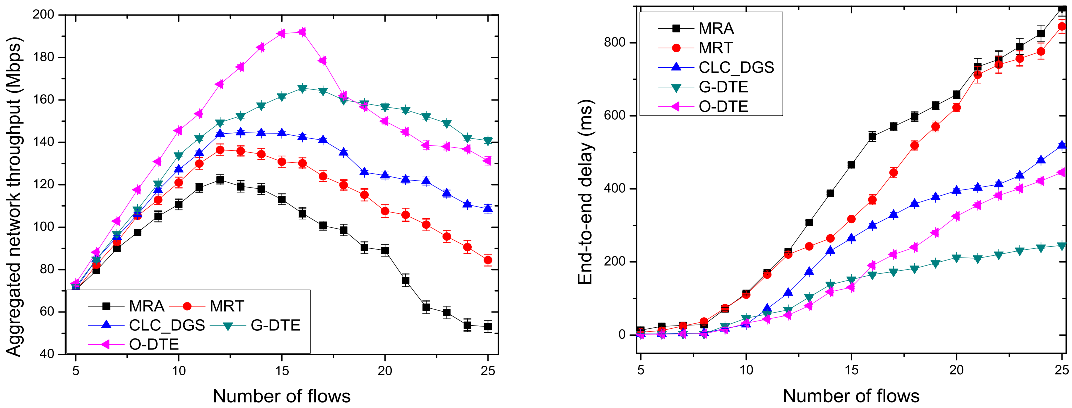
- *Integrated performance gain* ($\mathcal{F}^i$): We measure the integrated performance of each studied mechanism as $\frac{\mathcal{F}^t \times \mathcal{F}^r}{\mathcal{F}^o \times \mathcal{F}^d}$, which quantifies the overall performance of the approach. We then calculate the G-DTE performance gain, $\mathcal{F}^i = \frac{\mathcal{F}^i_{DTE}}{\mathcal{F}^i_X}$, where, $X \in$ {MRA, MRT, CLC_DGS, O-DTE}.

3.6.3 Simulation Results

For each data value provided in the graphs, we have taken the average results from 20 simulation runs and have shown their confidence intervals.

3.6.3.1 Impacts of increasing number of flows

In this experiment, we randomly select sources to generate flows at 15 Mbps rate and vary the number of flows from 5 to 25. In MRA, minimum-hop-count based path construction leads to bottleneck congestion, which is not addressed and adjusted while traffic forwarding. Thus, throughput drops abruptly as flow intensity is increased as shown in Fig. 3.3(a). The MRT keeps adding multiple paths as long as higher throughput is guaranteed. However, the capacity variations over the selected paths due to link quality and/or

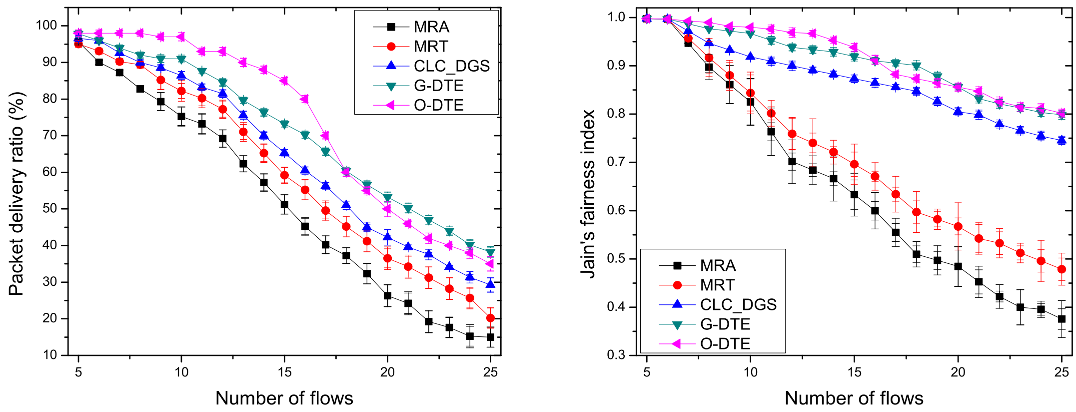


(a) Throughput (b) Average end-to-end delay

Figure 3.3: Throughput and delay performance vs. number of flows in WMNs

increased flows are not rectified, causing degraded network throughput. The CLC_DGS shows significant throughput improvement over MRA and MRT as each forwarding node dynamically splits traffic towards least congested gateways. The distributive and dynamic traffic splitting policy of G-DTE routers based on real-time measurement of the forwarding link's quality and capacity helps it to exploit good quality next hops toward destinations. Near-optimal power allocation over forwarding links induces increased spatial reuse of channels in neighborhood and concurrent flows are thus allowed to experience higher throughput, contributing to raising overall network performance. As O-DTE computes the optimal traffic splitting, it exhibits higher throughput than all other approaches in lightly loaded scenarios. However, the O-DTE routers require higher computation time to take traffic forwarding decisions under higher traffic load and varying network conditions; deteriorating throughput performance.

Fig. 3.3(b) shows the average end-to-end packet delay for the studied approaches under varying traffic loads, which reveals that the proposed G-DTE ensures the lowest packet delivery delay. Static traffic splitting policy employed by MRA and MRT restricts them to forward traffic over pre-computed routes which may become saturated under excessive traffic demand. Thus, packets experience collisions, drops and retransmissions;



(a) Packet delivery ratio (b) Flow fairness

Figure 3.4: Packet delivery ratio and flow fairness vs. number of flows in WMNs

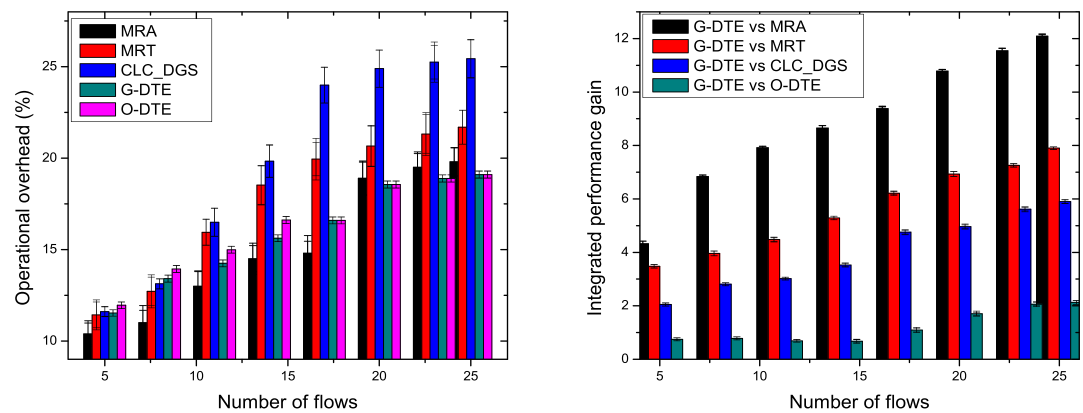
greatly impacting delivery time. On the other hand, as G-DTE is capable of adaptively splitting traffic over higher capacity downstream links, traffic is always routed through least congested areas. Thus packet service time and rate is significantly improved at each hop to maintain timeliness of delivery. Due to higher computing time, O-DTE is unable to react on instantaneous network conditions, which may lead to forward traffic over congested and interfered paths; deteriorating end-to-end packet transmission delay. In CLC_DGS, as packet scheduling is governed by central controller, frequency of control message exchange between the forwarding routers and the controller significantly increases with higher number of flows activated in the network, resulting in enlarged packet delays.

In Fig. 3.4(a), G-DTE is shown to achieve higher packet delivery ratio than the state-of-the-art works under higher traffic load due to its interference and congestion-aware dynamic traffic splitting policy. Real-time monitoring of downstream link quality, experienced interference and offered rates, allow each G-DTE router to choose good quality routes that maximize the packet delivery probability. In O-DTE, the prolonged traffic splitting decision restricts the forwarding router to react to the network dynamics promptly, resulting in poor forwarding decision and hampering successful packet delivery.

However, due to the static traffic splitting policy, MRA and MRT show poor reliability in terms of successful packet delivery.

Ensuring flow fairness in multi-hop wireless networks is a challenging issue which should be addressed by the traffic forwarding mechanism of a node. As shown in Fig. 3.4(b), the fairness index significantly falls with increasing offered load in MRA as flows traversing several hops are unfairly regulated. In MRT, sources willing to inject flows in a highly loaded neighborhood fails to find an accommodation, as usage of link bandwidth is already saturated. Thus, under the presence of immense traffic volume, only a subset of flows are properly regulated. Upstream arriving traffic at an O-DTE router receives unfair treatment due to obsolete forwarding decisions, dropping the flow fairness index. In G-DTE, LIV notifications regulate upstream flows according to rate adjustment factor, where each flow is awarded a fair share of its constituent demand. Thus, demand-proportional upstream flow rate control ensures weighted flow fairness even in a congested network, which is a distinguishable achievement of our proposed G-DTE approach.

Now, all the improvements in throughput, delay, delivery ratio and flow fairness do not materialize without any outlay. While forwarding aggregated traffic over multiple next



(a) Operation overhead

(b) Integrated performance gain

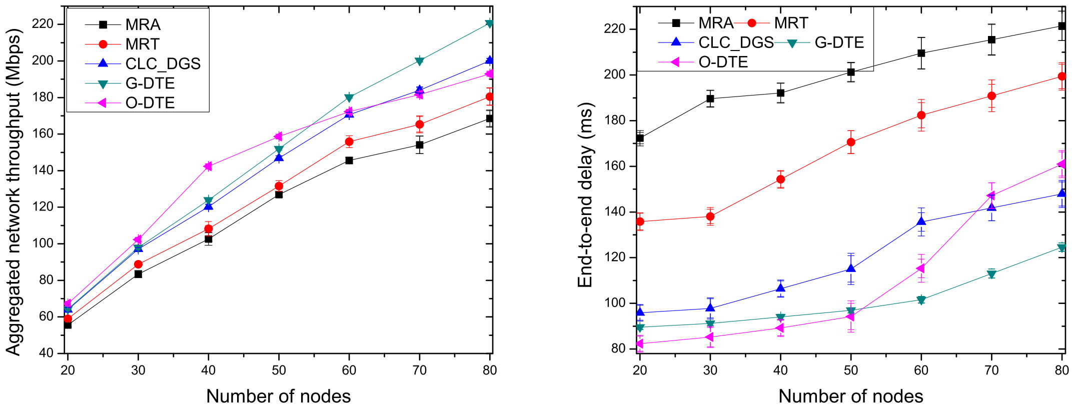
Figure 3.5: Operation overhead and integrated performance gain vs. number of flows in WMNs

hops, the O-DTE and G-DTE routers solely depend on LIV feedbacks of downstream routers. Each LIV packet is 25 bytes long (2 bytes of frame control + 8 bytes SINR feedback ($\hat{\gamma}$) + 4 bytes of rate adjustment factor (β) + 2 bits of queue congestion status (ψ) + 6 bytes of receiver address + 4 bytes of FCS). The parameters ($\hat{\gamma}$, β, ψ) in LIV helps DTE to exactly model the consequence of selecting the corresponding downstream for traffic forwarding. Thus, exchange of additional control packets over each radio interface periodically (in every 1 second), along with the RTS/CTS, ACK, etc. packets, notably increase the operation overhead of DTE. As shown in Fig. 3.5(a), the operation overheads of our proposed O-DTE and G-DTE systems are much lower than those of MRT and CLC_DGS, but slightly higher than that of MRA. However, this small overhead is nicely compensated by the integrated performance gain of our proposed systems, as shown in Fig. 3.5(b). In order to schedule collision-free transmission, MRT and CLC_DGS have to consider significant overheads due to exchange of huge control messages. Particularly in CLC_DGS, the central controller needs to know the queue occupancy status at each router to take routing and scheduling decisions. The overall performance improvements of O-DTE over G-DTE is significantly higher as long as traffic load is moderate, but worsens with excessive load conditions. Also, note that, our proposed G-DTE approach exhibits higher stability which is revealed from reduced confidence interval, as depicted in Fig. 3.3 - 3.5.

3.6.3.2 Impacts of varying network size

Scalability is one of the most critical factors influencing WMN performances. The network performance typically degrades with increase in network size. In this section, we have considered different dimensions of WMNs to test the scalability of DTE and state-of-the-art approaches. We have varied the network size by varying the number of nodes from 20 to 80 and maintained the same node density. The offered load to each network is kept in between the range of 65% to 75% of the network's total effective capacity.

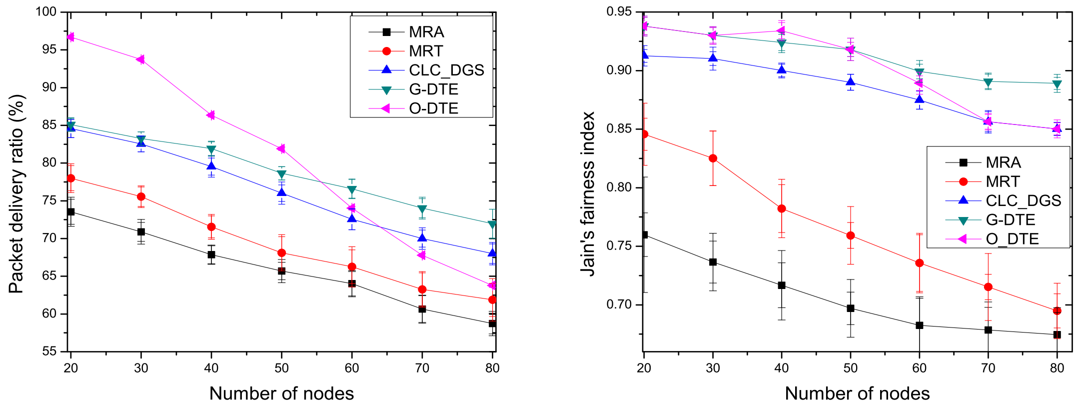
The dynamic traffic splitting policy of G-DTE adapts the changing network environment and thus results in throughput enhancement, as depicted in Fig. 3.6(a). For



(a) Throughput (b) Average end-to-end delay

Figure 3.6: Throughput and delay performance vs. number of nodes in WMNs

increased number of nodes, a G-DTE router gets the opportunity to explore more alternate downstream links to forward aggregated traffic through dynamic power allocation, minimizing neighborhood interference and granting other contending routers access to the channel to improve overall network throughput. In O-DTE, the time gap between network environmental changes and the execution of the corresponding traffic splitting decisions increases exponentially with the number of nodes in the network. As a consequence, traffic splitting decisions are executed based on old forwarding table. The simulation results show how the aggregated network throughput deteriorates with varying network size. In MRA, source node computes interference-free paths toward destination by computing maximal independent set from given path graph, which is an NP-hard problem and associates high overhead with higher network dimensions, impacting delay and throughput. As MRA does not incorporate interflow interference and path congestion during path selection, each source is forced to forward traffic towards network bottleneck, which further degrades the performance. The MRT and CLC_DGS suffer from higher forwarding delay in large scale network due to dissemination of huge control signals that can consume network bandwidth and impact on flow throughput. Though the real time traffic splitting policy of G-DTE requires LIV message exchanges and incurs additional

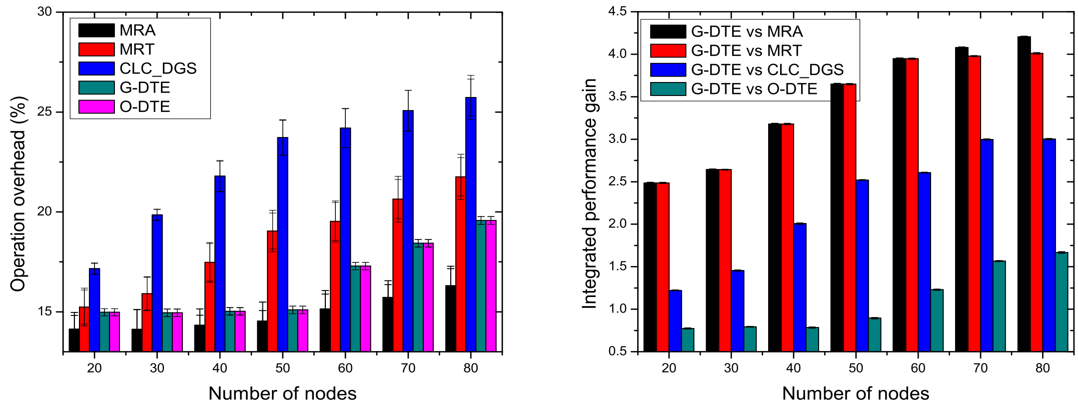


(a) Packet delivery ratio (b) Flow fairness

Figure 3.7: Packet delivery ratio and flow fairness vs. number of nodes in WMNs

overhead, unlike other state-of-the-art work, it refrains from multi-hop control message propagation, helping it to show improved performance.

Fig. 3.7(a) shows the inclination in successful packet delivery ratio with increased network size. Networks with smaller number of nodes exhibit lower losses because of lower interferences and less number of hops between source-destination pairs. The delivery ratio deteriorates with growing network size, as can be anticipated theoretically. G-DTE outperforms all other schemes significantly, as the learning of forwarding link quality in every time epoch through LIV guarantees successful data forwarding towards destination through less-congested areas. Fig. 3.6(b) reveals that average end-to-end delay performance decline in networks of larger dimensions in all the studied algorithms as the number of hop count between each source-destination pair increases. The MRT is impacted most due to its conservative choice of routing paths. Our in-depth look into the simulation log files suggests that the proposed G-DTE minimizes the number of concurrent transmitting links over the same channel, queuing time at buffers as well as packet service time, and thus reducing packet delivery time significantly. On the other hand, the end-to-end delay of data packets in O-DTE system increases exponentially at higher network size due to the accumulated longer decision making times at intermediary hops



(a) Operation overhead

(b) Integrated performance gain

Figure 3.8: Operation overhead and integrated performance gain vs. number of nodes in WMNs

between source-destination pairs.

Each forwarding router in our proposed G-DTE framework pro-actively regulates the incoming traffic flow rates in proportion to their demands. Thus, each upstream flow receives proportionally fair treatment from each downstream routers, which is reflected in the graphs of Fig 3.7(b). But in O-DTE, with increased number of nodes, as the traffic-split decision time grows exponentially, incoming flows are refrained from being rewarded with required proportionate fairness. We also observe that with increasing number of nodes in the network, the operational overhead of MRT and CLC_DGS is very high, as shown in Fig. 3.8(a), and this is caused by excessive control message transmissions in between the routers and the central controller. As a consequence, we find in Fig. 3.8(b) that the proposed G-DTE has significant integrated performance gain over other approaches.

3.6.3.3 Impacts of bursty traffic arrivals

Responsiveness of any traffic forwarding algorithm can prove crucial in dynamic scenarios and depends on the speed with which it recalculates and applies route computation and

Table 3.3: Traffic bursts activated during different time intervals of the simulation period

100s - 120s: 30 - 40 flows	300s - 320s: 50 - 60 flows
150s - 165s: 50 - 60 flows	350s - 365s: 70 - 80 flows
200s - 220s: 70 - 80 flows	400s - 420s: 40 - 50 flows
250s - 270s: 30 - 40 flows	450s - 465s: 50 - 60 flows

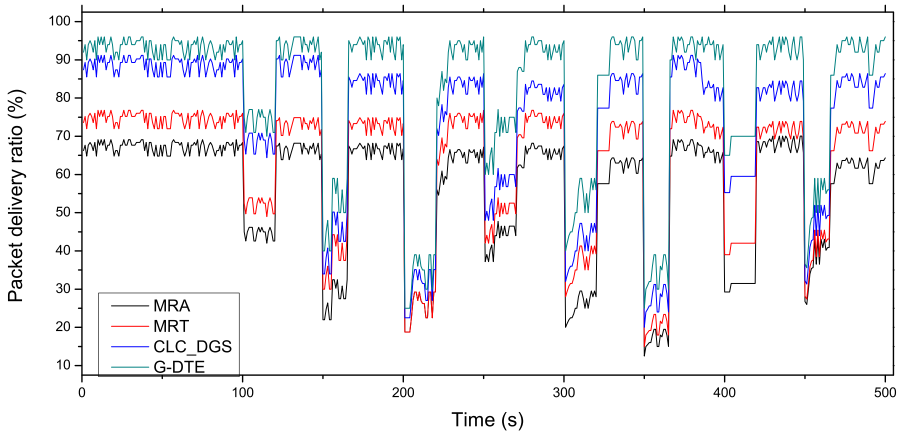


Figure 3.9: Impacts of bursty traffic arrival in aggregated network throughput.

traffic splitting when network conditions change. In this subsection, we illustrate the importance of responsiveness under a highly dynamic traffic model. Here, we consider the impact of inducing dynamic traffic bursts at different time instants in a WMN consisting of 50 nodes. During the 500 seconds duration of the simulation period, we have randomly activated 15 - 20 flows in the network with a data rate of 10 Mbps each, along with the events of dynamic traffic arrivals during the time periods as listed in Table 3.3.

From the graphs of Fig. 3.9 and 3.10, we observe that the adaptation capability of our proposed G-DTE is higher than that of other approaches. Along with ensuring steady flow throughput during moderate traffic loads, the G-DTE is able to retain higher throughput than other approaches even at bursty traffic durations. The MRT and CLC_DGS are

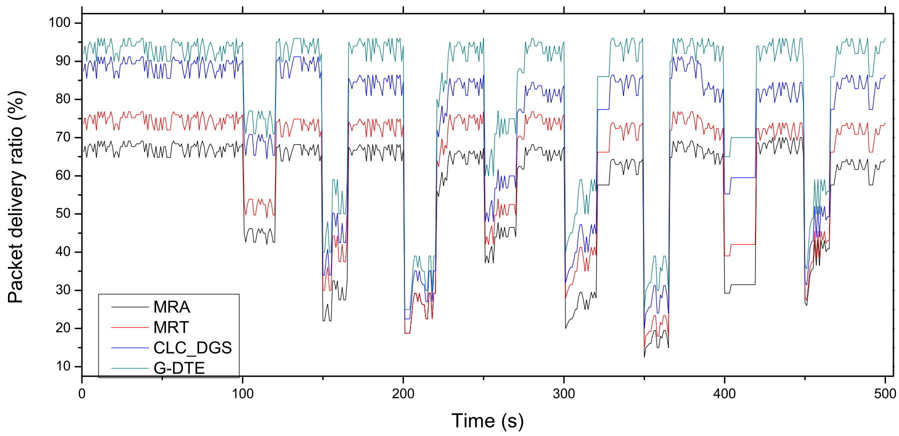


Figure 3.10: Impacts of bursty traffic arrival in packet delivery ratio.

prone to congestion collapse due to exhaustive exchange of control messages among the forwarding routers and the central controller that might incur higher number of collisions, resulting in degraded network performances. The MRA reacts to sudden traffic surge worst as the sources are bound to inject traffic into pre-computed mutually interference-free paths. Thus, dynamic traffic arrival, which is a common phenomena in WMNs carrying the Internet traffic, can be better addressed and accommodated by our proposed G-DTE approach.

Though it is revealed through simulation traces and performance analysis in the previous paragraphs that the G-DTE system outperforms in most of the cases over the simulated parameters compared to the state-of-the-art works, there are some scenarios where the performance improvement is not very significant. In networks with smaller number of nodes, there are very few available alternate paths between pair of forwarding routers, which limits the choice of forwarding links in traffic splitting operation of G-DTE. In those cases, the G-DTE has rewarded performance outcome comparable to MRT and CLC_DGS. Also real-time congestion and interference monitoring through exchange of LIVs between every forwarding link pair induces around 12% to 21% of overhead, which is significant in networks with lower bandwidth capacities.

3.7 Summary

In this work, we advance the study of high-throughput data forwarding strategies in Wireless Mesh Networks (WMNs) and explore two dynamic traffic engineering (DTE) approaches: optimal DTE (O-DTE) and greedy DTE (G-DTE). Since the O-DTE explores all possible power and rate allocations to available outgoing links, it maximizes the throughput via minimizing interference and congestion; however, it becomes an NP-hard problem. The G-DTE routers contribute to obtain near optimal throughput in distributed fashion via suitable selection of forwarding links and rate allocations over them. The results of simulation experiments depict that the proposed O-DTE and G-DTE systems achieve 19%, 12% and 5% higher throughput compared to MRA, MRT and CLC_DGS, respectively.

One of the important limitations, of the proposed DTE solutions, is the consideration of static channel allocation over the communication links in between mesh routers. Thus DTE routers are unable to divert traffic over least interfered and congested channels dynamically. In future, we intend to develop dynamic traffic engineering policies for WMNs, those are able reallocate channels over radio interfaces to enhance flow performance.

Chapter 4

Traffic Engineering in Mesh Networks with Dynamic Channel Allocation

4.1 Introduction

Wireless Mesh Networks (WMNs) have gained high popularity in the past few years since it facilitates easy deployment of wireless Internet infrastructure to wide variety of devices and applications running on desktops, smartphones, tablets, sensor nodes, etc [2, 3]. The exponential growth of traffic volume, has imposed the need for greater capacity and throughput. Wireless mesh routers, equipped with multiple radio interfaces that can operate on multiple orthogonal (non-overlapping) channels, are expected to provide better data delivery services [22, 89]. However, the network performance greatly depends on the appropriate assignment of channels on different links and allocation of powers on those. It's a challenging problem due to dynamically varying network conditions - noise and interferences, traffic volume and congestion, etc.

The aforementioned problem has been studied in the literature exploiting different ways - jointly selecting the routing path and channels on the links in [82, 109, 110], routing path and rate selection in [111], and routing path and channel selection along with their rate allocations [8, 22, 89]. End-to-end least congested path computation and link-load sensitive channel allocation approach to forward time-varying traffic is studied in [82]. In [109] and [110], topology and channel bandwidth information is disseminated over the network to facilitate each node to distributively compute path and channel allocation. A centralized approach for multipath traffic splitting and rate allocation aiming at minimizing queue congestion has been presented in [111]. The poor scalability problem of [111] has been addressed by a distributed traffic forwarding mechanism proposed in [112], which considers instantaneous link interference and path congestion. Though efficient rate allocation by controlling transmission power enables [112] to improve throughput performance, but consideration of static channel allocation limits link capacity. The routing path selection, channel assignment and rate allocation problems are jointly addressed in [22] and [89], where flows are routed over least-loaded and minimal-interfered single shortest path. Though [22] is able to improve spatial channel reuse by intelligent power control over links, consideration of protocol model to find interference and central controller-based solution limit its practical applicability. Furthermore, single-path data delivery is often unable to accommodate flow demand. In [8], traffic is forwarded over those multiple paths that exhibit less co-channel interferences. However, using fixed end-to-end paths in a highly dynamic network environment, can't often achieve good throughput.

In this Chapter, we develop a joint link-channel selection and power allocation system, namely LCP, that follows hop-by-hop traffic splitting approach. Each LCP router exploits single-hop information only to forward its upstream traffic over least-congested and minimally-interfered link-channel pairs, which in turn improves spatial reuse of bandwidth channels and thus helps to improve overall network throughput.

4.1.1 Contributions

The major contributions of this work are summarised as follows,

- We develop a mixed integer non-linear programming (MINLP) optimization, namely optimal LCP (OLCP), that maximizes the forwarding traffic throughput while reducing co-channel interference and congestion.

- Due to NP-hardness of the above OLCP, we then develop a greedy heuristic solution for the problem, namely GLCP, which greedily chooses good quality link-channel pairs and heuristically assigns the higher powers or selects more link-channel pairs.

- Our simulation results from ns-3 [51] show better performance in terms of throughput, delay and fairness compared to state-of-the-art works.

4.1.2 Organization

The rest of this Chapter is organized as follows. Section 4.2 reviews related works. Section 4.3 presents network model and assumptions. In Section 4.4, the joint optimization problem is formed and the greedy heuristic solution is described in Section 4.5. Section 4.6 presents the simulation performances and Section 4.7 concludes the Chapter.

4.2 Related Works

A significant number of centralized and distributed traffic forwarding solutions are proposed for enhancing the performances of multi-radio multi-channel (MRMC) WMNs based on routing, channel assignment (CA) and rate allocation (RA); either independently or jointly.

Dynamic channel allocation is able to improve network throughput by minimizing co-channel interference and thus allowing more concurrent transmissions, but is greatly impacted by routing solution of traffic streams. So, many state-of-the-art works consider cross layer solutions to routing and channel allocation jointly. A centralized solution presented in [109], characterizes dynamic network traffic to identify cycles of similar pattern and for each traffic profile, computes optimal multiple paths toward multiple gateways and channel allocations over them to minimize congestion. The performance of the solution solely depends on accurate traffic profiling. Available link bandwidth is estimated incorporating interferers' transmissions and disseminated over the network, to assist each node to distributively compute optimal paths in [110]. However, this approach requires significant overhead and network updates. A hybrid MRMC WMNs architecture is proposed in [82], where fixed end-to-end routing paths are established over fixed radios, and dynamic radios communicates over least congested channel under higher traffic demand. Use of only one dynamic radio interface, refrains forwarding router to utilize higher achievable bandwidth over least interfered channels.

Considering the channel switching overhead, many works in the literature considers fixed channel allocation over multiple radios in WMNs, and focus on finding flow routes and link-rates to improve flow performance. A joint traffic splitting, rate control, routing and scheduling algorithm is developed in [111], aiming to maximize network aggregated throughput, where each router optimally apportions the traffic of a flow over multiple paths in a ratio to their corresponding downstream node's queue congestion status, leading toward multiple gateways. Here, a centralized controller is responsible to schedule collision-free transmissions prioritizing links with higher backlogged traffic. However, the employment of a centralized controller increases the scheduling delay, which is often based on obsolete information. However, the distributed traffic forwarding solution G-DTE (Greedy Dynamic Traffic Engineering) [112], proposed in our earlier work, exploits one-hop neighboring state to select optimal set of forwarding links and rate (power) allocations over those; is able to react to instantaneous changes promptly. But, consideration of static channel allocations over the multiple radios here limit the link-capacity under interfered and congested neighborhood.

Works focused to solve joint routing, channel and rate allocation problem has recently attracted the researchers. [89] is a centralized joint approach, where flows are routed over least loaded shortest paths toward destinations. Here a channel allocation heuristic is used to assign channels over links aiming at minimizing neighborhood interference while prioritizing the congested ones. [22] first computes routes for flows and then determines the load over each link. High loaded links are assigned higher rate by intelligent power allocation. However, consideration of protocol model to find interference limits its practical applicability. Aiming to improve channel spatial reuse, [7] computes set of active links and maximum possible rates over those links through minimizing their interference range by optimal transmission power allocation. Further, routes are computed over them to find higher capacity paths for the flows. Both the optimal and suboptimal solutions proposed in ROPIM (Robust Outage Probability based Interference Margin) [8], split traffic over multiple paths by selecting the channels over the links so that links experience minimum interference and corresponding link-rate in increased. Considering fixed end-to-end path along with known traffic demand, limits the performance of the solution in a dynamic environment. All the aforementioned joint solutions depend on a central controller, which require a complete view of the network dynamics in order to solve the joint problem. Thus, the required convergence time can make those solutions unsuitable for highly dynamic scenarios.

4.3 System Model and Assumptions

To represent a wireless mesh network, we use a graph, $\Gamma = (\mathbb{V}, \mathbb{E})$, as considered in Section 3.3. Furthermore, we consider $\mathbb{C} = \{c_1, c_2, \ldots, c_k\}$ to hold the set of orthogonal frequencies to be used for data transmission in Γ and each node $v \in \mathbb{V}$ has I_v number of radio interfaces, which operates on an orthogonal channel chosen from the channel set $\mathbb{C}_v \subset \mathbb{C}$ dynamically, so as to facilitate enhanced network capacity [89]. We assume a wireless link (vw), if a frequency channel c, where $c \in \mathbb{C}_{(vw)}$ and $\mathbb{C}_{(vw)} = \mathbb{C}_v \bigcap \mathbb{C}_w$, is assigned to one of the radio interfaces of node v and w, over which they communicate. Again, we consider the binary variable $x_{(vw)}$ to contain 1 if the link (vw) is active, and 0 otherwise (same as Section 3.3). For each node $v \in \mathbb{V}$ and channel $c \in \mathbb{C}_v$, we define the node-channel variable as follows:

$$z_v^c = \begin{cases} 1 & if\ \exists (vw) \in \mathbb{E} \mid x_{(vw)}^c = 1, \\ 0 & otherwise. \end{cases} \tag{4.1}$$

While transmitting over link (vw) and channel c, node v selects a discrete transmission power, $p_{(vw)}^c$, from the set $\mathbb{P} = \{p^{min}, \ldots, p^{max}\}$, allowing corresponding achievable data rate, $r_{(vw)}^{c,p} \in \mathbb{R}$, using a specific MCS (modulation and coding scheme) [8], as discussed in Section 3.3.2. Here $\mathbb{R}$ consists of set of discrete rate values in the range $[r^{min}, \ldots, r^{max}]$, where each achievable rate r, has a signal-to-noise-plus-interference ratio (SINR), $\gamma(r)$, requirement. IEEE 802.11a/g system supports 8 different transmission rates, $r \in \mathbb{R}$, corresponding to minimum SINR values, $\gamma(r)$, as shown in Table 3.1 [8]. The SINR value computed at receiver w, when transmitter v uses power $p \in \mathbb{P}$ to transmit over link (vw) and channel c, is as bellows:

$$\gamma_{(vw)}^{c,p} = \frac{p_{(vw)}^{c} \mathcal{G}_{(vw)}}{\eta_{(vw)}^{c} + N_0}, \tag{4.2}$$

where, $\mathcal{G}_{(vw)}$ represents channel gain, that depends on path loss, fading and shadowing etc.; $\eta_{(vw)}^{c}$ is the corresponding interference experienced at node w due to concurrent transmission of neighboring links on channel c and N_0 is the Gaussian noise. Each node $w \in \mathbb{V}$, senses the amount of interference present at each channel $c \in \mathbb{C}_w$ and communicates to its one-hop neighbors periodically. Thus each router $v \in \mathbb{V}$, is aware of the interference present at each downstream link $(vw) \in \mathcal{L}_v^d$, $\eta_{(vw)}^{c}$, $\forall c \in \mathbb{C}_v$. In order to achieve rate $r \in \mathbb{R}$, over link (vw), the experienced SINR should meet the threshold value requirement; i.e. $\gamma_{(vw)}^{c,p} = \frac{p_{(vw)}^{c} \mathcal{G}_{(vw)}}{\eta_{(vw)}^{c} + N_0} \geq \gamma(r)$. Now, to find the maximum interference tolerable over link (vw) to achieve $\gamma(r)$, on transmission power p and channel c is as follows:

$$\eta_{(vw)}^{c,p}(r) = \frac{p_{(vw)}^{c} \mathcal{G}_{(vw)}}{\gamma(r)} - N_0 \tag{4.3}$$

Thus, the interference degree of link (vw), operating on channel c and power p can be defined as:

$$\xi_{(vw)}^{c,p} = \frac{\eta_{(vw)}^{c}}{\eta_{(vw)}^{c,p}(r)}, \tag{4.4}$$

where, $0 \leq \xi_{(vw)}^{c,p} \leq 1$ and higher values indicate higher interference present over link (vw) on channel c.

4.4 Optimization Framework for Link-Channel Selection and Power Allocation

In this section, we formulate and analyze the joint problem of downstream link-channel selection and power allocation for each forwarding router $v \in \mathbb{V}$ in the network. Our goal for the joint problem is to maximize the network aggregated throughput, by finding a feasible traffic forwarding decision, at each router while minimizing neighborhood interference, path congestion, overhead and ensuring flow fairness.

Let, for each link $(vw) \in \mathcal{L}_v^d$, the tuple $(x_{(vw)}, c_{(vw)}, p_{(vw)})$ represents the activation status, channel and power allocation over link (vw) at any given time, where $x_{(vw)}^c \in \{0,1\}$, $c \in \mathbb{C}_{(vw)}$ and $p \in \mathbb{P}$. Let $\mathbb{Q}_{(vw)} = \{(x_{(vw)}, c_{(vw)}, p_{(vw)})\}$, be the set of all possible allocation vectors over each link $(vw) \in \mathcal{L}_v^d$ and $\mathbb{S}_v = \prod_{(vw)\in\mathcal{L}_v^d} \mathbb{Q}_{(vw)}$ be the set of all possible allocations over set of downstreams of node v. Now, our problem boils down to finding a suitable allocation, s_v, for each router $v \in \mathbb{V}$, consisting of allocation tuples, $\big\{(x_{(vw)}, c_{(vw)}, p_{(vw)})\big\}$, that achieves the aforementioned goal.

While selecting the optimum s_v, for each $v \in \mathbb{V}$, we opt to maximize the capacity-demand ratio of the allocation s_v to ensure maximum upstream flow throughput, which is defined as following:

$$\sigma(s_v) = \frac{\sum_{(vw)\in s_v} r_{(vw)}}{\sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)}} \tag{4.5}$$

where, $\sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)}$ is the aggregated upstream traffic and $\sum_{(vw)\in s_v} r_{(vw)}$ is the aggregated downstream traffic split over the set of selected downstream links $(vw) \in s_v$.

Here, in order to distribute aggregated upstream traffic toward destinations through the set of selected forwarding links, $(vw) \in s_v$, in proportion to downstream links' capacity in terms of congestion and contention, each router $v \in \mathbb{V}$ splits traffic over the links with the designated power levels specified in the selected allocation vector, s_v, as follows:

$$r_{(vw)} = min\Bigg\{r_{(vw)}^o, r_{(vw)}^{c,p}, \sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)} \times \frac{r_{(vw)}^{c,p}}{\sum_{(vw)\in s} r_{(vw)}^{c,p}}\Bigg\}, \tag{4.6}$$

where $r_{(vw)}^o$, is the offered rate over link $(vw) \in \mathcal{L}_v^d$, considering the congestion present at downstream node w, where detailed computation of $r_{(vw)}^o$ is given in Algorithm 2 in Section 3.5.2.1.

While maximizing $\sigma(s_v)$, for each router $v \in \mathbb{V}$, our aim is also to enhance the spatial reusability by allocating optimal transmission powers over the selected links $(vw) \in s_v$;

which is possible by assigning the least interfered channels over the links. Thus, we require to allocate optimum set of powers over $(vw) \in s_v$ to activate required rates, $r^{c,p}_{(vw)}$, $\forall (vw) \in s_v$, while minimizing total interference degree of allocation s_v, $\sum_{(vw)\in s_v} \xi^{c,p}_{(vw)}$.

Hence, our proposed optimal link-channel selection and power (rate) allocation problem, OLCP, is formulated as follows:

$$\underset{s_v \,\in\, \mathbb{S}_v}{\textbf{argmax}} \quad \left\{ \sigma(s_v) - \frac{\sum_{(vw)\in s_v} \xi^{c,p}_{(vw)} \times \hat{p}^{c}_{(vw)}}{|s_v|} \right\} \tag{4.7}$$

s.t.

$$x_{(vw)} \in \{0,1\}, \forall (vw) \in \mathbb{E}, \forall c \in \mathbb{C} \tag{4.8}$$

$$y^c_v \in \{0,1\}, \forall v \in \mathbb{V}, \forall c \in \mathbb{C} \tag{4.9}$$

$$\sum_{c\in\mathbb{C}} x_{(vw)} \leq 1, \forall (vw) \in \mathbb{E} \tag{4.10}$$

$$\sum_{c\in\mathbb{C}} z^c_v \leq I_v, \forall v \in \mathbb{V} \tag{4.11}$$

$$\sum_{c\in\mathbb{C}} x_{(vw)} = \sum_{c\in\mathbb{C}} z^c_v, \forall v \in \mathbb{V} \tag{4.12}$$

$$p^{min} \leq p^c_{(vw)} \leq p^{max}, \forall (vw) \in \mathbb{E}, \forall c \in \mathbb{C} \tag{4.13}$$

$$0 \leq r_{(vw)} \leq r^{c,p}_{(vw)} \leq r^{o}_{(vw)} \leq r^{max}, \forall (vw) \in \mathbb{E}, \forall c \in \mathbb{C}, \forall p \in \mathbb{P} \tag{4.14}$$

$$\sum_{(uv)\in\mathcal{L}^u_v} r_{(uv)} \geq \sum_{(vw)\in s} r_{(vw)}. \forall v \in \mathbb{V} \tag{4.15}$$

Constraint (4.8) and Constraint (4.9) depict the activation status of link (vw) and node v on channel c, respectively. Further, Constraint (4.10) ensures that each individual link (vw) in the network, is allowed to transmit on a single channel at a time. The maximum number of channels used by a node is limited by its interface constraint, which is enclosed in Constraint (4.11). Constraint (4.12) ensures that each radio of node v is assigned a separate channel. The transmission power $p^c_{(vw)}$ allocated over a link (vw), operating on channel c, is bounded by minimum (p^{min}) and maximum (p^{max}) values, depicted in constraint (4.13). Constraint (4.14) shows that the transmission rate $r_{(vw)}$ split over a link (vw) is limited either by an achievable rate $r^{c,p}_{(vw)}$ on the link (vw) for a given power p and link SINR condition, or by $r^o_{(vw)}$, or by r^{max}, whichever is smaller. Finally, constraint (4.15) states that the outbound traffic must not exceed the total inbound traffic at each $v \in \mathbb{V}$.

Note that the objective function, formulated in Eq. 4.7, selects a set of forwarding links (with corresponding channels and powers) that maximizes the aggregate forwarding rate, minimizes neighborhood interference, as well as node level congestion. The Eqs. 4.7 - 4.15 belong to a mixed-integer nonlinear programming (MINLP) problem that contains both combinatorial and continuous constraints. Thus, its real-time solution is intractable in a typical mesh router and the problem therefore becomes an NP-hard one [89]. Due to the intractability of the joint problem, we propose a greedy heuristic solution to obtain a near-optimal solution, which we describe in the next section.

4.5 Greedy Heuristic Link-Channel Selection and Power Allocation

In order to find a near-optimal traffic forwarding decision in reasonable amount of time, we propose a greedy heuristic LCP (GLCP) to find the set of link-channel pairs and power allocation over those that maximizes upstream flow throughput. We greedily choose the least interfered and higher capacity link-channel pairs aiming to boost resource availability for contenting flows and to enhance overall network throughput. Therefore, comprehending congestion and interference, each GLCP router v computes weight for each downstream link, $(vw) \in \mathcal{L}^d_v$, as follows,

$$\vartheta^c_{(vw)} = \hat{r}^o_{(vw)} \times \big(1 - \hat{\xi}^{c,p}_{(vw)}\big), \tag{4.16}$$

where, $\hat{r}^o_{(vw)}$ is the normalized offered rate over link (vw) (i.e. $\hat{r}^o_{(vw)} = \frac{r^o_{(vw)}}{r^{max}}$), and $\hat{\xi}^{c,p}_{(vw)}$ is the interference degree of downstream link (vw), for channel c and transmission power p^{min} to achieve the SINR threshold for minimum transmission rate r^{min}. The value $\vartheta^c_{(vw)}$ varies between 0 and 1, and exhibits higher values for better quality link-channel pairs.

Next, a GLCP router v assigns sufficient amount of power(s) to maximally fulfill the upstream flow demand. To do so, the router can either (1) allocate higher powers over one or two good quality link-channel pairs or (2) increase number of link-channel pairs with minimum power allocation. The first method is preferable when resource availability is very limited; otherwise, the second approach is desirable. In the case, all nodes in the network deterministically chooses any of the above methods, an imbalance in resource utilization would be observed. In this work, we go for heuristic solution to allow routers to exercise both approaches so as to increase the overall network throughput.

The working procedure of GLCP is presented in Algorithm 3. Initially, the GLCP sorts all link-channel pairs in descending order of their weights. We then exclude very poor quality link-channel pairs (in line 2) that are unable to provide the basic data rate. Next, we employ a heuristic (line 4 and 5) to pick one of the two alternate methods, as described earlier. As there are $|\mathbb{Z}'_v|$ number of good quality link-channel pairs available for node v, a random value, y, is chosen between 1 and $|\mathbb{Z}'_v|$ and compared with a predefined threshold τ. The τ is a system design parameter and for simulation experiments in this paper we set $\tau = 2$ as depicted through numerous experiments. If y holds higher value than τ, method (1) is invoked (lines 6 - 11), otherwise method (2) is called (lines 13 - 18). While computing s_v in function *FINDALLOC()* (lines 20 - 26), the backlogged traffic is minimized by selecting the required power allocations over the link-channel pairs. Finally, the traffic is split proportionately over the selected set of link-channel pairs, with the computed power levels as listed in line 28.

The complexity of Algorithm 3 is quite straightforward. Firstly, in order to sort the set $\mathbb{Z}_v$ in descendent order in line 1, we use quick sort algorithm which has the worst-case complexity of $O(|\mathbb{Z}_v| \cdot \log |\mathbb{Z}_v|)$. The statements in 6 - 11 iterates $|\mathbb{Z}_v|$ times and the statements 7 - 10 iterates $|\mathbb{P}|$ times. Thus the complexity is $O(|\mathbb{Z}_v| \cdot |\mathbb{P}|)$. On the other hand, 13 - 18 iterates $|\mathbb{P}|$ times and the statements 14 - 17 iterates $|\mathbb{Z}_v|$ time. Thus, the complexity is same, $O(|\mathbb{Z}_v| \cdot |\mathbb{P}|)$. The rest of the statements have constant unit time complexities. Therefore, the worst-case computational complexity of the algorithm is $O(|\mathbb{Z}_v| \cdot \log |\mathbb{Z}_v|)$.

4.6 Performance Evaluation

In this section, we implement GLCP, OLCP, G-DTE and ROPIM [8] in a discrete-event network simulator, ns-3 [51] and discuss the relative performance findings.

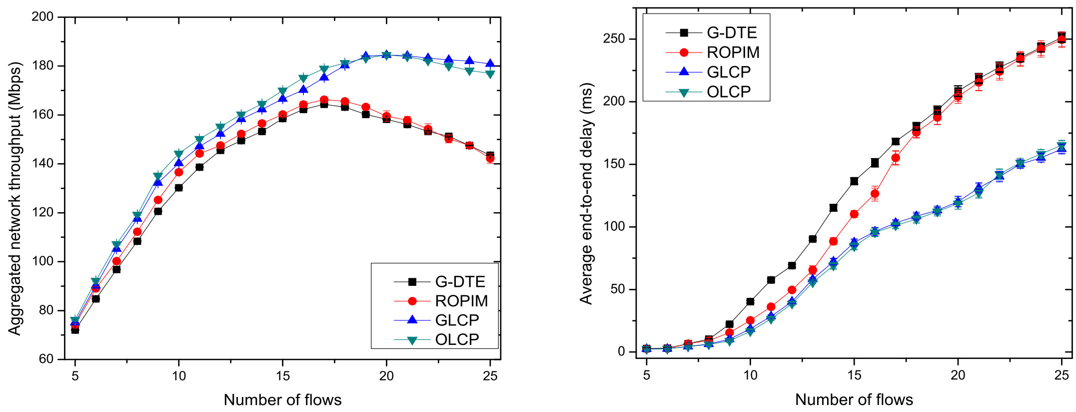
4.6.1 Simulation Environment

In our simulation experiments, we consider a WMN of $1000 \times 1000\ m^2$ area, where 50 nodes (46 mesh routers and 4 gateways) are deployed following a uniform random distribution, where 4 routers are considered as gateways. Each router has 4 802.11a radio interfaces and there are 12 orthogonal channels available in the network. Each link is allowed to choose from 10 different discrete power level, e.g. $\mathbb{P} = \{10mW, 20mW, \ldots 100mW\}$; and the feasible data rates available for transmission are - 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. Here, the constant bit rate (CBR) traffic model is used under UDP for data transmission with a packet size of 1000 bytes. In each simulation run, random sources initiate flows, that remain unchanged over the simulation period.

4.6.2 Performance Metrics

To evaluate the performance of the studied traffic forwarding solutions, G-DTE, ROPIM, GLCP and OLCP, we have used 6 metrics - (i) *aggregated flow throughput*: amount of successful data bytes received at destinations in unit time, (ii) *average end-to-end delay*: the average of latency for all received packets at destinations, (iii) *packet delivery ratio*: the ratio of the number of packets received at all destinations and the number of packets that have been sent from all sources. (iv) *flow fairness*: Jain's fairness index [108], varying between 0 and 1, is used to measure flow fairness, (v) *operation overhead* : amount of control bytes exchanged per successful data byte transmission, and (vi) *integrated performance gain*: quantifies the overall performance of the proposed approach.

However, as the solution of OLCP converges slowly (due to its NP-hardness), for the convenience of the comparison, all the parameters presented here for the optimal solution, OLCP, are taken after the completion of the total computation.



(a) Network throughput (b) Average end-to-end delay

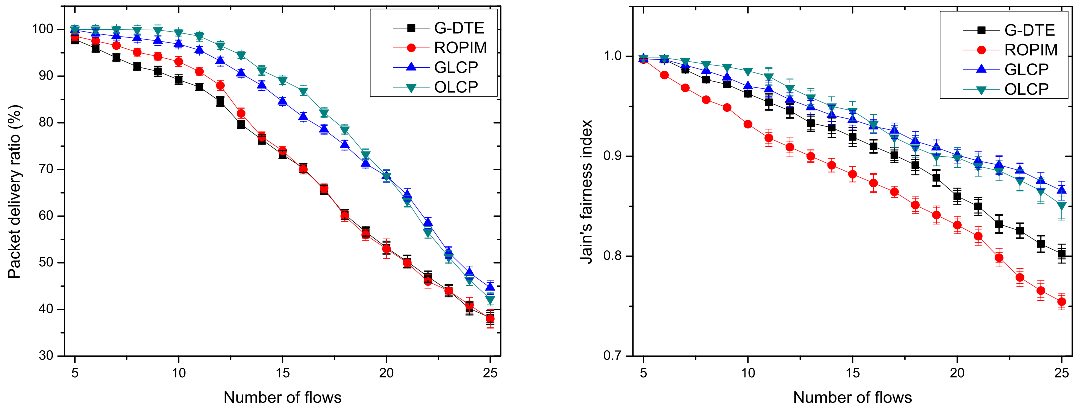
Figure 4.1: Throughput and delay performance vs. number of flows in WMNs

4.6.3 Simulation Results

For each data value provided in the graphs, we have taken the average results from 20 simulation runs and have shown their confidence intervals.

4.6.3.1 Impacts of increasing number of flows

In this experiment, to analyze the impact of increased offered load in network performance, we randomly selected sources to generate varying number of flows (5 to 25) at a rate of 10Mbps. As the network resources (number of idle channels and downstream links) are limited, the increasing number of flows intensifies the interference and congestion, which eventually causes the throughput degradation, as depicted in the curves of Fig. 4.1(a). However, the proposed OLCP and GLCP offers higher throughput than G-DTE and ROPIM due to using link-channel weight parameter (Eq. 4.16) to dynamically pick best link-channel pairs in terms of least interference and higher capacity. Static end-to-end multiple path computation restricts ROPIM to explore under-loaded forwarding links under high traffic load and centralized controller driven mechanism induces significant control overhead when network is highly congested. Throughput performance of



(a) Packet delivery ratio (b) Flow fairness

Figure 4.2: Packet delivery ratio and flow fairness vs. number of flows in WMNs

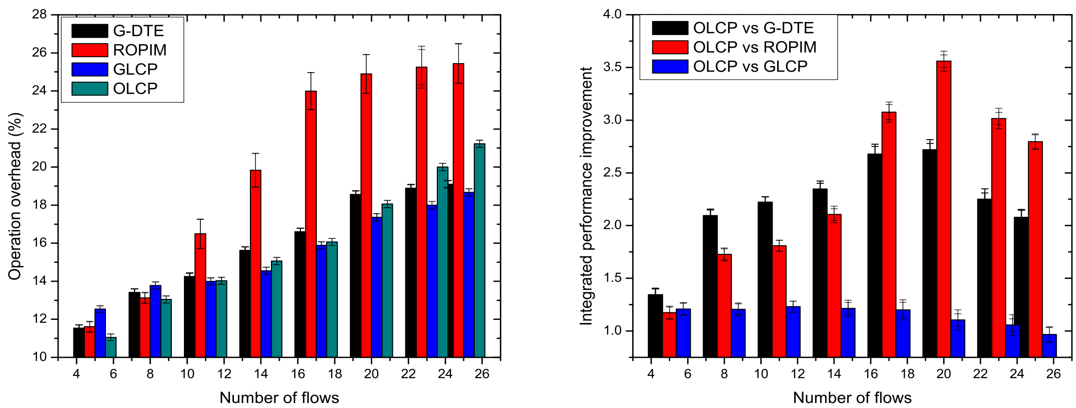
G-DTE is poor under higher load, due to conservative choice of fixed channels over the radios.

The end-to-end packet transmission delays for the studied approaches are depicted in Fig. 4.1(b). The ROPIM experiences higher delay, due to exchange of control messages among routers and central agent, which saturates network's capacity and lingers the forwarding decision under higher traffic loads. As the forwarding decisions at each OLCP and GLCP router exploits one-hop neighborhood information only, instant adaptation to link, channel and load condition is possible, which in turn facilitates quick forwarding decisions and thus minimizes the transmission latency in the network. As G-DTE routers employ fixed channel over radios, they are unable to switch radios to least loaded channels or divert traffic to a least loaded downstream node with which they do not share common channels. Thus, packets forwarded over congested links experience collisions and retransmissions, eventually deteriorating flows' delay performance.

OLCP and GLCP routers are able to offer higher forwarding capacity, as opposed to G-DTE, as they are able to explore diversified downstream nodes by switching to any suitable channel. Thus, higher load is allowed to be delivered to destinations, improving packet delivery ratio, as depicted in Fig. 4.2(a). Besides, employment of dynamic hop-by-hop traffic forwarding mechanism in LCP, allows is to handles network dynamics in better ways than ROPIM, where static route resource allocation (end-to-end paths, channels over links and rates) faces degraded reliability. However, under high congestive state of the network, little variation in channel condition highly impacts the associated link's capacity. As OLCP experiences longer delay to address these variations, packets experience higher prolonged delivery time, frequent collisions and buffer drops; lessening packet delivery probability.

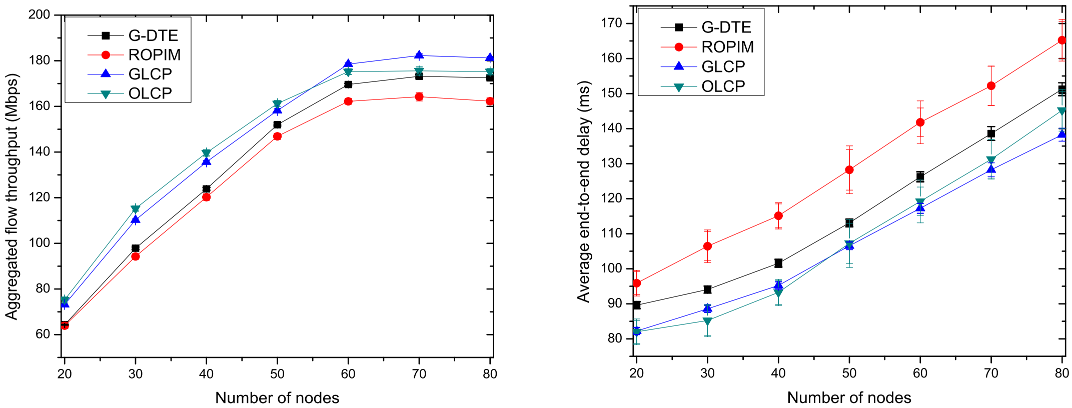
As shown in Fig. 4.2(b), our proposed solutions secure fair treatment for all flows in the network when all links are exhausted under excessive traffic demand. Here, flow rates are regulated in proportion to their demands and path capacities. As the flow routes are fixed for ROPIM, flows originating in a congested region are treated unfairly than those in under-loaded regions.

The effectiveness of a traffic forwarding mechanism depends on the timely and accurate measurement of downstream congestion and channel conditions. In our proposed LCP solution, each forwarding router periodically broadcasts a NCIV (Node-Channel Information Vector) message to one-hop neighbors. Here, each NCIV packet is 125 Bytes



(a) Operation overhead (b) Integrated performance gain

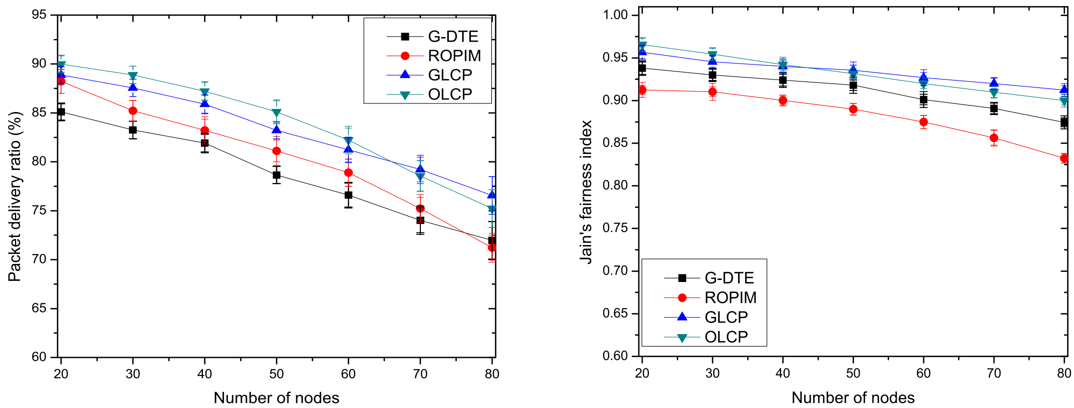
Figure 4.3: Operation overhead and integrated performance gain vs. number of flows in WMNs



(a) Throughput (b) Average end-to-end delay

Figure 4.4: Throughput and delay performance vs. number of nodes in WMNs

long, containing the measured interference over each orthogonal channel and the information required to compute corresponding nodes's offered rate (similar to LIV message as discussed in Section 3.6.3.1). Thus, exchange of additional control packets periodically (in every 1 second), along with the RTS/CTS, ACK, etc. packets, notably increase the operation overhead of LCP. As shown in Fig. 4.3(a), the operation overheads of our proposed OLCP and GLCP systems are much lower than ROPIM, but slightly higher than that of G-DTE under higher traffic load. However, this small overhead is nicely compensated by the integrated performance gain of our proposed systems, as shown in Fig. 4.3(b). In order to schedule collision-free transmission, ROPIM have to consider significant overheads due to exchange of huge control messages. Particularly in ROPIM, the central controller needs to know the channel status and link load at each router to take routing and scheduling decisions. The overall performance improvements of O-LCP over G-DTE is significantly higher as long as traffic load is moderate, but worsens with excessive load conditions.



(a) Packet delivery ratio (b) Flow fairness

Figure 4.5: Packet delivery ratio and flow fairness vs. number of nodes in WMNs

4.6.3.2 Impacts of increasing number of nodes

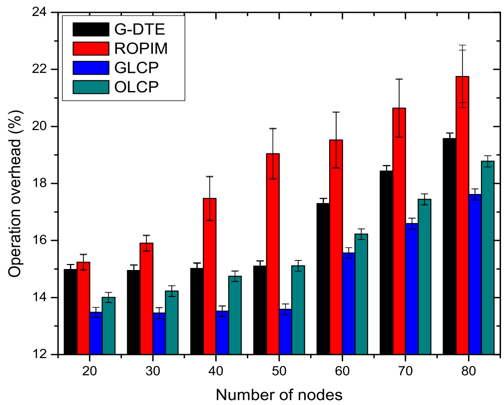
In this section, we have considered different dimensions of WMNs to test the scalability of the studied approaches. Here, we varied the number of nodes from 20 to 80 in the network while preserving the same node density. In each environment, the offered load in the network is varied between 60% to 70% of the networks' total effective capacity.

Fig. 4.4(a) and 4.4(b) show the impacts of increased nodes in the network in terms of the achievable aggregated network throughput and average end-to-end packet transmission delay, respectively. Here OLCP, GLCP and G-DTE retain higher throughput than ROPIM as the increase in the number of mesh nodes gives opportunity to each forwarding router to explore more alternate downstream links to forward aggregated traffic through dynamic power allocation, minimizing neighborhood interference and granting other contending routers access to the channel to further improve the overall network throughput. Moreover, in larger networks, ROPIM experiences most degraded throughput due to propagation of local information to the central agent. Hence delay performance is also impacted as path length increases between source-destination pairs. But, as OLCP employs hop-by-hop dynamic forwarding link-channel selection policy, traffic is split over more reliable links. Still, in larger networks OLCP

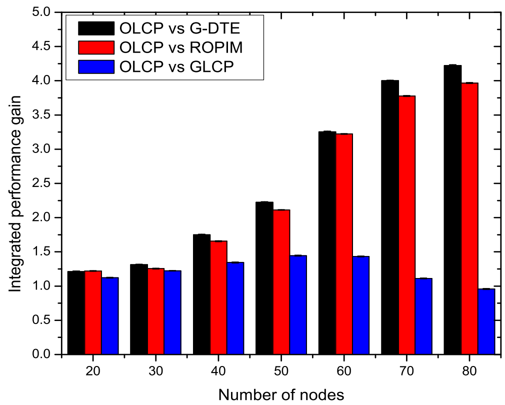
As shown in Fig. 4.5(a), with increased hop-counts, huge control message dissemination between central controller and routers in ROPIM significantly delays forwarding decisions and thus deteriorates packet delivery ratio at the destinations. On the other hand, G-DTE in unable to dynamically utilize good quality channels, restricting it to choose limited downstream resources while traffic forwarding, which finally drops down packet delivery ratio. However, LCP is able to dynamically exploit the least interfered channels to improve it's data delivery, at the same time help in improving the spatial channel reuse for neighboring nodes through minimum power allocation over the transmitting links. Thus, the flows in the network are allowed to find more alternate high capacity paths to improve their data delivery performance.

In a multi-hop network, flows originating furthest from the desired destinations are treated unfairly than those that are closer to the destinations. However, a closer analysis to the simulation trace data and the performance curves in Fig. 4.5(b) depict that each flow in our proposed LCP mechanism is awarded with more fair share of the available bandwidth than the state-of-the-art approaches. In centralized ROPIM mechanism, with increased number of nodes, as the traffic-split decision time grows rigorously, incoming flows are refrained from being rewarded with required proportionate fairness.

We also observe that with increasing number of nodes in the network, the operational overhead of ROPIM is significant, as shown in Fig. 4.6(a), and this is caused by excessive control message transmissions in between the routers and the central controller. In our proposed traffic engineering solutions, LCP routers periodically transmit NCIV message to assist neighboring routers to distributively learn downstream's congestion status and channel conditions. Though, NCIV incurs adequate operation overhead (as seen in Fig. 4.6(a), it is able to grant optimum resources to transmitting flows to ensure high throughput data delivery while minimizing delay and ensuring fairness. Thus, the performance curves in Fig. 4.6(b), clearly highlights performance improvement of OLCP over other approaches despite of incurring additional operational overhead.



(a) Operation overhead



(b) Integrated performance gain

Figure 4.6: Operation overhead and integrated performance gain vs. number of nodes in WMNs

4.6.3.3 Impacts of bursty traffic arrivals

In this subsection, we demonstrate the responsiveness of our studied traffic engineering solutions in WMNs under a highly dynamic traffic model. Here, we consider the impact of inducing dynamic traffic bursts at different time instants in a WMN consisting of 50

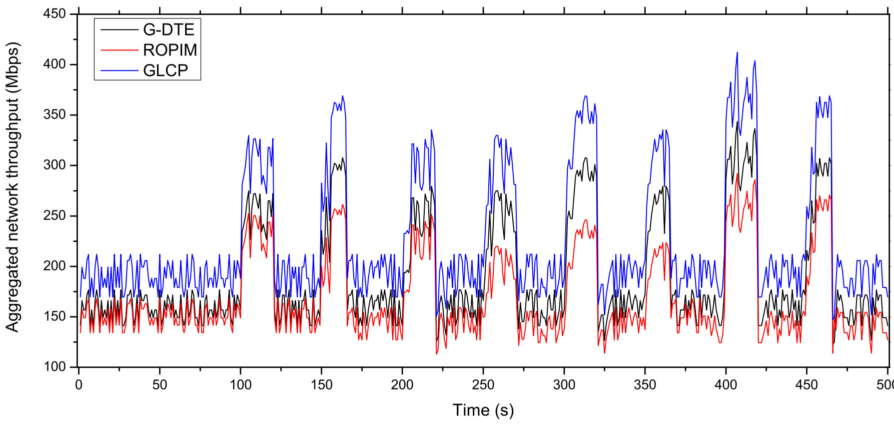


Figure 4.7: Aggregated network throughput under bursty traffic arrivals.

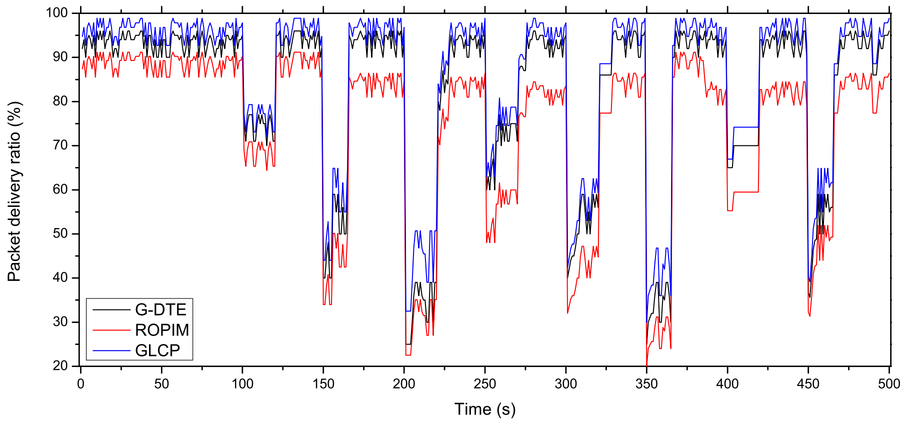


Figure 4.8: Packet delivery ratio under bursty traffic arrivals.

nodes in the similar way that we exercised in subsection 3.6.3.3.

From the graphs of Fig. 4.7 and 4.8, we observe that the adaptation capability of our proposed GLCP is higher than that of other approaches. Along with ensuring steady flow throughput during moderate traffic loads, the GLCP is able to retain higher throughput than other approaches even at bursty traffic durations. The ROPIM is prone to congestion collapse due to exhaustive exchange of control messages among the forwarding routers and the central controller that might incur higher number of collisions, resulting in degraded network performances. Though, G-DTE routers distributively and dynamically adjusts routing path and rate allocation considering the instantaneous upstream flow demand, due to fixed channel allocations over the interfaces, it is unable to shift traffic to higher capacity downstreams operating over better quality channels. Thus, dynamic traffic arrival, which is a common phenomena in WMNs carrying the Internet traffic, can be better addressed and accommodated by our proposed GLCP approach.

4.7 Summary

To address the problem of high-throughput data delivery in MRMC WMN, in this Chapter we developed both optimal (OLCP) and sub-optimal (GLCP) traffic engineering solutions that explore dynamic link-channel selection and power allocation at each forwarding router. The results depict that, in a dynamic network environment, hop-by-hop multi-link traffic forwarding offers better performances, compared to using end-to-end multi-path routing. This study also concludes that the throughput enhancement can be achieved by utilizing higher powers on minimum number of links or higher number of link-channel pairs at minimum powers through exploiting a dynamic traffic forwarding policy that considers current interference and congestion situations of the network.

Algorithm 3 GLCP at each router $v \in \mathbb{V}$

Input: $\sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)}$; $\omega^c_{(vw)}$, $\forall (vw) \in \mathcal{L}_v^d$ and $\forall c \in \mathbb{C}_{(vw)}$; $r^o_{(vw)}$, $\forall (vw) \in \mathcal{L}_v^d$

Output: s_v

Initialization: $b = \sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)},\ \ s_v = \emptyset,\ \ r^{prev}_{(vw)} = 0$

1: $\mathbb{Z}_v = \Big\{\big((vw_i), c_j\big) \mid (vw_i) \in \mathcal{L}_v^d, c_j \in \mathbb{C}_{(vw)},\ \omega^{c_1}_{(vw_1)} \geq \omega^{c_2}_{(vw_2)} \geq \dots\ AND\ (vw_1) \neq (vw_2) \neq \dots \neq (vw)_{|\mathcal{L}_v^d|}\ AND\ c_1 \neq c_2 \neq \dots \neq c_{\mathbb{C}_v}\Big\}$

2: $\mathbb{Z}'_v \leftarrow \mathbb{Z}_v - \{((vw_i), c_j) \mid r^{c_j, p^{min}}_{(vw_i)} < r^{min}\}$

3: $\forall (vw) \in \mathbb{Z}_v,\ q_{(vw)} = \emptyset$

4: $y \leftarrow$ pick a random number from the range $1 \sim |\mathbb{Z}'_v|$

5: **if** $\big(y \geq \tau\big)$ **then**

6:     **for** $\big((vw), c\big) \in \mathbb{Z}_v$ **do**

7:         **for** $p \in \mathbb{P}$ **do**

8:             **if** $\big($FindAlloc$((vw), c, p) == 0\big)$ **then** break; go to line 28

9:             **end if**

10:         **end for**

11:     **end for**

12: **else**

13:     **for** $p \in \mathbb{P}$ **do**

14:         **for** $\big((vw), c\big) \in \mathbb{Z}_v$ **do**

15:             **if** $\big($FindAlloc$((vw), c, p) == 0\big)$ **then** break; go to line 28

16:             **end if**

17:         **end for**

18:     **end for**

19: **end if**

20: **function** FindAlloc((vw),c,p)

21:     $x_{(vw)} = 1,\ c_{(vw)} = c, p_{(vw)} = p$

22:     $s_v \leftarrow s_v \bigcup \{x_{(vw)}, c_{(vw)}, p_{(vw)}\} - q_{(vw)}$

23:     $b = b - r_{(vw)} + r^{prev}_{(vw)}$

24:     $r^{prev}_{(vw)} = r_{(vw)}$

25:     $q_{(vw)} = \{x_{(vw)}, c_{(vw)}, p_{(vw)}\}$

26:     **return** b

27: **end function**

28: Compute $r_{(vw)}$, $\forall (vw) \in s_v$ using Eq.4.6

Chapter 5
Traffic Engineering in Cognitive Radio Mesh Networks

5.1 Introduction

The flow performance in Wireless mesh networks (WMNs) is deteriorated due to spectrum scarcity [24]. To ensure the required data delivery services, solutions are required to offer higher capacities. Fortunately, cognitive radio (CR)-enabled mesh routers offer increased network performance (in terms of throughput, delay and data delivery ratio) by facilitating opportunistic utilization of licensed spectrum resources [24, 66, 100]. However, resource allocation problem in cognitive radio wireless mesh networks (CR-WMNs) is a complicated and challenging one mainly due to highly dynamic resource availability, network congestion and interference.

The existing works in the literature on allocating radio resources opportunistically in CR-WMNs, can broadly be divided into two categories: resource allocation for *single path* and *multi-path* data delivery models. In the first category of works, joint routing and channel allocation strategies proposed in [93] and [94] aim to minimize interference with primary users (PU) while forwarding traffic. Authors in [101], try to mitigate interflow and intra-flow interference over end-to-end path considering fixed traffic demand. However, under dynamic traffic load, eventually the above works are victim of network congestion collapse. On the other hand, time-varying traffic is routed over a pre-computed end-to-end path in [95] and [96] while minimizing the neighborhood interference and congestion. Methods in [97] and [100], rely on centralized server to compute interference-free link scheduling and channel assignment to enhance flow throughput considering single-path data delivery between each source-destination pairs. Due to instantaneously varying network conditions, decision execution at a central point leads to unstable system condition and the single path data delivery approach experiences restricted forwarding capacity.

In multi-path data forwarding model, proposed in [99], a source node distributively splits aggregated traffic over least interfered routes to address the Quality-of-Service (QoS) requirement of each traffic flow. Taking path interference into consideration, a central controller in [98] computes multiple edge-disjoint paths between source-destination pairs to ensure the bandwidth requirements of the traffic flows. In [64], along with route and channel selection, allocation of transmission power over forwarding links are also controlled to minimize interference, allowing more concurrent transmissions to enhance flow throughput. However, consideration of centralized controller limits the system to be expandable.

In this work, we propose a multi-path traffic forwarding mechanism in CR-WMNs, where we jointly investigate the problem of selecting link-channel pairs and to allocate data rates on them (by selecting appropriate transmission powers) for each forwarding router so that the throughput of the network is maximized. More specifically, we are particularly interested in how the traffic in the multi-hop cognitive radio mesh networks should be directed, under the influence of random behaviors of primary users, neighborhood interference, channel error and congestion in order to improve the network throughput. Here, the proposed problem is targeted to maximize the aggregated utility of a CR-WMN, where the choice of utility guarantees maximum throughput at each forwarding router, which belongs to mixed integer non-linear programming (MINLP) problem class. In order to obtain a solution in polynomial time, we use Lagrangian dual method [113] to decompose the MINLP problem into a set of sub problems. Finally, a distributed traffic engineering solution is proposed to make the system scalable.

5.1.1 Contributions

The key contributions of our work are summarized as follows:

- We formulate the traffic engineering problem in CR-WMNs as an MINLP problem, where the centralized controller jointly selects downstream link-channel pairs and allocates power over them to forward traffic from source to destination considering channel idle probability, link interference and path congestion so as to maximize the network throughput.

- Due to the NP-hardness of the optimal solution, we decompose the problem into two subproblems - link-channel selection and power (or rate) allocation, offering a suboptimal solution.

- Finally, we develop a distributed traffic engineering solution, where each forwarding router greedily chooses the local-optimum link-channel pair(s) and rate allocation aiming to minimize link/channel interference and congestion to boost up overall throughput performance of the network.

- The simulation results, experimented on ns-3 [51], show that the proposed traffic engineering methods outperform the state-of-the-art works in terms of throughput, delay, reliability, fairness and convergence cost.

5.1.2 Organization

The rest of the Chapter is organized as follows. Section 5.2 studies state-of-the-art works and the Section 5.3 overviews the system model and assumptions of the work. The operation principles of the proposed TE methods are explored in Section 5.4. Section 5.5 presents the simulation performance results and Section 5.6 concludes the Chapter.

5.2 Related Works

The cognitive radio (CR) enabled mesh routers opportunistically share the licensed resources to mitigate the spectrum scarcity problem and it is of great importance to efficiently allocate the limited resources to all nodes in the network so that the performance is increased. Existing approaches in the literature explored channel allocation with/without scheduling, power allocation or routing data traffic over single or multiple paths so to increase the resource utilization.

A channel allocation algorithm based on channel ranking function, computed based on primary user activity duration and error rate, is proposed in [91]. A cluster-based channel allocation approach is developed in [65], where each cluster head is responsible for allocating non-interfering channels to its members following their joint perception. However, these approaches fail to serve the required flow demand over the selected forwarding links as link's effective capacity is over-estimated by not undertaking the inter-flow interferences and congestion conditions. A resource allocation mechanism, proposed in MaxTh (Decentralized throughput maximization) [95], significantly improves service rate of each traffic flow with time varying demands over a pre-computed end-to-end path by maintaining flow conservation constraint at each router and minimizing the interferences amongst the contending neighboring links. Later, Lagrangian duality theory is employed to get a distributed solution of the problem. However, the use of fixed-power transmission and single-path data delivery in MaxTh causes intra-flow contention and congestion along the path, which in turn degrades the network throughput performance.

At present, cross-layer optimization to utilize network resources to improve throughput performance in CR-WMNs has widely been studied. Aiming to improve the co-existence with other PU users and CR networks; joint routing and channel allocation strategy has been proposed in [93] and [94] considering the traffic demand. In [93], a source-destination pair chooses route so as to minimize cumulative SU interference towards PUs in the network through satisfying the flow demand. Work in [94] aims to minimize the number of operating channels. A high throughput end-to-end path along with channel allocation over them considering intra- and inter-flow interferences has been developed in [101]. All these aforementioned works forward traffic over single path; which is prone to interference affects by both SU and PU, thus resulting in degraded throughput performance. Under dynamic traffic condition, they also faces severe performance degradation due to link/path congestion, as the route selection mechanisms do not incorporate traffic load present at each link. Again, single-path data forwarding approach proposed in [96] considering neighborhood interference (using protocol model), PU activity and node congestion, is unable to fulfill the Quality-of-Service (QoS) requirement of delay sensitive traffic under random PU behavior. Here multi-path traffic splitting can guarantee packet delivery over alternate paths under sudden cease of channels over some forwarding paths.

Centralized approaches, opting to maximize network throughput by opportunistically utilizing licensed channels in CR-WMNs, have been well-studied in the literature. In [97], the spectrum management server is responsible to schedule a set of link-channel pairs and route flow over them. In [100], a nested optimization framework based on genetic algorithm (GA) finds a feasible channel allocation for each link while computing a source-destination route that minimizes backlogged traffic at each forwarding link to minimize congestion. As the channel state is highly vulnerable in cognitive radio network due to PU's random arrival/departure behavior, an existing channel may become unavailable to a mesh node sporadically, finding a new allocation solution from a central entity leads to an unstable system condition.

Multi-path data forwarding allows higher flow throughput, ensures reliable data delivery and minimizes the effects of PU arrival by selecting suitable paths and spectrum allocation. Source to destination edge-disjoint multiple paths are computed by a central controller in [98], where the channel allocation over the links ensures the bandwidth requirements of the traffic flows. Here, the central controller incurs huge control information exchange overhead. A traffic engineering approach proposed in [99], distributively split aggregated traffic over least interfered routes to address the QoS requirement of each traffic flow. Route computation and traffic splitting is done by the source node. Work in [64] proposes a GA based optimum channel and power allocation at link-physical layer, and a linear programming (LP) based source-destination route selection at network layer, GA-CO (Genetic algorithm based cross layer optimization), aiming to fairly allocate the capacity of the network among the set of contending flows, by maximally satisfying their demands. Here, power control over the links controls the size of the neighborhood collision domain, eventually minimizing interference to obtain the required rate over each link in the network. However, under dynamic varying flow demands, path and resource-allocation (channel and power) are recomputed, hindering the convergence time of the mechanism to trigger unstable state of the network. All the aforementioned works establish end-to-end paths among source-destination.

Our proposed joint downstream link-channel selection and power allocation, for each forwarding node exhibits distinctive characteristic while aiming to maximize the network throughput. Unlike single-path data delivery approach in [95], our work explores multi-path data delivery towards multiple gateways (GWs) so as to increase the data flow throughput. In [64], it requires that the current channel allocations over the links and set of flow demands over the network is fully observable at a centralized decision maker, which is often not practical; on the contrary, our DGTE system exploits single hop neighborhood information only to decide data routing over multiple paths in a distributed fashion. Moreover, rather than using end-to-end path based traffic delivery approach in existing works [95, 64], this work considers hop-by-hop traffic engineering so as to take routing decisions based on instantaneous resource availability and link conditions. The key strengths of the proposed methods are (1) hop-by-hop traffic engineering, (2) downstream link-channel selection considering PU idle probabilities, neighborhood interference and downstream congestion states and (3) rate allocation over selected downstream links that maximizes upstream flow throughput by ensuring optimum power allocation over the links so as to enhance spatial reuse.

5.3 System Model and Assumptions

We consider a directed graph $\Gamma = (\mathbb{V}, \mathbb{E})$ as the model of cognitive mesh network, where each vertex $v \in \mathbb{V}$ represents a cognitive mesh node. As shown in Fig. 5.1, primary users (PUs) and cognitive radio-enabled secondary users (SUs) are randomly distributed in the same region. We also let k number of non-overlapping licensed channels available in the CR-WMNs for data transmission, denoted as $\mathcal{C} = \{\varsigma_1, \varsigma_2, \ldots, \varsigma_k\}$.

5.3.1 Spectrum Sensing

Each cognitive mesh node will opportunistically access idle primary channels to transmit its packets. Local channel availability can be detected using one of the different spectrum sensing mechanism, namely cooperative and non-cooperative sensing. In non-cooperative sensing [114, 115, 116], each SU relies on its sole effort to detect the presence of a PU transmission on a particular spectrum band. Two methods were proposed in literature to detect the presence of a PU transmission without any form of cooperation between

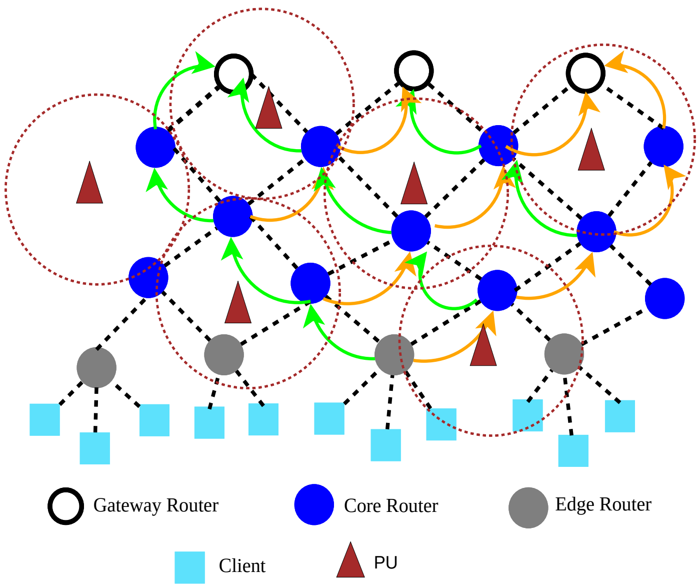


Figure 5.1: An example of multi-path data forwarding in CR-WMN

SUs, and those are energy detection [114, 115] and signal feature detection [117, 118]. Using the energy detection approach, an SU concludes that a neighboring PU is receiving on a particular spectrum band if a weak PU signal (the signals energy is above certain threshold) is detected at the SU. The second method used in non-cooperative sensing is signal feature detection. Using this method, an SU looks for some feature in the received signal to confirm that it is coming from a PU. These features are usually modulation-dependent.

On other hand, cooperative sensing [119, 120, 121, 122, 123, 124] allows SUs to co-operate and consolidate their spectrum sensing efforts in order to reach a more accurate conclusion about spectrum availability. This approach of spectrum sensing comes as a solution to a major drawback of non-cooperative sensing, that is the effect of the hidden node problem on the sensing outcome. If the SU which is currently sensing the spectrum, non-cooperatively, is hidden from the PU transmitter, it will not be able to detect the PU signal. Therefore, the SU will conclude that the corresponding spectrum band is vacant, and start using it and consequently harming the PU receiver. The same scenario may happen due to shadowing. Such scenarios can be avoided if SUs cooperate with each other to estimate spectrum status instead of independently doing this estimation on their own. Cooperative sensing can be either distributed [122] or centralized [121, 123]. In the distributed implementation, SUs exchange their personal sensing outcomes over a Common Control Channel (CCC) [125] and then use a certain estimation model to map all received outcomes to a final decision about the status of the corresponding spectrum band. In the centralized implementation, on the other hand, all personal sensing out-comes are sent, over a CCC, to a centralized entity where the decision about spectrum status is made and then sent back, again over the CCC, to SUs.

5.3.2 Primary User Behavior

Since the spectrum perceiving methods are out of the scope of this work, we assume that each CR-enabled router either uses a dedicated interface for channel sensing [126] or exploits cooperative sensing technique [127] to keep a record of PUs' activity in each licensed band. Rather than using the instantaneous PU behavior, we consider historical sensing data to compute the channel idle probability. Each node v considers last h number of sensing intervals to find the idle probability, α_v^ς, of a channel $\varsigma \in \mathcal{C}$. Let the decision variable $\rho_v^{\varsigma,t}$ contains 1 if the node v senses the channel ς idle in t-th sensing interval; and 0 otherwise. Then, the channel idle probability is computed as,

$$\alpha_v^\varsigma = \frac{\sum_{t=1}^{h} \rho_{(v)}^{\varsigma,t} \times t}{\sum_{t=1}^{h} t}. \tag{5.1}$$

Note that the calculation of α_v^ς gives higher weights to the recent data compared to older sensing results and thus, it enables more reliable channel prediction under random PU behavior.

5.3.3 Channel Capacity Measurement

When two nodes v and w are within transmission range of each other and communicates over a common channel $\varsigma \in \mathcal{C}$, we consider an edge $(vw) \in \mathbb{E}$ between them. The transmission power $p_{(vw)}^\varsigma$, bounded in the range $[p^{min}, p^{max}]$, over link (vw) operating on channel ς is dynamically chosen to achieve a certain data rate $r_{(vw)}^{\varsigma,p}$, depending on link's signal-to-noise-plus-interference ratio (SINR) value. This rate is computed using Shannon's equation [128] as follows,

$$r_{(vw)}^{\varsigma,p} = B \times log_2(1 + \gamma_{(vw)}^{\varsigma,p}), \tag{5.2}$$

where B is the channel bandwidth and $\gamma_{(vw)}^{\varsigma,p}$ is the received SINR, calculated as using Eq. 4.2.

In order to maximally fulfill the aggregated traffic demand at each router $v \in \mathbb{V}$, our work focus on selecting one/more downstream links toward next-hop, along with channel and power allocations over those, as shown in Fig. 5.1. We assume that each router has pre-computed next hops using multi-path routing algorithm [55], to forward aggregated traffic toward the gateways. Let $y_{(vw)}^\varsigma$ denote a link-channel assignment decision variable to characterize the licensed channel assignment for link (vw). If channel ς is allocated to link (vw), then $y_{(vw)}^\varsigma = 1$, otherwise 0.

5.4 Proposed Traffic Engineering Methods for Cognitive Radio Mesh Networks

In this section, we first explore a centralized TE method that optimally selects link-channel pairs and power over those for all forwarding routers in the network. Then we develop a sub-optimal solution of the same using Lagrangian dual decomposition method. Finally, we develop a distributed TE method, where each router greedily chooses the good performing link-channel pair(s) and assigns power on them so that the overall throughput of the network can be enhanced.

5.4.1 Optimal Traffic Engineering

Considering the aggregated traffic demand in the network, we focus on finding a set of downstream links for each forwarding router $v \in \mathbb{V}$, along with suitable channel and power (corresponding rate) allocations over them to maximize aggregated flow throughput. Let, $\forall v \in \mathbb{V}$, a 2-dimensional matrix, $\Psi_v = \{y^{\varsigma}_{(vw)}\}_{|\mathcal{L}^d_v| \times |\mathcal{C}_{(vw)}|}$, stores the link-channel assignment status for each downstream link $(vw) \in \mathcal{L}^d_v$. Again, we let $\Phi_v = \{p^{\varsigma}_{(vw)}\}$ be the vector holding the power allocation information on each of the active downstream links $(vw) \in \mathcal{L}^d_v$. It is obvious that for any link $(vw) \in \mathcal{L}^d_v$, if $y^{\varsigma}_{(vw)} = 0$, then $p^{\varsigma}_{(vw)}$ will also be 0.

While selecting downstream links, the links offering higher link utility values are preferred. We compute the expected utility $u^{\varsigma,p}_{(vw)}$ of a link $(vw) \in \mathcal{L}^d_v$, for a given channel ς and power p by considering the idle probability of the channel (α^{ς}_v), the amount of interference present on the link, and the degree of congestion experienced by the corresponding downstream router $k \in \mathbb{V}$. The amount of congestion present at downstream node k restricts the corresponding upstream nodes to adjust their forwarding rates. Thus the achievable rate at each forwarding router, $r^{\varsigma,p}_{(vw)}$, is computed as in Algorithm 2, which incorporates the affects of interference and congestion present on the link-channel pair.

Therefore, the link utility is computed as follows,

$$u^{\varsigma,p}_{(vw)} = \left\{ \alpha^{\varsigma}_v \times y^{\varsigma}_{(vw)} \right\} \times \left\{ \hat{r}^{\varsigma,p}_{(vw)} \times (1 - \hat{p}^{\varsigma}_{(vw)}) \right\} \quad (5.3)$$

where, $\hat{r}^{\varsigma,p}_{(vw)} = \frac{r^{\varsigma,p}_{(vw)}}{r^{max}}$ and $\hat{p}_{(vw)} = \frac{p_{(vw)}}{p^{max}}$ are, respectively, the normalized achievable data rate and normalized allocated transmission power on the link (vw). Here, a link will provide the highest utility value for a channel exhibiting the highest idle probability along with being least interfered by neighboring concurrent transmissions and experiencing reduced downstream congestion.

Now, for each forwarding router $v \in \mathbb{V}$, we seek to find out an optimal link-channel assignment (Ψ_v) and corresponding power allocation vector (Φ_v), such that the upstream aggregated traffic demand is maximally fulfilled by splitting the traffic over at most $m \leq |\mathcal{L}^d_v|$ number of downstream links. We set the value of m either by the maximum number of outgoing interfaces of a mesh router or by the maximum paths allowed by the underlined multi-path routing protocol. The total utility of node v under such an allocation is computed as follows,

$$U_v = \sum_{(vw) \in \Psi_v, p \in \Phi_v} u^{\varsigma,p}_{(vw)}. \tag{5.4}$$

Thus, the mixed-integer nonlinear programming (MINLP) optimization problem, referred as Centralized Optimal Traffic Engineering (COTE), can be formulated as,

$$\mathop{\mathbf{arg\,max}}_{\Psi,\Phi} \quad \sum_{v\in\mathbb{V}} U_v \tag{5.5}$$

s.t.

$$y^{\varsigma}_{(vw)} \in \{0,1\}, \quad \forall (vw) \in \mathbb{E},\ \forall \varsigma \in \mathcal{C} \tag{5.6}$$

$$p^{min} \leq p^{\varsigma}_{(vw)} \leq p^{max}, \quad \forall (vw) \in \mathbb{E},\ \forall \varsigma \in \mathcal{C} \tag{5.7}$$

$$0 \leq r_{(vw)} \leq r^{\varsigma,p}_{(vw)} \leq r^{max}, \quad \forall (vw) \in \mathbb{E},\ \forall \varsigma \in \mathcal{C} \tag{5.8}$$

$$\sum_{(uv)\in\mathcal{L}^u_v} r_{(uv)} \geq \sum_{(vw)\in\Psi_v} r_{(vw)}, \qquad \forall v \in \mathbb{V} \tag{5.9}$$

$$\sum_{\varsigma\in\mathcal{C}} y^{\varsigma}_{(vw)} \leq 1, \qquad \forall (vw) \in \mathbb{E} \tag{5.10}$$

$$\sum_{(vw)\in\Psi_v} y^{\varsigma}_{(vw)} \leq m, \qquad \forall v \in \mathbb{V},\ \forall \varsigma \in \mathcal{C} \tag{5.11}$$

where, $\Psi = \bigcup_{v \in \mathbb{V}} \Psi_v$ and $\Phi = \bigcup_{v \in \mathbb{V}} \Phi_v$ are, respectively, the link-channel assignment matrix and power allocation vector global for the entire network. Thus, the objective function in Eq. (5.5) aims to find out the Ψ and Φ values that maximizes the total utility for all nodes in the network.

The constraint (5.6) ensures that the link-channel assignment variable can only take a value of 0 or 1. The transmission power $p^{\varsigma}_{(vw)}$ allocated over a link $(vw) \in \mathbb{E}$ is bounded by $[p^{min}, p^{max}]$, depicted in constraint (5.7). In order to minimize downstream congestion and neighboring interference the data rate over each link, the downstream link rate $r_{(vw)}$ is limited by $r^{\varsigma,p}_{(vw)}$ and r^{max}, as mentioned in constraint (5.8). Constraint (5.9) states that the outbound traffic cannot exceed the inbound traffic at each forwarding router $v \in \mathbb{V}$. Constraint (5.10) restricts each link to be assigned at most one channel at a time. As each router is able to split its aggregated upstream traffic over at most m number of multiple forwarders in order to minimize the interference, constraint (5.11) is imposed for each feasible allocation.

Now, solution to the COTE problem becomes an intractable one for increasing number of nodes, links, channels and power/rate levels. We run the above objective function in NEOS Optimization server (2 Intel Xeon E5-2698 @2.3GHz CPUs and 192GB RAM)[105] for given 20 snapshots of the network environment, described in Section 6.1, and find that it requires, on an average, several hundreds of seconds for 25 nodes, each with at most 4 interfaces, 12 orthogonal channels and 8 different data rate levels. Thus, the objective function in Eq. 5.5 will not be useful in many practical applications.

5.4.2 Sub-optimal Traffic Engineering

As the real-time solution of COTE is often impractical, in this section, we were motivated to use dual decomposition method [129] to segregate the joint problem of COTE into multiple subproblems so as to diminish the computation complexity. We then present algorithms to solve the subproblems that gives suboptimal solution, referred as centralized Sub-Optimal Traffic Engineering (SOTE) approach.

In order to decompose COTE, we relax the constraints in (5.9) and (5.11), and then derive the Lagrangian function as follows:

$$\begin{aligned}
L(y^{\varsigma}_{(vw)}, p^{\varsigma}_{(vw)}, \lambda^1, \lambda^2) &= \sum_{v\in\mathbb{V}} U_v - \sum_{v\in\mathbb{V}} \lambda^1_v \Big\{ \sum_{(vw)\in\Psi_v} r_{(vw)} - \sum_{(uv)\in\mathcal{L}^u_v} r_{(uv)} \Big\} \\
&\quad - \sum_{v\in\mathbb{V}} \lambda^2_v \Big\{ \Big(\sum_{(vw)\in\Psi_v} y^{\varsigma}_{(vw)} \Big) - m \Big\} \\
&= \sum_{v\in\mathbb{V}} \sum_{(vw)\in\Psi_v} u^{\varsigma,p}_{(vw)} - \sum_{v\in\mathbb{V}} \lambda^1_v \sum_{(vw)\in\Psi_v} r_{(vw)} - \sum_{v\in\mathbb{V}} \lambda^2_v \sum_{(vw)\in\Psi_v} y^{\varsigma}_{(vw)} \\
&\quad + \sum_{v\in\mathbb{V}} \lambda^1_v \sum_{(uv)\in\mathcal{L}^u_v} r_{(uv)} + \sum_{v\in\mathbb{V}} \lambda^2_v m \\
&= \sum_{v\in\mathbb{V}} \sum_{(vw)\in\Psi_v} \Big\{ u^{\varsigma,p}_{(vw)} - \lambda^1_v r_{(vw)} - \lambda^2_v y^{\varsigma}_{(vw)} \Big\} + \sum_{v\in\mathbb{V}} \Big\{ \sum_{(uv)\in\mathcal{L}^u_v} \lambda^1_v r_{(uv)} + \lambda^2_v m \Big\} \\
&= \sum_{v\in\mathbb{V}} \Bigg[\sum_{(vw)\in\Psi_v} \Big\{ u^{\varsigma,p}_{(vw)} - \lambda^1_v r_{(vw)} - \lambda^2_v y^{\varsigma}_{(vw)} \Big\} + \Big\{ \sum_{(uv)\in\mathcal{L}^u_v} \lambda^1_v r_{(uv)} + \lambda^2_v m \Big\} \Bigg]. \qquad (5.12)
\end{aligned}$$

The dual function, $\Theta(\lambda^1, \lambda^2)$, can be calculated by maximizing the Lagrangian function as follows,

$$\Theta(\lambda^1, \lambda^2) = \mathop{\textbf{arg max}}_{(\Psi,\Phi)} \quad L(y^{\varsigma}_{(vw)}, p^{\varsigma}_{(vw)}, \lambda^1, \lambda^2)$$

$$\begin{aligned}
= \sum_{v\in\mathbb{V}} \Bigg[\underbrace{\mathop{\arg\max}_{\Psi_v} \sum_{(vw)\in\Psi_v} \overbrace{\mathop{\arg\max}_{p^{\varsigma}_{(vw)}\in\Phi_v} \Big\{ u^{\varsigma,p}_{(vw)} - \lambda^1_v r_{(vw)} - \lambda^2_v y^{\varsigma}_{(vw)} \Big\}}^{\text{subproblem 1}}}_{\text{subproblem 2}} \\
+ \Big\{ \sum_{(uv)\in\mathcal{L}^u_v} \lambda^1_v r_{(uv)} + \lambda^2_v m \Big\} \Bigg]. \qquad (5.13)
\end{aligned}$$

As highlighted in Eq. 5.13, the dual function can be expressed by two nested subproblems: power allocation and link-channel selection. In addition, to find the values of the Lagrange multipliers, we need to solve the dual problem that minimizes the dual function. What follows next, we present the solutions of the subproblems 1 and 2, and the dual problem.

5.4.2.1 Subproblem 1: power allocation

The power allocation subproblem is defined for each link $(vw) \in \Psi_v$, that has been selected for data transmission, i.e. $y^{\varsigma}_{(vw)} = 1$. Here, we decide the transmission power, $p^{\varsigma}_{(vw)}$, for the link (vw) on channel ς by solving subproblem 1 (given below), when the link-channel assignment decision, $y^{\varsigma}_{(vw)}$, and the Lagrange multipliers (i.e., λ^1 and λ^2) are given.

$$\mathop{\arg\max}_{p^{\varsigma}_{(vw)} \in \Phi_v} \left\{ u^{\varsigma,p}_{(vw)} - \lambda^1_v r_{(vw)} - \lambda^2_v y^{\varsigma}_{(vw)} \right\} \tag{5.14}$$

s.t.

$$p^{min} \leq p^{\varsigma}_{(vw)} \leq p^{max}, \tag{5.15}$$

$$0 \leq r_{(vw)} \leq r^{\varsigma,p}_{(vw)} \leq r^{max}. \tag{5.16}$$

Let $p^{\varsigma^*}_{(vw)}$ denote the solution of the objective function (5.14) that represents the optimal transmission power over link (vw), such that the overall throughput is maximized. As the problem formulated in Eq. 5.14 through 5.16, is a convex optimization problem and has a single scalar variable, we can derive the value of $p^{\varsigma^*}_{(vw)}$ by using bisection method, as in [130].

5.4.2.2 Subproblem 2: link-channel assignment

Given the optimum value for subproblem 1, subproblem 2 is formulated to find the link-channel assignment matrix, Ψ_v, for node v, such that the node utilization is maximized:

$$\mathop{\arg\max}_{\Psi_v} \sum_{(vw) \in \Psi_v} \mathop{\arg\max}_{p^{\varsigma}_{(vw)} \in \Phi_v} \left\{ u^{\varsigma,p}_{(vw)} - \lambda^1_v r_{(vw)} - \lambda^2_v y^{\varsigma}_{(vw)} \right\} \tag{5.17}$$

s.t.

$$y^{\varsigma}_{(vw)} \in \{0,1\}, \quad \forall (vw) \in \mathcal{L}^d_v, \varsigma \in \mathcal{C} \tag{5.18}$$

$$\sum_{\varsigma \in \mathcal{C}} y^{\varsigma}_{(vw)} \leq 1, \quad \forall (vw) \in \mathcal{L}^d_v, \varsigma \in \mathcal{C} \tag{5.19}$$

We find a sub optimal solution to subproblem 2 by using the greedy method proposed in [131], where we let $\Psi_v^*(\lambda^1, \lambda^2)$ be the solution. Also, we let $p_{(vw)}^{\varsigma^*}(\lambda^1, \lambda^2)$ be the solution to subproblem 1 when the link-channel assignment matrix is $\Psi_v^*(\lambda^1, \lambda^2)$. Then, $\Psi_v^*(\lambda^1, \lambda^2)$ and $p_{(vw)}^{\varsigma^*}(\lambda^1, \lambda^2)$ are the optimal link-channel assignment matrix and the optimal transmission power allocation vector, respectively, when the Lagrange multipliers λ^1 and λ^2 are given.

5.4.2.3 Dual problem

Next, we define the dual problem of the primal problem of Eq. 5.5 as follows:

$$\operatorname*{\mathbf{arg\,min}}_{\lambda^1,\lambda^2} \quad \Theta(\lambda^1, \lambda^2) \tag{5.20}$$

s.t.

$$\lambda^1 \geq 0, \quad \forall v \in \mathbb{V} \tag{5.21}$$

$$\lambda^2 \geq 0, \quad \forall (vw) \in \mathbb{E} \tag{5.22}$$

$$\tag{5.23}$$

Due to the strict concavity of the primal function, its dual defined in Eq. 5.20 is differentiable. Thus, the gradient of the Lagrangian function L, with respect to λ_1 and λ_2 are computed as:

$$\frac{\partial L}{\partial \lambda^1} = \sum_{(vw)\in\Psi_v} r_{(vw)} - \sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)}, \tag{5.24}$$

$$\frac{\partial L}{\partial \lambda^2} = \Big(\sum_{(vw)\in\Psi_v} y_{(vw)}^{\varsigma} \Big) - m. \tag{5.25}$$

Next, we apply the gradient projection method [132], to compute the Lagrange multipliers iteratively as below until it converges to the optimal solution:

$$\lambda^1(i+1) = \left[\lambda^1(i) + d(i) \frac{\partial \lambda^1}{\partial L} \right]^+, \tag{5.26}$$

$$\lambda^2(i+1) = \left[\lambda^2(i) + d(i)\frac{\partial \lambda^2}{\partial L}\right]^+, \tag{5.27}$$

where, $d > 0$ is the gradient step size, and $[.]^+$ denotes $max(0,.)$. If the step size satisfies $d(i) > 0$, and $\sum_{i=0}^{\infty} d(i) = \infty$ and $\sum_{i=0}^{\infty} d(i)^2 < \infty$, the value of $\lambda^1(i)$ and $\lambda^2(i)$ are guaranteed to converge to the optimal values $(\lambda^1)^*$ and $(\lambda^2)^*$, respectively. Alternatively, if we use the constant step size, $\lambda^1(i)$ and $\lambda^2(i)$ will converge to within some range of $(\lambda^1)^*$ and $(\lambda^2)^*$. As $\lambda^1(i)$ and $\lambda^2(i)$ converge to the optimal Lagrange multipliers, link-channel selection matrix, $\Psi_v^*(\lambda^1, \lambda^2)$, and the power allocation vector, $p_{(vw)}^{\varsigma^*}(\lambda^1, \lambda^2)$, also converge to the optimal solutions.

5.4.3 Distributed Greedy Traffic Engineering

Resource allocation driven by any central controller requires global information about the network. That is, all mesh routers need to communicate their local information to the central point, causing significant communication overhead and often it becomes impractical; especially for networks with large number of nodes. Therefore, a distributed and scalable solution is highly desirable.

In this section, we develop a Distributed Greedy Traffic Engineering (DGTE) scheme that facilitates each forwarding router to independently determine the downstream link-channel assignment and power allocation so as to maximize flow throughput. While computing a feasible link-channel assignment, Ψ_v, a router $v \in \mathbb{V}$ emphasizes to pick good quality link-channel pair(s), where the weight of a link-channel pair is assigned considering the amount of interference and congestion present on it, as well as the idle probability of the selected channel. Thus, each DGTE router v uses the following weight parameter, μ_{jk}^{ς}, to quantify the quality of a link-channel pair:

$$\mu_{(vw)}^{\varsigma} = \alpha_v^{\varsigma} \times \hat{r}_{(vw)}^{\varsigma,p(min)} \times \hat{r}_{(vw)}^{o}, \tag{5.28}$$

where, $\hat{r}_{(vw)}^{\varsigma,p(min)} = \frac{r_{(vw)}^{\varsigma,p}}{r^{max}}$ and $\hat{r}_{(vw)}^{o} = \frac{r_{(vw)}^{o}}{r^{max}}$ are, respectively, the normalized values of achievable data rate in minimum transmission power p^{min} and offered rate on the link (vw). Note that the value of μ_{jk}^{ς} lies in between 0 to 1, and it exhibits higher values for

Algorithm 4 DGTE at any node $v \in \mathbb{V}$

Input: $\sum_{\forall(uv)\in\mathcal{L}_v^u} r_{(uv)}$; $r^o_{(vw)}$, $\mathcal{C}_{(vw)}$, $\forall(vw) \in \mathcal{L}_v^d$; α_v^ς, $\forall\varsigma \in \mathcal{C}$; m

Output: $\Psi_v,\ \Phi_v,\ r_{(vw)}\ \forall(vw) \in \Psi_v$

1: **Initialization:** $\Psi_v = \emptyset$, $\Phi_v = \emptyset$

2: Compute $\mu^\varsigma_{(vw)}$, $\quad \forall(vw) \in \mathcal{L}_v^d$, $\forall\varsigma \in \mathcal{C}_{(vw)}$ using Eq. (5.28)

3: Compute $\mathbb{A}_v$, $\mathbb{P}(\mathbb{A}_v)$

4: **for** $t = 1, 2, \ldots, m$ **do**

5:     Compute K_t

6:     $y = \underset{z\ \in\ K_t}{\mathbf{arg\,max}}\big(\sum_{(vw)\in z} \mu^\varsigma_{(vw)}\big)$

7:     **for** $p \in P$ **do**

8:         **if** $\big(\sum_{(vw)\in y} r^{\varsigma,p}_{(vw)} - \sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)} \geq 0\big)$ **then**

9:             $\Psi_v = y; \quad \Phi_v = p^\varsigma_{(vw)}$;

10:             go to line (17)

11:         **end if**

12:     **end for**

13: **end for**

14: **if** $(\Psi_v == \emptyset$ AND $\Phi_v == \emptyset)$ **then**

15:     $\Psi_v = y$, $\Phi_v = p^{max}$

16: **end if**

17: Compute $r_{(vw)} = min\Big\{r^o_{(vw)},\ \sum_{(uv)\in\mathcal{L}_v^u} r_{(uv)} \times \frac{r^{\varsigma,p}_{(vw)}}{\sum_{(vw)\in\Psi_v} r^{\varsigma,p}_{(vw)}}\Big\}$, $\forall(vw) \in \Psi_v$

good quality link-channel pairs. In a feasible allocation, at most m number of downstream links are allowed to be active (i.e., $\sum_{(vw)\in\Psi_v} y^\varsigma_{(vw)} \leq m$). Let $\mathbb{A}_v = \mathcal{L}_v^d \times \mathcal{C}_v$, where each element $a \in \mathbb{A}_v$ contains an individual channel allocation over a downstream link $(vw) \in \mathcal{L}_v^d$ and the corresponding power set $\mathbb{P}(\mathbb{A}_v)$ contains all possible groups of link-channel assignments over the set of downstream links. From $\mathbb{P}(\mathbb{A}_v)$, we extract only link-channel assignment groups having m or less number of downstream links and put them in corresponding sets $K_1, K_2, \ldots, K_m$ (in line 5 of Algorithm 4) and omit duplicate assignments. We now take the group of link-channel assignments that maximizes the overall transmission quality (line 6) and try to find optimal power allocation over the set of link-channel pairs (lines 7 - 12), $(vw) \in \Psi_v$, so as the flow conservation constraint is satisfied (lines 8 - 11). Finally, the total upstream traffic is split over the selected downstream links proportionate to their capacities (line 17). However, when the DGTE becomes unable to find a feasible allocation that fulfills the upstream demand, it greedily selects Ψ_v and Φ_v that maximally satisfy its requirements (lines 14- 16).

Algorithm 4 firstly computes the power set of the set $\mathbb{A}_v$, $\mathbb{P}(\mathbb{A}_v)$, in line 3. Here, the complexity is $O(2^{|\mathbb{A}_v|})$. Then the algorithm iterates over lines 4 - 13, which has complexity of $O(m \cdot \mathbb{P})$. The rest of the statements have constant unit time complexities. Therefore, the worst-case computational complexity of the algorithm is $O(2^{|\mathbb{A}_v|})$.

5.5 Performance Evaluation

In this section, we study the performances of COTE, SOTE, DGTE, MaxTh [95] and GA-CO [64] in a discrete-event network simulator, ns-3 [51], and present the discussions on their comparative results.

5.5.1 Simulation Environment

To evaluate the effectiveness of our proposed TE approaches, in all simulation experiments, we consider a static mesh network with 50 CR-enabled nodes (46 mesh routers and 4 gateways) deployed uniformly in an area of $1000 \times 1000\ m^2$. Each node is equipped with at most four IEEE 802.11a interfaces and each interface is able to communicate using one of 12 available orthogonal channels. Primary nodes also follow a uniform random distribution over the same region and we vary the number of active PUs in between 10 and 20. The transmission power of a mesh router ranges from $10mW$ to $100mW$ and the maximum data rate supported is 54 Mbps. The end users, attached with edge routers, generate constant bit rate (CBR) traffic with a packet size of 1000 bytes and transmit through UDP connections. The sources are selected independently at random for each simulation run and kept fixed during the simulation period. All data traffic is flowed from the edge routers toward the gateways. Each node computes the set of next hops (i.e., multiple paths) toward destination gateways using MP-OLSR [55] routing algorithm.

5.5.2 Performance Metrics

We have used following metrics for the comparative performance analysis.

- *Network aggregated flow throughput*: The total amount of data bytes received at all destination gateways in unit time is averaged to quantify the network aggregated flow throughput.
- *Average end-to-end delay*: We use this parameter to weight the timeliness of packet delivery. It is defined as the average of the latencies (i.e., end-to-end delivery delay) for all received packets at destinations.
- *Packet delivery ratio*: Transmission reliability is quantified in terms of the ratio between the number of bytes received by all the gateway nodes and the number of

Table 5.1: Simulation parameters

Parameter	Value
Total area	$1000 \times 1000\ m^2$
Number of mesh nodes, GWs	46, 4
Number of PUs	10 - 20
Wi-Fi standard	IEEE 802.11a
Path loss model	FrissPathLossModel
RTS/CTS	Enabled
Transmit power	10mW - 100mW
Noise density	-174 dBm/Hz
Number of radios/node, orthogonal channels	4, 12
Traffic type, packet size	UDP, 1000 Bytes
Simulation time	1000s

bytes transmitted by all the source nodes over the simulation period.

- *Flow fairness*: To scrutinize the fairness granted to the contending flows by the studied mechanisms, Jain's fairness index [108] is used. The value of the index tends to 1, when the bandwidth allocation in the network is more fairer among the flows.

- *Aggregated utility*: To measure the optimality of COTE approach, we calculate the aggregated utility value using Eq. 5.5. For effective comparison of SOTE and DGTE - with COTE, the utility values are calculated using Eq. 5.3 in each node separately and aggregated later. Then, we take the percentage of the aggregated utility value with respect to the optimal one obtained by COTE using Eq. 5.5, under the same network environment constraints.

- *Convergence cost*: The convergence cost is measured by the time required by each approach to reach its maximum utility point. The higher convergence cost adds overhead to the algorithm performance and lingers the allocation process.

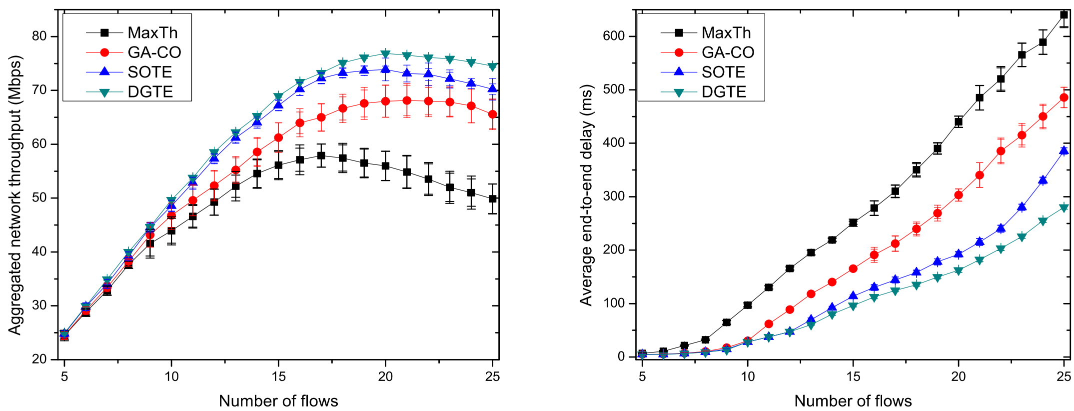
5.5.3 Simulation Results

To cancel out the effect of random deployment and activation of primary nodes, business of channels, and selection of the sources generating traffic flows, each scenario is repeated 50 times and the results are averaged over these scenarios. We have also shown the confidence intervals for the obtained results.

5.5.3.1 Impacts of increasing number of flows

In this experiment, we randomly selected sources to generate flows at 10 Mbps rate and vary the number of flows from 5 to 25. The curves of Fig. 5.2(a) depict the aggregated network throughput (in Mbps) increases with number of flows as long as the injected load is below forwarding routers' effective capacity, but it is decreased significantly for all the studied systems when the network is overloaded. As the network resources (number of idle channels and downstream links) are limited, the increasing number of flows intensifies the interference and congestion, which eventually causes the throughput degradation. However, the proposed DGTE offers higher throughput than MaxTh and GA-CO due to interference limiting and congestion avoiding multiple downstream link/channel selection by using the link-channel weight parameter (Eq. 5.28) at each hop dynamically. End-to-end single path flow propagation limits MaxTh to cope with network congestion due to higher traffic demand. Again static end-to-end multiple path computation restricts GA-CO to explore under-loaded forwarding links under high traffic load and centralized controller driven mechanism induces significant control overhead when network is highly congested. Throughput performance of SOTE is close to that of DGTE as long as the traffic load in the network is nominal, but at higher loads, the performance is reduced due to the detrimental affect of longer forwarding decision time taken by the central controller of SOTE mechanism.

The end-to-end packet transmission delays for the studied approaches are depicted in Fig. 5.2(b). The MaxTh suffers from higher end-to-end delay as flows forwarded over single end-to-end paths become congested due to higher arrival rates, resulting in increased service time at intermediate hops. On the other hand, in SOTE, allocating



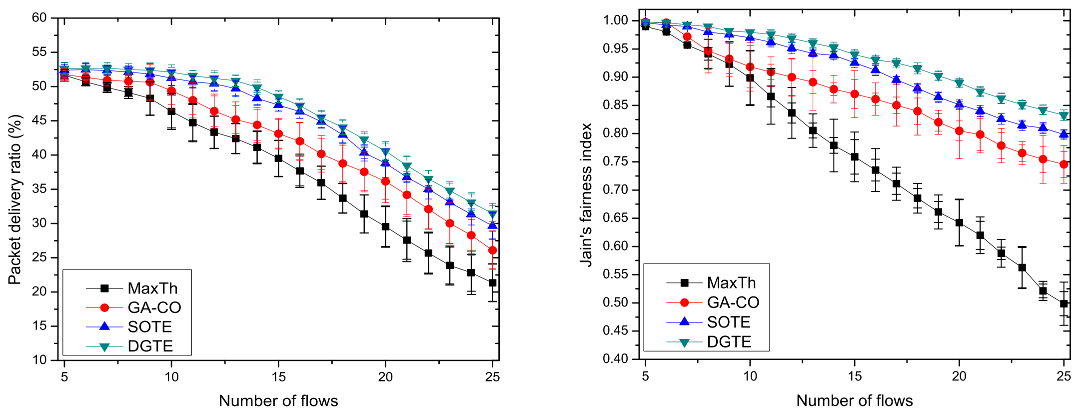
(a) Network throughput

(b) Average end-to-end delay

Figure 5.2: Throughput and delay performance vs. number of flows in CR-WMNs

stable channels (a channel with higher idle probability) over least congested links ensures higher service rate for transmitting packets. However, SOTE requires to communicate control messages toward the central agent, which saturates network's capacity and lingers the forwarding decision under higher traffic loads. Thus, the packets experience higher queuing delay, retransmissions and buffer drops, incurring additional delay for each flow. As the forwarding decisions at each DGTE router exploits one-hop neighborhood information only, instant adaptation to link, channel and load condition is possible, which in turn facilitates quick forwarding decisions in greedy manner and thus minimizes the average end-to-end packet transmission delay in the network.

The reliability of the studied approaches can be realized through the performance curves shown in Fig 5.3(a). In SOTE, the central controller has the complete view of network topology and collision domains, perceived PU statistics, aggregated flow demand and congestion at each forwarding router. Thus, the centralized resource allocation decision in CR-WMN ensures maximum number of packet delivery by selecting non-interfering and least congested links, assigning channels with higher idle probabilities (that are more stable/do not require frequent channel switching) and allocating optimal power (that eliminates co-channel interference) over transmitting links. Again

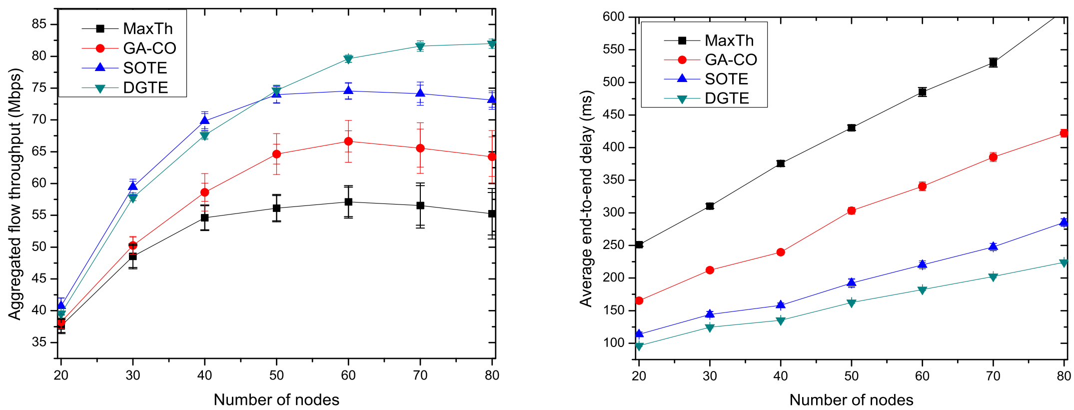


(a) Packet delivery ratio (b) Flow fairness

Figure 5.3: Packet delivery ratio and flow fairness vs. number of flows in CR-WMNs

each DGTE router retains higher packet delivery ratio by greedily selecting the higher weighted link-channel pairs, at the same time selection of optimal power for transmission assists in reliable transmission of the neighboring links. The traffic forwarding policy of MaxTh is unable to accommodate source traffic over pre-computed single path, initiating large number of packet drops. Though the GA-CO system ensures higher packet delivery through the use of multiple forwarding paths; use of end-to-end static forwarding decision limits its reliability performance compared to our proposed TE mechanisms.

Under excessive traffic demand, when all links are exhausted, flow rates are regulated in proportion to their demands and path capacities which secure fair treatment for all flows in the network for SOTE, as shown in 5.3(b). Downstream routers' backpressure based notification contains rate scale factor computed for upstream nodes in DGTE, regulating flow rates fairly under higher load. As the flow routes are fixed for MaxTh, flows originating in a congested region are treated unfairly than those in underloaded regions.



(a) Aggregated network throughput

(b) Average end-to-end delay

Figure 5.4: Throughput and delay performance vs. number of nodes in CR-WMNs

5.5.3.2 Impacts of varying number of nodes

Scalability is one of the most critical factors for designing a data forwarding mechanism influencing CR-WMN performances. In this section, we have considered different dimensions of CR-WMNs to test the scalability of the proposed TE system and state-of-the-art approaches. We have kept the number of available primary channels fixed at 12 and varied the network size (by using increasing number of nodes from 20 to 80 and keeping the node density constant). The offered load to each network is kept in the range 60% to 70% of the networks' total effective capacity.

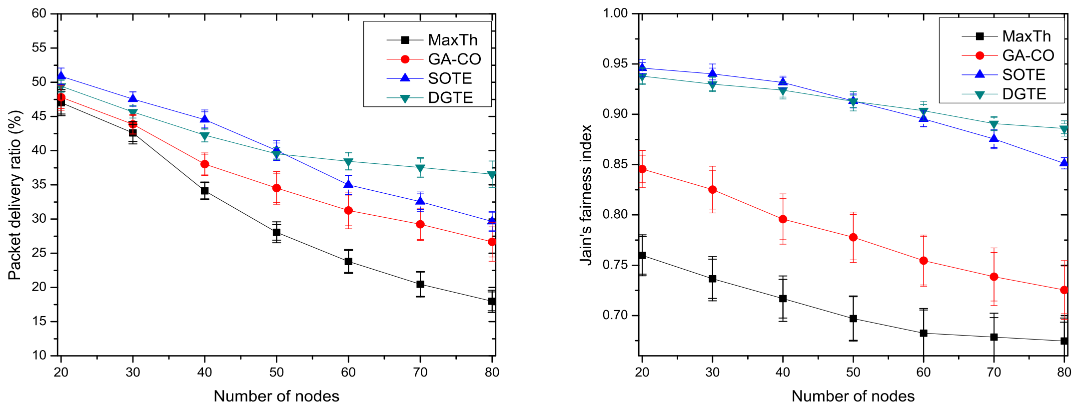
Fig. 5.4(a) and 5.4(b) show the insights of increased secondary mesh nodes in terms of the achievable aggregated network throughput and end-to-end packet transmission delay, respectively. Here SOTE and DGTE retain higher throughput than the other approaches as the increase in the number of mesh nodes gives opportunity to each forwarding router to explore more alternate downstream links to forward aggregated traffic through dynamic power allocation, minimizing neighborhood interference and granting other contending routers access to the channel to further improve the overall network throughput. But, in larger networks, SOTE is unable to keep increasing its throughput due to propagation of local information to the central agent to compute resource allocation. The MaxTh requires huge end-to-end control message propagation during resource allocation schedule, which impacts delay performance in larger networks as path length increases between source-destination pairs.

Fig. 5.5(a) shows the inclination of successful packet delivery ratio with increased network size. Networks with smaller number of nodes exhibit lower losses because of lower interferences as can be anticipated theoretically. Due to random behavior of PUs, selection of channels based on instant availability without analyzing the historical behavior forces SUs to switch channel frequently, affecting radiabilities of MaxTh and GA-CO systems; whereas, selection of stable channels in our TE approaches and traffic splitting over least congested links ensure higher data delivery. As shown in Fig. 5.5(b), in network with increased nodes, each flow in our proposed TE mechanisms is awarded with fair share of the available bandwidth than the state-of-the-art approaches. Each forwarding router in our proposed DGTE framework pro-actively regulates the incoming traffic flow rates in proportion to their demands. Thus, each upstream flow receives proportionally fair treatment from each downstream routers. But in SOTE, with increased number of nodes, as the traffic-split decision time grows rigorously, incoming flows are refrained from being rewarded with required proportionate fairness.

5.5.3.3 Impacts of primary user density in the network

Here, we discuss on the performance results for varying primary user densities, i.e., we control transmissions from PUs such that their channel occupancy percentage varies from 10% to 80% at a given time. The other parameters are kept constant, e.g., the number of SUs is 50 and 20 flows each with a data rate of 10 Mbps are generated from random sources.

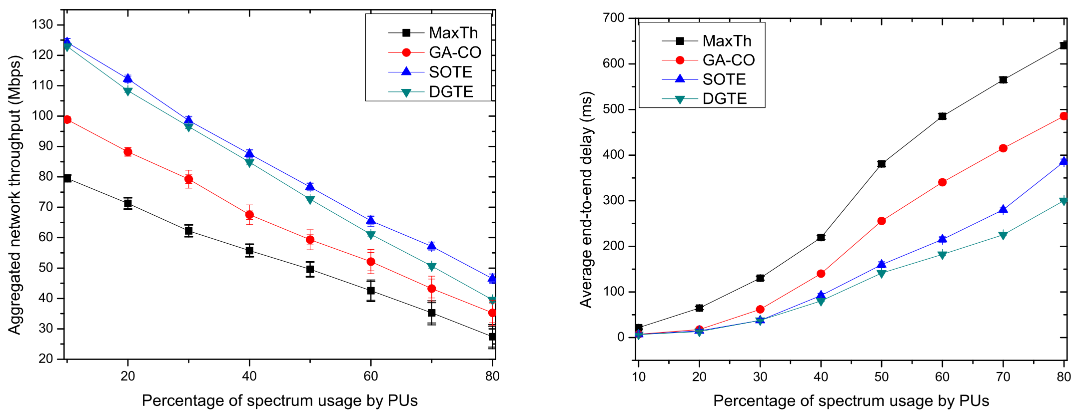
When less PU activity is experienced in the network, more channel resources are available to the mesh routers to accommodate their upstream flows, which entails higher network performance as shown in Fig. 5.6 and 5.7. As revealed from the simulation result analysis in Fig. 5.6(a), our proposed TE approaches provide the higher throughput performance even in tight resource constraints than other state-of-the-art approaches.



(a) Packet delivery ratio (b) Flow fairness

Figure 5.5: Packet delivery ratio and flow fairness vs. number of nodes in CR-WMNs

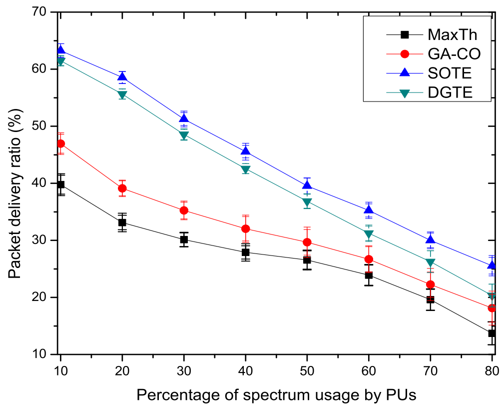
Though the link-channel selection is done at each DGTE router independently, neighboring routers collaboratively contribute to enhance their flow throughput through optimal power allocation. Here, spatial channel utilization is increased by allowing more concurrent transmissions from neighboring nodes at optimal powers on the least interfering channels, opposing to defer transmissions on a channel in MaxTh. SOTE outperforms DGTE under high PU activity, as the central controller can pick the optimal set of link-channel pairs and allocate minimum power over them to ensure the maximum interference free concurrent transmission, whereas DGTE router greedily allocates maximum power over the forwarding path to accommodate the upstream flow, degrading the neighborhood interference and thus the throughput. The delay curve is drawn as the function of the number of available PU channels in Fig. 5.6(b). Under higher number of PU transmissions, traffic get stuck at forwarding mesh routers due to resource scarcity. But, the GA-CO, SOTE and DGTE systems can control powers over the downstream links, allowing them to transmit at lower powers and rates, which minimize the packet delay at node buffers. In GA-CO, fixed multiple path activation at each node restricts other neighbors to get a chance to access a channel, resulting in node level congestion as well as delayed packet delivery.



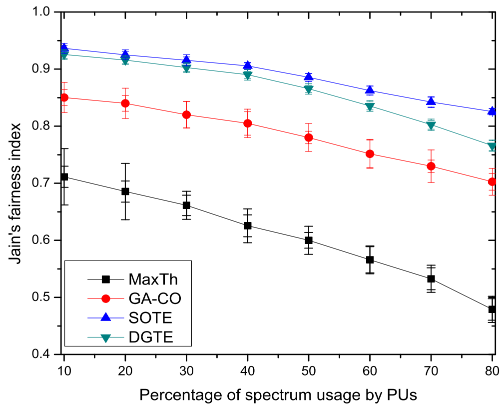
(a) Aggregated network throughput

(b) Average end-to-end delay

Figure 5.6: Throughput and delay performance vs. PU density in CR-WMNs.



(a) Packet delivery ratio



(b)Flow fairness

Figure 5.7: Packet delivery ratio and flow fairness vs. PU density in CR-WMNs.

Under high PU activity, packets start to drop and the delivery ratio decreases significantly. But, hop-by-hop dynamic forwarding policy facilitates our SOTE and DGTE to cope with the versatile PUs, ensuring more reliable transmission, as depicted in Fig. 5.7(a). When the primary channels are more occupied, the usable bandwidth per second node is reduced and thus the flows are prohibited from acquiring a link-channel to be forwarded. However, as the traffic forwarding decision is carried out by the central agent in SOTE considering the individual flow's demand, channel availability and congestion, the resource allocation is fairer than the other approaches, as revealed in Fig 5.7(b).

5.5.3.4 Convergence analysis

Fig. 5.8 and 5.9 depict the convergence behavior of the studied TE approaches for 30 flows in a 40-node network and 40 flows in a 80-node network, respectively. The simulation parameters are considered to be as in Table 5.1. It can be seen that with fewer number of nodes in the network, the MaxTh, GA-CO, SOTE and DGTE achieve their maximum throughput in about 100s; whereas, the COTE takes approximately 400s. The convergence time for COTE further accelerates with increased number of nodes in the network, as noticed in graphs of Fig. 5.9. This is caused by the fact that the available sets of downstream links at each forwarding router increases with number of nodes in the network and thus the COTE system requires more iterations to find the optimal traffic forwarding decision. Furthermore, the graphs reveal that the convergence speed of DGTE has the least impact for large scale networks, as nodes perform their traffic forwarding decisions independently following the single-hop neighborhood information only. On the other hand, in SOTE and GA-CO, the central controller driven resource

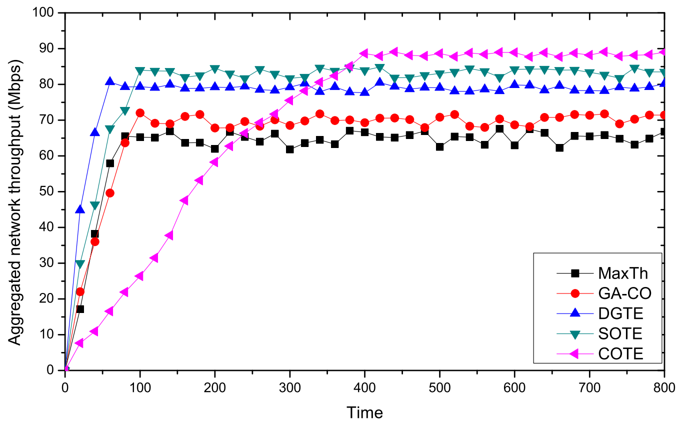


Figure 5.8: Convergence time for 40 nodes.

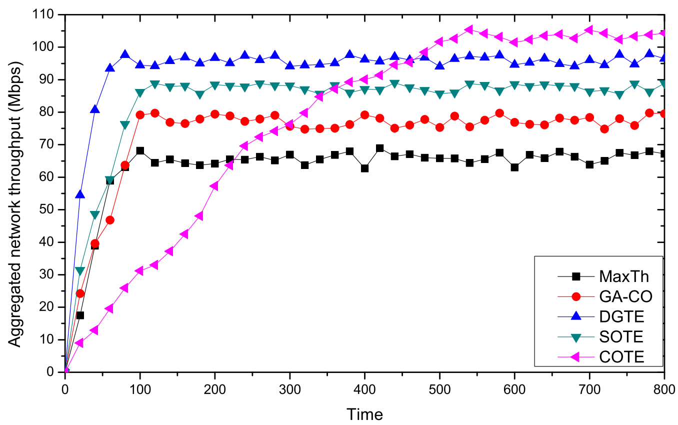


Figure 5.9: Convergence time for 80 nodes.

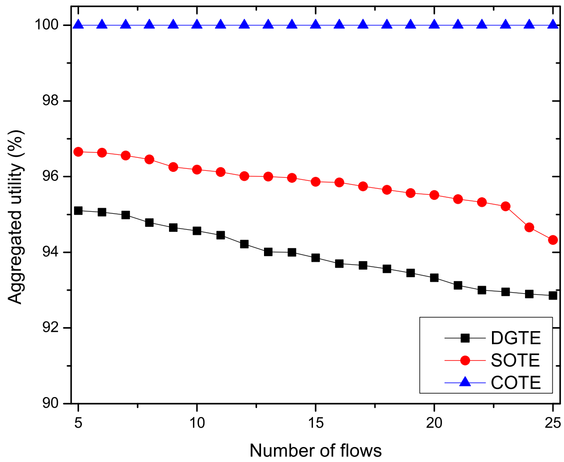


Figure 5.10: Aggregated utility for varying flows.

allocation requires huge control message propagation latency, elapsing more time to reach at equilibrium state. Though the MaxTh reaches its peak performance point rapidly, but it fails to achieve higher throughput due to its single path routing policy.

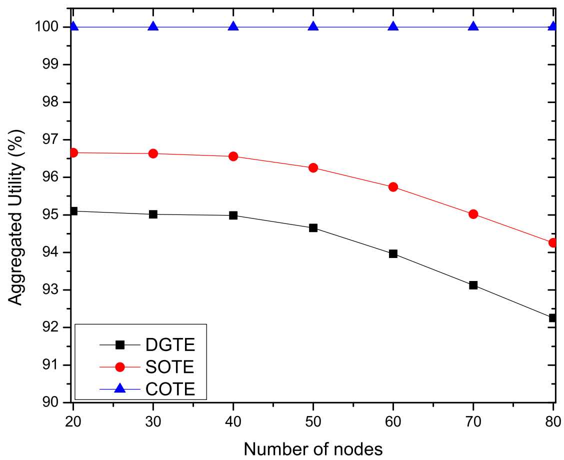


Figure 5.11: Aggregated utility for varying nodes.

5.5.3.5 Estimation of aggregated utility

Finally, we present the utility values achieved by MaxTh, GA-CO, SOTE and DGTE systems (after they reach at equilibrium state) compared to the optimal result obtained by COTE. We use Eq. 5.5 - 5.11 to measure the aggregated utility value of the COTE system and regard it as 100%. The graphs of the Fig. 5.10 and 5.11 depict the comparative utility values achieved by DGTE and SOTE systems for increasing number of flows and nodes, respectively. Both the systems achieve comparable performances.

5.6 Summary

This work first develops a centralized optimal traffic engineering (COTE) system that considers the random behavior of PUs, congestion and interference in selecting link-channel and powers on them for each mesh router so that the data delivery performances are maximized. Then, a sub-optimal solution (SOTE), via the Lagrangian primal-dual approach, is devised to achieve optimal solution in polynomial time, opposing to COTE. We further propose a distributed and greedy solution (DGTE) to enhance the scalability of the traffic engineering approaches. Simulation results demonstrate the competency of the proposed TE solutions, and their ability to acclimate to varying network traffic loads, number of nodes and availability of PU channels. It has been revealed that, for a given amount of network resources, the proposed TE approaches (that exploit multi-path data forwarding) can accommodate more traffic streams, incur less delay, provide higher reliability and fairness compared to the state-of-the-art approaches. The results also depict that a distributed solution, that explores only single-hop neighborhood information, is more effective for large networks in achieving higher data delivery performances.

Chapter 6

Conclusions

6.1 Summary of Research

This dissertation has addressed one of the most crucial challenges in Wireless Mesh Networks (WMNs), namely the high-throughput data delivery. The traffic engineering methods developed and analyzed in this thesis work are expected to facilitate many emerging applications in the WMNs.

Our proposed optimal traffic engineering solutions, O-DTE, OLCP and COTE are targeted to operate over MRMC WMNs, where the radios are assigned to fixed channels, able to dynamically reallocate channels and employ cognitive sensing to opportunistically access licensed channels, respectively. To find the optimal set of forwarding links and the rate (or power) allocations over those that maximizes the flow throughput, we devise O-DTE framework in Section 3.4 that distributively minimizes backlogged traffic while ensuring flow fairness. In Section 4.4, the proposed OLCP framework employs joint link-channel selection and power allocation, which also follows hop-by-hop traffic splitting approach, exploits single-hop information to forward traffic over least-congested and minimally-interfered link-channel pairs, which in turn improves spatial reuse of links and channels. Thus, OLCP allows more concurrent flow transmissions, helping to improve overall network throughput. Finally, to increase spectrum capacity in WMNs, a centralized optimal traffic engineering framework, COTE, is devised in Section 5.4.1, where the forwarding routers deploy cognitive radios to opportunistically access the vacant licensed channels over forwarding links. Here, a centralized controller jointly selects downstream link-channel pairs and allocates power over them to forward traffic considering PU-channel idle probability, link interference and path congestion so as to maximize the network throughput. As, the proposed optimal traffic engineering frameworks belong to mixed integer nonlinear programming (MINLP) class, their solutions are intractable in real-time. In networks with small number of nodes, optimal TE mechanism converge quickly to high-throughput data delivery solutions, as revealed in our simulation experiments depicted in Sections 3.6.3, 4.6.3 and 5.5.3. But, in large networks and under high traffic load, due to being computation intensive, they fail to take real-time decisions.

Therefore, we propose greedy heuristic TE solutions that work locally at each node without global network information and end-to-end path setup, which help them to be scalable, self adaptable to network dynamics and accommodate bursty traffic arrivals. As the proposed TE solutions learn the downstreams' congestive state and neighboring interference intensity in ahead of time, their hop-by-hop traffic forwarding mechanisms pro-actively distribute the traffic loads toward less interfered and congested links and thus implement interference minimized and load balanced data dissemination frameworks. Therefore, the network nodes would not be overshooted with high traffic volume as well as the interference levels would be minimum, which in turn would boost up aggregated network throughput. Also, timely response to the fluctuating link conditions (e.g., interference, load and error) by dynamically updating the neighborhood information allows the proposed TE mechanisms to adapt the near-optimal set of forwarding links. Here, to restrict link data rate according to respective downstream's forwarding capacity and congestive status, a flow-demand proportional fair rate control mechanism is employed that prevents flows to experience performance degradation due to adverse affects of congestion. Besides, optimal power allocation over the forwarding links to obtain the required transmission rate enhances spatial channel reusability in neighborhood. Thus, more concurrent transmissions are allowed, which in turn improves the overall forwarding capability of neighboring nodes to contribute higher aggregated network throughput.

Simulation results show that our proposed TE solutions offer higher flow throughput, reliability and fairness while improving delay performance and convergence cost as compared to state-of-the-art works. At the same time, they incur reasonable operational overhead under varying network dimensions, offered load, available channels and traffic conditions. Thus, the developed traffic engineering solutions cultivate outstanding flow performances in large scale WMNs, particularly in which the intensity of users and traffic volume is highly dynamic, as found in Section 3.6.3.3 and 4.6.3.3. However, there are some cases, where the performance improvement of the proposed TE mechanisms are not very significant. In networks with smaller number of nodes, there are very few available alternate paths between pair of forwarding routers, which limits the choice of forwarding links in traffic splitting operation. Also real-time congestion and interference monitoring through exchange of control messages between every forwarding node pair induces significant amount of operation overhead, which is expensive in networks with lower bandwidth capacities.

6.2 Discussions

Aim of this thesis work was to find a high-throughput data delivery mechanism over the existing architectures, available resources and offered capacity of Wireless Mesh Networks. We opt to develop dynamic traffic forwarding solutions that would be robust, scalable and deployable without incurring much overhead. As many MRMC WMNs employ static channel allocation over radios, we first developed dynamic traffic engineering solution, DTE, that considers the underlying radio-channel bindings to be fixed. DTE solutions are well suited in WMNs for building automation, health care, security surveillance etc., where the traffic arrival is quite stable over time. But to provide seamless Internet connections to home/office users, emergency response, transportation systems etc. over WMNs, bursty traffic arrivals and diversified environments have to be considered. Therefore, we developed a low overhead dynamic link-channel selection mechanism, LCP, to address traffic demand destined toward Internet. Further, to add more capacity to the transmitting links, we deployed cognitive-enabled routers that are able to pick more stable licensed channel to ensure uninterrupted data delivery.

In our work, we first developed optimal TE frameworks for high-throughput data delivery in WMNs. But, the performance of these mechanisms, as obtained from the optimization tools and NS-3 experiments, reveal the practical infeasibility of adapting these mechanisms in large large scale and highly dynamic networks. Thus, under diversified network and load condition, greedy heuristic mechanisms provide near-optimal solutions in feasible time.

6.3 Future Works

The TE mechanisms presented in this thesis have been evaluated using simulator tool. This simulation results help us to study the behaviour of proposed solution mechanisms and compare with other systems with diverse topologies, traffic patterns, environmental parameters and different parameters of the algorithms. Even with the most sophisticated network simulation tools, however, it is difficult to predict how these protocols perform in real hardware. A next step research, therefore, is to experiment with the approaches presented in this thesis in a real test-bed implementation.

Secondly, in our proposed solutions, we have considered CSMA/CA based channel access mechanism, which may degrade flow performance due to contention in high density and large scale networks. Thus, to alleviate packet collisions and drops, and improve scalability; devising a cross layer solution that encompasses medium access control, routing and congestion control functionalities to further improve flow performance.

Furthermore, our proposed traffic engineering efforts in WMNs, are focused on capacity, throughput, and fairness. However, many applications in WMNs, need to support multimedia communication. Thus, the traffic forwarding mechanism should consider the multiple QoS metrics such as delay, packet loss ratios, and delay jitter, while taking the forwarding decision.

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Appendix A

List of Acronyms

AP	Access Point
ACK	Acknowledgement
ADCA	Adaptive Dynamic Channel Allocation protocol
AIMD	Additive Increase Multiplicative Decrease
AOMDV	Multi-path Distance Vector
AR-TP	Adaptive and Responsive Transport Protocol
BER	Bit Error Rate
CA	Channel Allocation
CAS	Channel Assignment Server
CCAS	Clustered Channel Assignment Scheme
CCC	Common Control Channel
CDMA	Code Division Multiple Access
CFRC	Congestion Aware Fair Rate Control
CIV	Channel Information Vector
CLICA	Centralized Channel Assignment Algorithm
COTE	Centralized Optimal Traffic Engineering
CR	Cognitive Radio
CRAFT	Channel and Routing Assignment with Flow Traffic
CR-WMN	Cognitive Radio Wireless Mesh Networks
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DGTE	Distributed Greedy Traffic Engineering

DSL	Digital Subscriber Line
DTE	Dynamic Traffic Engineering
ECN	Explicit Congestion Notification
EED	Expected End-to-end Delay
EFT	Expected Forwarding time
ELFN	Explicit Link Failure Notification
ESS	Extended Service Set
ETM	Expected Transmission cost in Multi-rate wireless networks
ETOP	Expected Number of Transmissions On a Path
ETT	Expected Transmission Time
ETX	Expected Transmission Count
EWCCP	Explicit Wireless Congestion Control Protocol
FCC	Federal Communications Commission
GA	Genetic Algorithm
GA-CO	Genetic algorithm based Cross layer Optimization
G-DTE	Greedy Dynamic Traffic Engineerign
GLCP	Greedy Heuristic Link-Channel selection and Power allocation
G-PaMeLA	Generalized Partitioned Mesh network traffic and interference aware channeL Assignment
GW	Gateway
HWMP	Hybrid Wireless Mesh Protocol
iAWARE	Interference Aware Routing Metric
ICAR	Interference and Congestion Aware Routing protocol
ILP	Integer Linear Programming
IPD	Iterative Path Discovery
IRS	Interference-minimizing Routing and Scheduling
ISM	Industrial, Scientific and Medical Radio
JCAR	Joint Channel Assignment and Routing
JOBD	Joint Optimization of Bandwidth and Delay

JOCAC	Joint Optimal Channel Assignment and Congestion Control
JRCRA	Joint Routing, Channel and Rate Allocation
JRCS	Joint Routing and Channel Selection
JRRA	Joint Routing and Resource Allocation)
LBA	Load Based Algorithm
LCP	Link-Channel selection and Power allocation
LLAP	Link Layer Adaptive Pacing
LMMBA	Lexicographical Max-min fair Bandwidth Allocation
LMMBA	Lexicographical Maxmin fair Maximum Bandwidth allocation
LP	Linear Programming
LRTP	Link-Aware Reliable Transport Protocol
MAC	Medium Access Control
MAP	Mesh Adaptive Pacing
MARA	Metric Aware Rate Adaptation
MaxTh	Decentralized Throughput Maximization)
MC	Mesh Client
MCCA	Multi-radio Centralized Channel Allocation
MCG	Multi-radio Conflict Graph
MCS	Modulation and Coding Scheme
MIC	Metric of Interference and Channel switching
MILP	Mixed Integer Linear Programming
MIMO	Multi-Input Multi-Output
MINLP	Mixed Integer Non Linear Programming
MIP	Mixed Integer Programming
MMBA	Maxmin fair Maximum throughput Bandwidth Allocation
MMF	Max-Min Flow
MPSPT	Minimum Power Shortest Path Tree
MR	Mesh Router
MRA	Multi-path Refinement Algorithm

MRAB	Multi-radio Achievable Bandwidth
MRAC	Routing and Admission Control Protocol ()
MRMC	Multi-Radio Multi-Channel
MRRA	joint Multi-path Routing and Rate Allocation
MRSA	Multi-path Routing and Spectrum Allocation
MRSA	Multi-path Routing and Spectrum Allocation
MRT	Maximum Multi-path Routing Throughput
MVCRA-R	Minimum Variation Channel and Rate Reassignment Algorithm
NCIV	Node-Channel Information Vector
NICC	Neighborhood-Aware and Overhead-Free Congestion Control
NLIP	Non-Linear Integer Programming
NP	Non-deterministic Polynomial
NSGA	Non-dominated Sorting Genetic Algorithm
O-DTE	Optimal Dynamic Traffic Engineerign
OID	Out-of-Interference Delay
OLCP	Optimal Link-Channel selection and Power allocation
OSA	Opportunistic Spectrum Allocation
P2P	Peer-to-Peer
PDR	Packet Delivery Ratio
PHY	Physical
PPD	Parallel Path Discovery
PU	Primary User
QoS	Quality of Service
RA	Rate Allocation
RBA	Receiver Based Channel Allocation
RCL	joint Routing, Channel and Link scheduling
ROMA	Routing Over Multi-radio Access Network
ROPIM	Robust Outage Probability based Interference Margin
RREP	Route Reply

RREQ	Route Request
RTT	Round Trip Time
SCA	Spatial-reusable Channel Allocation
SECC	Simple and Effective Congestion Control
SINR	Signal-to-Interference-Noise Ratio
SIR	Search Interference Range
SNR	Signal-to-Noise Ratio
SOTE	Sub-Optimal Traffic Engineering
SPT	Shortest Path Tree
SRSC	Single-Radio Single-Channel
STE	Stochastic Traffic Engineering
SU	Secondary User
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TE	Traffic Engineering
TIC	Traffic-Independent Channel selection
TICA	Topology-controlled Interference-aware Channel-assignment Algorithm
UDP	User Datagram Protocol
WCETT	Weighted Cumulative Expected Transmission Time
WCP	Wireless Control Protocol
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Inter-operability for Microwave Access
WLAN	Wireless Local Area Network
WMNs	Wireless Mesh Networks

Appendix B

List of Notations

Parameter	Description
$\Gamma = (\mathbb{V}, \mathbb{E})$	A graph Γ with set of nodes $\mathbb{V}$ and links $\mathbb{E}$
$\mathbb{G}$	Set of gateways
$\mathbb{P}$	Set of discrete transmission power levels
$\mathbb{R}$	Set of discrete rate levels
$\mathbb{C}$	Set of unlicensed channels
$\mathcal{C}$	Set of licensed channels
$\mathcal{L}_v^d$	Set of downstream links of node v
$\mathcal{L}_v^u$	Set of upstream links of node v
I_v	Number of radio interfaces at node v
$\mathbb{S}_v$	Set of allocation vectors of node v
(vw)	Link between node v and w
$p_{(vw)}$	Allocated transmission power over link (vw)
$p_{(vw)}^c$	Allocated transmission power over link (vw) on channel $c \in \mathbb{C}$
$p_{(vw)}^\varsigma$	Allocated transmission power over link (vw) on channel $\varsigma \in \mathcal{C}$
p^{max}, p^{min}	Maximum and minimum transmission power over a link
$c_{(vw)}$	Allocated channel $c \in \mathbb{C}$ over link (vw)
$\gamma_{(vw)}^p$	SINR over link (vw) at transmission power p
$\gamma_{(vw)}^{p,c}$	SINR over link (vw) at transmission power $p \in \mathbb{P}$ and channel $c \in \mathbb{C}$
$\gamma_{(vw)}^{p,\varsigma}$	SINR over link (vw) at transmission power p and channel $\varsigma \in \mathcal{C}$
$r_{(vw)}^p$	Data rate of link (vw) at power p
$r_{(vw)}^{c,p}$	Data rate of link (vw) at power p on channel $c \in \mathbb{C}$

$r^{\varsigma,p}_{(vw)}$	Data rate of link (vw) at power p and channel $\varsigma \in \mathcal{C}$
r^{max}, r^{min}	Maximum and minimum rate over a link
$r^{o}_{(vw)}$	Offered data rate of link (vw)
Φ^{max}	Maximum buffer size at any node
Φ_v	Current buffer size at node $v \in \mathbb{V}$
ψ_v	Queue congestion status at node $v \in \mathbb{V}$
β_v	Rate adjustment factor towards node $v \in \mathbb{V}$
$x_{(vw)}$	Binary variable indicating activation status of link (vw)
z^c_v	Binary variable indicating activation status of channel c at node v
$y^{\varsigma}_{(vw)}$	Binary variable indicating activation status of link (vw) in channel ς
$\omega_{(vw)}$	Weight of a G-DTE link (vw)
δ_v	Backlogged traffic index at DTE node $v \in \mathbb{V}$
$\vartheta^{c}_{(vw)}$	Weight of a GLCP link (vw)
$\xi^{c,p}_{(vw)}$	Interference degree of link (vw) on transmission power $p \in \mathbb{P}$ on channel $c \in \mathbb{C}$
$\sigma(s_v)$	Capacity-demand ratio of allocation $s_v \in \mathbb{S}_v$
α^{ς}_v	Idle probability of licensed channel $\varsigma \in \mathcal{C}$, perceived at node v
$u^{\varsigma,p}_{(vw)}$	Utility of link (vw) in channel $\varsigma \in \mathcal{C}$ and power p
Ψ_v	Link-channel assignment matrix of node v
Φ_v	Power allocation vector of node v

Appendix C

List of Publications

International Journal Papers

1. M. Islam, M.A. Razzaque, M.M. Rashid, M.M. Hasan and A. Alelaiwi, "Traffic Engineering in Cognitive Mesh Networks: Joint Link-Channel Selection and Power Allocation," *Submitted to the Computer Communications*, October 2016.

2. M. Islam, M.A. Razzaque, M.M. Rashid, M.M. Hasan, A. Almogren and A. Alelaiwi, "Dynamic Traffic Engineering for high through data delivery in Wireless Mesh Networks,"*Journal of Computers and Electrical Engineering*, Elsevier, published online on August 05, 2016 (DOI 10.1016/j.compeleceng.2016.08.004)

3. M. Islam, M.L. Rahman and M.M. Rashid, "An Efficient Traffic-Load and Link-Interference Aware Routing Metric for Multi Radio Multi Channel Wireless Mesh Networks Based on Links Effective Capacity Estimation,"*Computer and Information Science*, vol. 7, no. 4, pp. 129 - 144, 2014.

4. M. Islam, M.L. Rahman and M.M. Rashid, "Traffic Priority Based Adaptive and Responsive Congestion and Rate Control for Wireless Mesh Networks,"*Computer and Information Science*, vol. 7, no. 2, pp. 99 - 114, 2014.

Domestic Journal Papers

5. M Islam, Upama Kabir, "A Dynamic Load Balancing Approach For Solution Adaptive Finite Element Graph Applications On Distributed Systems."*Daffodil International University Journal of Science and Technology*, vol. 3, no. 1, pp. 1 7, January 2008.

6. M Islam, Upama Kabir. Mossadek Hossain Kamal, "A New Load Balancing Method Based on Dynamic Cluster Construction for Solution-Adaptive Finite Element Graphs on Distributed Memory Multicomputers." *East West University Journal*, vol. 1, no. 2, pp. 15 27, January 2008.

International Conference Papers

7. M. Islam, M.A. Razzaque, M.M. Rashid, "Joint Link-Channel Selection and Power Allocation in Multi-Radio Wireless Mesh Networks." *Submitted to IEEE International Conference on Communications*, October 2016.

8. M. Islam, M.A. Razzaque, M.M. Rashid, "Joint Link-Channel Selection and Rate Allocation Heuristic for Cognitive Radio Mesh Networks." *IEEE TENCON*, 2016.

9. M. Islam, M.L. Rahman and M.M. Rashid, "IL-CD: Interference and load aware congestion detection and bandwidth efficient rate allocation for wireless mesh networks." *IEEE International Symposium on Networks, Computers and Communications*, pp. 1-5, 2014.

10. M. Islam, M.L. Rahman and M.M. Rashid, "Load adaptive congestion control and rate readjustment for wireless mesh networks." *IEEE International Conference on Software Engineering and Service Science (ICSESS)*, pp. 1088-1092, 2014.

11. M. Islam, Upama Kabir, "A Dynamic Load Balancing Approach for Solution Adaptive Finite Element Graph Applications on Distributed Systems." *IEEE International Conference on Computer and Information Technology (ICCIT)*, December 2007.

12. M. Islam, "A New Cluster based Load-Balancing Method for Solution-Adaptive Finite Element Graphs on Distributed Memory Multicomputers." *IEEE International Conference on Computer and Information Technology (ICCIT)*, pp.

433-438, December 2005.