Joint Link-Channel Selection and Power Allocation in Multi-Radio Wireless Mesh Networks

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***Abstract*—The key challenges of high-throughput data delivery in multi-radio multi-channel Wireless Mesh Networks (WMNs) are fluctuating channel conditions, dynamic traffic flows, co-channel interferences, congestion, etc. In this paper, we first formulate a mixed integer non-linear programming (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 and fairness.**

I. Introduction

Wireless Mesh Networks (WMNs) have gained high popularity in the past few 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 [1] [2]. The exponential growth of traffic volume, particularly from wireless devices, 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 improved data delivery services [3] [4]. 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 varying network conditions such as interference, traffic volume and congestion [5].

The aforementioned problem has been studied in the literature being exploited in different ways - jointly selecting the routing path and channels on the links [6] [7] [8]; routing path and rate selection [9] [10]; and routing path and channel selection along with rate control [3] [4] [11]. End-to-end least congested path computation and link-load sensitive channel allocation approach to forward time varying traffic is proposed in [6] and in [7] [8], 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 [9]. The poor scalability problem of [9] has been addressed by a distributed traffic forwarding mechanism proposed in [10], which considers instantaneous link interference and path congestion. Though efficient rate allocation by controlling transmission power enables [10] to improve throughput performance, consideration of static channel allocation limits its link capacity. The path selection, channel assignment and rate allocation problems are jointly addressed in [3] and [4], where flows are routed over least-loaded and minimal-interfered single shortest path. Though [4] 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 [11], several fixed end-to-end multiple paths that minimise co-channel interference, are exploited for data delivery; however, using fixed end-to-end paths in a highly dynamic network environment can't often achieve good throughput.

In this paper, 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 to forward its upstream traffic over least-congested and minimally-interfered link-channel pairs, which in turn improves spatial reuse of channels and thus helps to improve overall network throughput. The major contributions of this paper 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 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 [12] show better performance in terms of throughput, delay, reliability and fairness compared to the state-of-the-art works.

The rest of the paper is organized as follows. Section II

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reviews related works. Section III presents network model and assumptions. In Section IV, the joint optimization problem is formed and the greedy heuristic solution is described in Section V. Section VI presents the simulation performances and Section VII concludes the paper.

II. 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 and rate allocation; 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 solutions for traffic streams [13][14]. So, many state-of-the-art works consider cross layer solution to routing and channel allocation jointly. A centralized solution presented in [6], characterizes dynamic network traffic to identify cycles of similar pattern and for each traffic pattern, computes 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 [7]. However, this approach requires significant overhead and network updates. A hybrid MRMC architecture is proposed in [8], where end-to-end routing paths are established over fixed radios. Under higher traffic demand, dynamic radios communicate over least congested channels. Use of only one dynamic radio interface refrains a forwarding router to utilize higher achievable bandwidth over least interfered channels.

Due to 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 [9], 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) [10], 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, the consideration of static channel allocation over the multiple radios here limits the link-capacity under interfered and congested neighborhood.

Works focused to solve joint routing, channel and rate allocation problem has recently attracted the researchers. [3] is a centralized 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. [4] 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, [15] computes a 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) [11], 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.

III. System Model and Assumptions

To represent a wireless mesh network, we use graph $\Gamma = (\mathbb{V},\mathbb{E})$, where $\mathbb{V}$ and $\mathbb{E}$ correspond to the set of multi-radio mesh nodes and links, respectively. Here, $\mathbb{C} = \{c_1, c_2, \ldots, c_k\}$ holds the set of orthogonal channels to be used for data transmission in Γ. Each node $v \in \mathbb{V}$ has I_v number of radio interfaces, where each radio can operate on an orthogonal channel chosen from the channel set $\mathbb{C}_v \subset \mathbb{C}$, to allow more concurrent transmissions [3]. 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. A binary variable $x_{(vw)}$ contains 1 if the link (vw) is active, and 0 otherwise. For each node $v \in \mathbb{V}$ and channel $c \in \mathbb{C}_v$, we define the node-channel variable, y^c_v, which contains 1 if $\exists (vw) \in \mathbb{E}$ and $x^c_{(vw)} = 1$, 0 otherwise.

While transmitting over link (vw) and channel c, node v selects a discrete transmission power, $p^c_{(vw)}$, from the set $\mathbb{P} = \{p^{min}, \ldots, p^{max}\}$, allowing corresponding achievable data rate, $r^{c,p}_{(vw)} \in \mathbb{R}$, using a specific MCS (modulation and coding scheme) [11]. 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 I [11]. When transmitter v uses power $p \in \mathbb{P}$ to transmit over link (vw) operating on channel c, the corresponding SINR value computed at receiver w is as follows:

$$\gamma^{c,p}_{(vw)} = \frac{p^c_{(vw)} \mathscr{G}_{(vw)}}{\eta^c_{(vw)} + N_0}, \tag{1}$$

TABLE I
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

where, $\mathscr{G}_{(vw)}$ represents channel gain, that depends on path loss, fading and shadowing etc.; $\eta^c_{(vw)}$ 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 $(vw) \in \mathscr{L}^d_v$, $\eta^c_{(vw)}$, $\forall c \in \mathbb{C}_v$. In order to achieve rate $r \in \mathbb{R}$, over link (vw), the experienced SINR should meet the threshold value requirement; i.e. $\gamma^{c,p}_{(vw)} = \frac{p^c_{(vw)}\mathscr{G}_{(vw)}}{\eta^c_{(vw)}+N_0} \geq \gamma(r)$. Now, to find the maximum interference tolerable over link (vw) to achieve $\gamma(r)$, on transmission power p and channel c is as follows:

$$\eta^{c,p}_{(vw)}(r) = \frac{p^c_{(vw)}\mathscr{G}_{(vw)}}{\gamma(r)} - N_0 \tag{2}$$

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

$$\xi^{c,p}_{(vw)} = \frac{\eta^c_{(vw)}}{\eta^{c,p}_{(vw)}(r)} \tag{3}$$

Most of the traffic in WMNs is generated from the users and are destined toward Internet through multiple gateways. For each forwarding router v, we let $\mathscr{L}^u_v$ and $\mathscr{L}^d_v$ be the set of upstream and downstream links, and I^u_v and I^d_v be the number of radios dedicated for upstream and downstream communication, respectively. In order to find $\mathscr{L}^d_v$, router v employs a suitable routing mechanism [16]. The aggregated upstream traffic, $\sum_{(uv)\in\mathscr{L}^u_v} r_{(uv)}$, at router v, is split over the each selected downstream link, $(vw) \in \mathscr{L}^d_v$ in a fair weighted rate, $r_{(vw)}$, limited to link achievable rate, $r^{c,p}_{(vw)}$ and offered rate, $r^o_{(vw)}$ [10].

IV. 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 $(vw) \in \mathscr{L}^d_v$, the tuple $(x_{(vw)}, c_{(vw)}, p_{(vw)})$ represents the activation status, channel and power allocation over link (vw) at any given time, where $x^c_{(vw)} \in \{0,1\}$, $c \in \mathbb{C}_{(vw)}$ 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 $(vw) \in \mathscr{L}^d_v$ and $\mathbb{S}_v = \prod_{(vw)\in\mathscr{L}^d_v} \mathbb{Q}_{(vw)}$ 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, $\{(x_{(vw)}, c_{(vw)}, p_{(vw)})\}$, 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:

$$\sigma(s_v) = \frac{\sum_{(vw)\in s_v} r_{(vw)}}{\sum_{(uv)\in\mathscr{L}^u_v} r_{(uv)}}. \tag{4}$$

where, $\sum_{(uv)\in\mathscr{L}^u_v} r_{(uv)}$ 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:

$$r_{(vw)} = min\left\{ r^o_{(vw)}, r^{c,p}_{(vw)}, \sum_{(uv)\in\mathscr{L}^u_v} r_{(uv)} \times \frac{r^{c,p}_{(vw)}}{\sum_{(vw)\in s_v} r^{c,p}_{(vw)}} \right\}, \tag{5}$$

where $r^o_{(vw)}$, is the offered rate over link $(vw) \in \mathscr{L}^d_v$, considering the congestion present at downstream node w. The detailed computation of $r^o_{(vw)}$ can be found in our previous work [10].

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:

$$\underset{s_v \,\in\, \mathbb{S}_v}{\textbf{argmax}} \quad \left\{ \sigma(s_v) - \frac{\sum_{(vw)\in s_v} \xi^{c,p}_{(vw)} \times \hat{p}^c_{(vw)}}{|s_v|} \right\} \tag{6}$$

s.t.

$$x_{(vw)} \in \{0,1\}, \forall (vw) \in \mathbb{E}, \forall c \in \mathbb{C} \tag{7}$$

$$y^c_v \in \{0,1\}, \forall v \in \mathbb{V}, \forall c \in \mathbb{C} \tag{8}$$

$$\sum_{c\in\mathbb{C}} x_{(vw)} \leq 1, \forall (vw) \in \mathbb{E} \tag{9}$$

$$\sum_{c\in\mathbb{C}} y^c_v \leq I_v, \forall v \in \mathbb{V} \tag{10}$$

$$\sum_{c\in\mathbb{C}} x_{(vw)} = \sum_{c\in\mathbb{C}} y^c_v, \forall v \in \mathbb{V} \tag{11}$$

$$p^{min} \leq p^c_{(vw)} \leq p^{max}, \forall (vw) \in \mathbb{E}, \forall c \in \mathbb{C} \tag{12}$$

$$0 \leq r_{(vw)} \leq r^{c,p}_{(vw)} \leq r^o_{(vw)} \leq r^{max}, \forall (vw) \in \mathbb{E}, \forall c \in \mathbb{C}, \forall p \in \mathbb{P} \tag{13}$$

$$\sum_{(uv)\in\mathscr{L}^u_v} r_{(uv)} \geq \sum_{(vw)\in s} r_{(vw)}. \forall v \in \mathbb{V} \tag{14}$$

Constraint (7) and Constraint (8) depict the activation status of link (vw) and node v on channel c, respectively. Further, Constraint (9) 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 (10). Constraint (11) 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 (12). Constraint (13) 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 (14) 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. (6), 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. (6) - (14) belong to a mixed-integer nonlinear programming (MINLP) problem that contains both combinatorial and continuous constraints. Now, solution to the OLCP 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)[17] for given 20 snapshots of the network environment, described in Section VI-A, and find that it requires, on an average, hundred of seconds for 50 nodes, each with at most 4 interfaces, 12 orthogonal channels and 8 different data rate levels. Thus, its real-time solution is intractable in a typical mesh router and the problem therefore becomes an NP-hard one [3]. 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. Thus, the objective function in Eq. 6 will not be useful in many practical applications.

V. Greedy Heuristic LCP

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, $(vw) \in \mathscr{L}^d_v$, as follows,

$$\omega^c_{(vw)} = \hat{r}^o_{(vw)} \times \big(1 - \hat{\xi}^{c,p}_{(vw)}\big), \tag{15}$$

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 $\omega^c_{(vw)}$ 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 1. 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 (lines 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

Algorithm 1 GLCP at each router $v \in \mathbb{V}$

Input: $\sum_{(uv)\in\mathscr{L}^u_v} r_{(uv)}$; $\omega^c_{(vw)}$, $\forall(vw) \in \mathscr{L}^d_v$ and $\forall c \in \mathbb{C}_{(vw)}$; $r^o_{(vw)}$, $\forall(vw) \in \mathscr{L}^d_v$
Output: s_v
Initialization: $b = \sum_{(uv)\in\mathscr{L}^u_v} r_{(uv)},\ s_v = \emptyset,\ r^{prev}_{(vw)} = 0$

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1: Z_v = { ((vw_i), c_j) | (vw_i) ∈ L_v^d, c_j ∈ C_(vw), ω^{c_1}_{(vw_1)} ≥ ω^{c_2}_{(vw_2)} ≥ … AND (vw_1) ≠ (vw_2) ≠ ⋯ ≠ (vw)_{|L_v^d|} AND c_1 ≠ c_2 ≠ ⋯ ≠ c_{C_v} }
2: Z'_v ← Z_v − {((vw_i), c_j) | r^{c_j, p^min}_{(vw_i)} < r^min}
3: ∀(vw) ∈ Z_v, q_(vw) = ∅
4: y ← pick a random number from the range 1 ∼ |Z'_v|
5: if (y ≥ τ) then
6:     for ((vw), c) ∈ Z_v do
7:         for p ∈ P do
8:             if (FindAlloc((vw), c, p) == 0) then break; go to line 28
9:             end if
10:        end for
11:    end for
12: else
13:    for p ∈ P do
14:        for ((vw), c) ∈ Z_v do
15:            if (FindAlloc((vw), c, p) == 0) 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 ← s_v ∪ {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), ∀(vw) ∈ s_v using Eq.5
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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 1 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 $O(|\mathbb{Z}_v| \cdot \log |\mathbb{Z}_v|)$.

VI. Performance Evaluation

In this section, we implement GLCP, OLCP, G-DTE [10] and ROPIM [11] in a discrete-event network simulator, ns-3 [12] and discuss the relative performance findings.

A. Simulation Environment

In our simulation experiments, we consider a WMN of 1000×1000 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.

B. Performance Metrics

To evaluate the performance of the studied traffic forwarding solutions, we have used 4 metrics - (i) *aggregated flow throughput*: amount of successful data bytes received at destinations in unit time, (ii) *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, (iii) *average end-to-end delay*: the average of latency for all received packets at destinations and (iv) *flow fairness*: Jain's fairness index [18], varying between 0 and 1, is used to measure flow fairness. 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.

C. Simulation Results

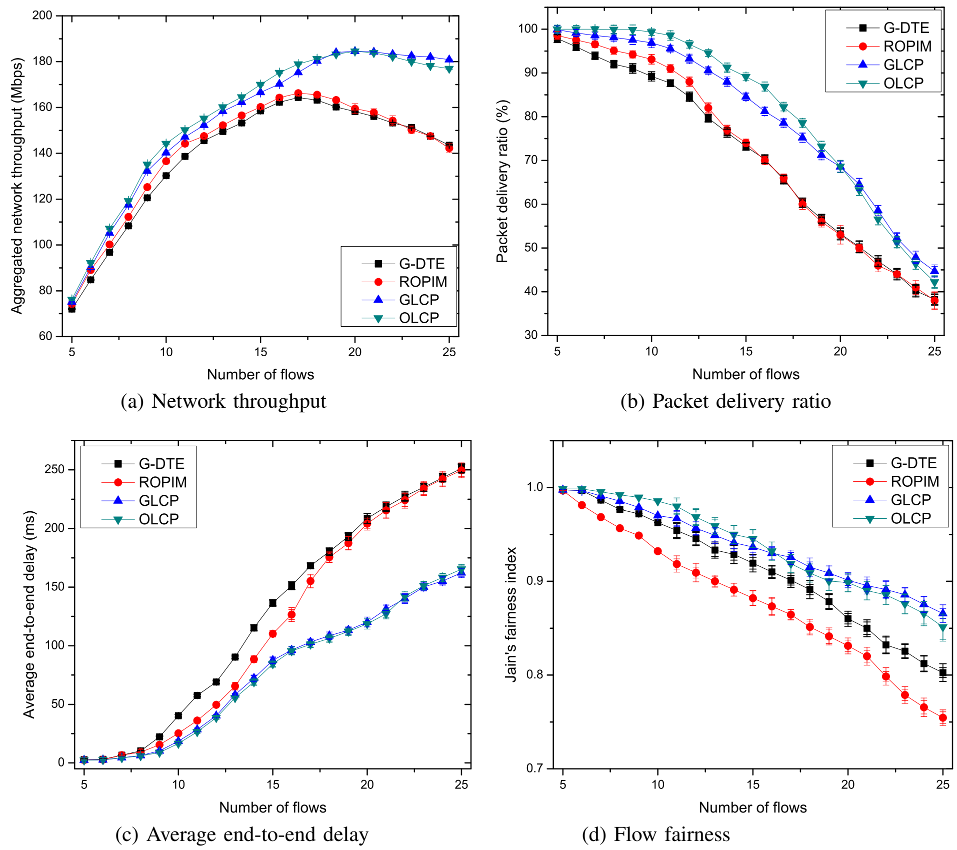
For each data value provided in the graphs, we have taken the average results from 50 simulation runs and have shown their confidence intervals.

1) Impacts of increasing number of flows: In this experiment, we analyzed the impact of increased offered load by randomly selecting sources to generate varying flows (5 to 25) at 10 Mbps rate. 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. 1(a). However, the proposed OLCP and GLCP offers higher throughput than G-DTE and ROPIM due to using link-channel weight parameter (Eq. 15) 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 G-DTE is poor under higher load, due to conservative choice of fixed channels over the radios.

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. 1(b). 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.

The end-to-end packet transmission delays for the studied approaches are depicted in Fig. 1(c). 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 shown in 1(d), 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.

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



(a) Network throughput (b) Packet delivery ratio

(c) Average end-to-end delay (d) Flow fairness

Fig. 1. Impacts of varying number of flows

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.s 2(a) and (c) show the impacts of increased nodes in the network in terms of the achievable aggregated network throughput and average end-to-end packet 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.

As shown in Fig. 2(b), 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.

As shown in Fig. 2(d), in network with increased nodes, each flow in our proposed mechanisms are awarded with fair share of the available bandwidth than the state-of-the-art approaches. In ROPIM, with increased number of nodes, as the traffic-split decision time grows rigorously, incoming flows are refrained from being rewarded with required proportionate fairness.

VII. Conclusion

This paper explores the problem of high throughput data delivery in MRMC WMN and both optimal (OLCP) and sub-optimal (GLCP) solutions are developed. 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.

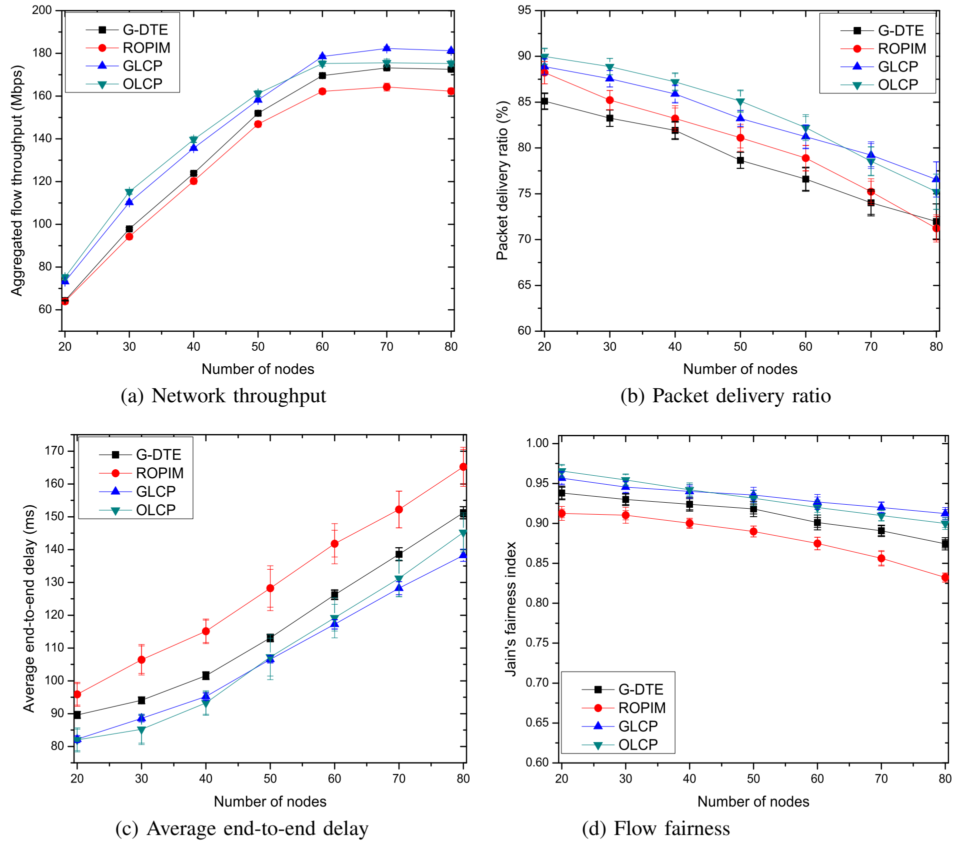


Fig. 2. Impacts of varying number of nodes

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