Logical Topology Design and Interface Assignment for Multi-Channel Wireless Mesh Networks

A. Hamed Mohsenian Rad and Vincent W.S. Wong
Department of Electrical and Computer Engineering
The University of British Columbia, Vancouver, Canada
e-mail: {hamed, vincentw}@ece.ubc.ca

***Abstract*— A multi-channel wireless mesh network (MC-WMN) consists of a number of stationary wireless routers, where each router is equipped with multiple network interface cards (NICs). Each interface operates on a distinct frequency channel. Two neighboring routers establish a logical link if each one has an interface operating on a common channel. Given the physical topology of the routers and other constraints, the logical topology formation algorithm determines the set of logical links. In general, since the number of NICs is limited, some logical links need to share an NIC in a router. The interface assignment algorithm determines the interface that a logical link should be attached to. In this paper, we formulate the logical topology design and interface assignment as a joint optimization problem to obtain an MC-WMN architecture, called *TiMesh*. We conducted extensive *ns-2* simulation experiments to evaluate our algorithm and compared it with another MC-WMN architecture called Hyacinth. Simulation results show that our proposed scheme achieves a higher aggregated network goodput and lower end-to-end delay for both TCP and UDP traffic.**

I. Introduction

A multi-channel wireless mesh network (MC-WMN) consists of a number of stationary wireless routers, forming a wireless backbone. Each router is equipped with multiple network interface cards (NICs) [1], [2]. Each interface operates on a distinct frequency channel in the IEEE 802.11a/b/g bands. The wireless routers serve as access points (APs) for wireless mobile devices. Some of them also act as gateways to the Internet via high-speed wired links. Two neighboring routers can establish a logical link if each one has an interface operating on the same channel. A logical topology is comprised of the sets of routers and logical links. Fig. 1 shows an MC-WMN logical topology with ten wireless routers. Nodes a and c also serve as gateways. Each router has three NICs. Six frequency channels are being used in the network.

Within the IEEE 802.11 frequency bands, the number of available channels is limited. The 802.11b/g bands and the 802.11a band provide 3 and 12 non-overlapping frequency channels, respectively. This implies that some logical links may be assigned the same channel. For example, in Fig. 1, both logical links (a, d) and (c, g) use channel number 1. In this case, interference will occur if these logical links are close to each other.

In addition, the number of NICs is also limited. In the experimental MC-WMN test-beds in [2] and [3], each mesh router is equipped with two NICs. Providing up to four NICs is also considered reasonable in [3]–[5]. A small number of NICs implies that some logical links in a router may need to *share* an NIC to transmit and receive data packets. For example, in Fig. 1, both logical links (e, h) and (e, i) share an NIC, so do logical links (f, g) and (f, j). When two logical links in a router share an NIC, they cannot be active simultaneously. It significantly decreases their *effective capacities*. The effective link capacities can be increased by removing some of the links from the logical topology. For example, by removing the links (e, d), (e, f), and (e, i) in Fig. 1, the number of logical links in node e will be decreased from six to three; thus, in node e, each remaining logical link (i.e., (e, a), (e, b), and (e, h)) is attached to an *exclusive* (not shared) NIC. However, this may increase the number of hops through some of the routing paths (e.g., from router i to a). In certain cases, the logical topology may not even be connected.

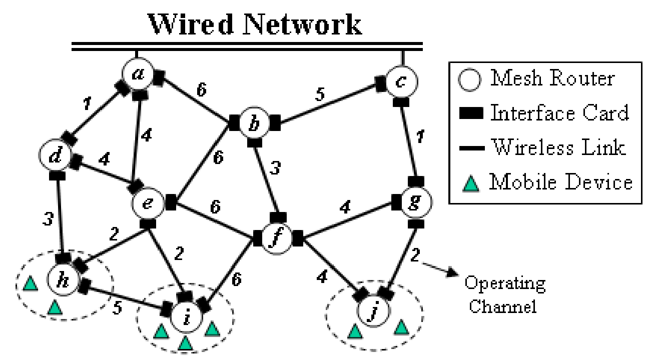

Fig. 1. An MC-WMN backbone with ten mesh routers, six frequency channels, and three NICs per router. The number on each link indicates the operating channel number.

The logical topology design and interface assignment have an impact on the channel allocation on each logical link. The key issue in the design of a decentralized channel allocation algorithm is the *channel dependency* among the logical links that share a common NIC in a router [3]. Consider the example in Fig. 1 where links (a, b) and (b, e) share an NIC in router b, links (b, e) and (e, f), share an NIC in e, and links (e, f) and (f, i) share an NIC in router f. When node a decides on a new channel to be used in link (a, b), it will trigger a channel switching on links $(b, e), (e, f)$, and (f, i). This is known as the *ripple effect*. The ripple effect makes it difficult for an individual node to predict the effect of a local channel re-allocation decision. It may also degrade the decentralized channel allocation efficiency.

To prevent the ripple effect, Raniwala *et al.* [3] proposed a logical tree topology for MC-WMNs, called *Hyacinth*. The tree construction mechanism is similar to the IEEE 802.1D spanning tree formation. The gateways are the roots. Each node uses an *UP-NIC* to *exclusively* connect to its parent and uses several (probably shared) *DOWN-NICs* to connect to its children. For a given node, the channel of the *UP-NIC* is assigned by its parent node. As a result, each router is only responsible for channel allocation of the links connected to its *DOWN-NICs*. In this case, the channel switching will only affect the neighboring routers (i.e., children) but not the routers that are more than one-hop away.

In summary, three important issues need to be addressed in MC-WMNs:

1) **Logical Topology Design**: Given the physical topology and other constraints, how should a logical topology be designed?
2) **Interface Assignment**: Given the logical topology, how should the logical links be assigned to each interface in a wireless mesh router?
3) **Channel Allocation**: Given the logical topology and interface assignment, how a frequency channel should be allocated on each logical link?

For the channel allocation issue, various centralized and distributed algorithms have recently been proposed for MC-WMNs [3]–[8]. The joint channel allocation and topology control problem has also been studied in [9] and [10]. The permanent channel allocation algorithm proposed in [9] aims to minimize the interference among the links while maintaining the network connectivity. In [10], the frequency channels are also permanently allocated so as to minimize the maximum number of interfering logical links within each neighborhood, subject to the constraint that the logical topology graph should be *K*-connected. Unlike [9] and [10], we consider topology control and channel allocation as two separate but related problems. The former takes care of the channel dependency, while the latter deals with the interference issue.

In this paper, we formulate the logical topology formation and interface assignment as a joint optimization problem. We call our proposed MC-WMN architecture as *TiMesh*. The contributions of our work are as follows:

- Our model formulation takes into account the number of allocated NICs in each wireless router, the channel dependency among the nodes that share a common NIC, the logical link degree, and expected traffic load between different source and destination pairs.
- Our proposed algorithm prevents *ripple effect* among channel dependent wireless logical links.
- Our proposed algorithm guarantees network connectivity, supports both *internal traffic* among the wireless routers and *external traffic* to the Internet.
- Simulation results show that *TiMesh* achieves a higher aggregate goodput and lower end-to-end delay than the *Hyacinth* MC-WMN architecture [3].

The rest of the paper is organized as follows. Our proposed joint logical topology formation and interface assignment algorithm is described in Section II. Performance evaluation and comparison are given in Section III. Conclusions are given in Section IV.

II. Logical Topology Formation and Interface Assignment Problem

In this section, we describe how we formulate the MC-WMN logical topology formation and interface assignment as a joint optimization problem. For the rest of this paper, the terms wireless mesh routers and nodes will be used interchangeably.

A. Problem Formulation

We first model an MC-WMN by a *physical topology graph* $G(N,E)$ where each node $n \in N$ represents a stationary wireless mesh router. For simplicity, we assume that $n = \{1, 2, \cdots, |N|\}$. For any two nodes $m, n \in N$, if they are within the communication range of each other, then there is an edge or link between them in set E. We use the notation e_{mn} (or equivalently e_{nm}) to denote the edge between nodes m and n.

Each wireless mesh router is equipped with I network interfaces. For any two nodes m and n such that $e_{mn} \in E$, we define two $I \times 1$ *interface assignment vectors*: $\bar{\mathbf{x}}_{mn}$ for node m, and $\bar{\mathbf{x}}_{nm}$ for node n. In the logical topology, if the i^{th} interface in node m is used to communicate with node n, then the i^{th} element in $\bar{\mathbf{x}}_{mn}$ is equal to 1; otherwise, it is equal to zero. As an example, assume that $I = 3$. In the logical topology, node m assigns its $1st$ NIC to communicate with node n. Node n assigns its $3rd$ NIC to communicate with node m. We have,

$$\begin{aligned} \bar{\mathbf{x}}_{mn} &= \left[\begin{array}{ccc} 1 & 0 & 0 \end{array} \right]^T \\ \bar{\mathbf{x}}_{nm} &= \left[\begin{array}{ccc} 0 & 0 & 1 \end{array} \right]^T \end{aligned} \tag{1}$$

Given $G(N,E)$ and other constraints, the vectors $\bar{\mathbf{x}}_{mn}$ not only provide solutions for the interface assignment problem, but also the information to create the logical topology.

B. Bidirectional Constraint

We assume that the logical links are bidirectional. That is,

$$\mathbf{1}^T \, \bar{\mathbf{x}}_{mn} \; = \; \mathbf{1}^T \, \bar{\mathbf{x}}_{nm} \leq 1, \qquad \forall \, m, n \in N, \;\; e_{mn} \in E \tag{2}$$

where $\mathbf{1}$ denotes an $I \times 1$ vector with all entries equal to one. The linear term $\mathbf{1}^T \bar{\mathbf{x}}_{mn}$ is equal to 1 if node m assigns one of its interfaces to communicate with node n, and is equal to 0 otherwise. There is a logical link between nodes m and n if both terms $\mathbf{1}^T \bar{\mathbf{x}}_{mn}$ and $\mathbf{1}^T \bar{\mathbf{x}}_{nm}$ are equal to 1. Due to the logical link sharing and channel dependency constraints, it is possible that there is a link between nodes m and n in the physical topology graph (i.e., $e_{mn} \in E$), but there is no logical link between them in the logical topology. In this case, $\mathbf{1}^T \bar{\mathbf{x}}_{mn}$ is equal to 0. The inequality in (2) implies that $\mathbf{1}^T \bar{\mathbf{x}}_{mn} \in \{0, 1\}$.

C. Channel Dependency Constraint

Recall that if multiple logical links are attached to the same NIC at a node, then these links have to be assigned the same frequency channel. In addition, these links cannot be active simultaneously. To restrict the channel dependency on each logical link, we set an upper bound Δ on the number of additional logical links that may share an NIC with a particular link. The channel dependency constraint is:

$$\sum_{k\in N,\ k\neq n,\ e_{mk}\in E} \bar{\mathbf{x}}_{mn}^T\,\bar{\mathbf{x}}_{mk} \leq \Delta, \quad \forall\, m,n \in N,\ \ e_{mn}\in E \tag{3}$$

In (3), for a logical link (m,n) in node m, the summation determines the number of additional logical links that share an interface with link (m,n). The larger the value of the summation in (3), the smaller the proportion of time that each logical link, including link (m,n), can access the shared NIC.

D. Ripple Effect Constraint

One approach to prevent ripple effect during distributed channel allocation is to assign an exclusive NIC to one end of *each* logical link. That is, if node m is responsible for channel allocation on logical link (m,n), then the NIC that is assigned by node n to attach to link (m,n) should not be used by any other logical link.

For any two nodes m and $n \in N$ such that $e_{mn}\in E$, we define an indicator variable δ_{mn} as follows:

$$\delta_{mn} = \begin{cases} 1, & \text{if node } m \text{ is responsible for channel allocation on} \\ & \text{logical link } (m,n)\text{, and} \\ & \text{link } (m,n) \text{ uses an exclusive NIC on node } n. \\ & \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

Note that δ_{mn} (or δ_{nm}) can be equal to 1 only if there is a logical link between nodes m and n (i.e., $\mathbf{1}^T\bar{\mathbf{x}}_{mn} = 1$). In addition, for any logical link (m,n), only one end is responsible for channel allocation (i.e., either node m or n, but not both). Thus, we have:

$$\delta_{mn} + \delta_{nm} = \mathbf{1}^T\bar{\mathbf{x}}_{mn}, \qquad \forall\, m,n\in N,\ \ e_{mn}\in E \tag{5}$$

The following equality constraint guarantees that if one side of the logical link is responsible for channel allocation, then the other side will provide an exclusive NIC.

$$\delta_{mn} \sum_{k\in N,\ k\neq m,\ e_{nk}\in E} \bar{\mathbf{x}}_{nm}^T\,\bar{\mathbf{x}}_{nk} = 0, \quad \forall\, m,n\in N,\ \ e_{nm}\in E \tag{6}$$

where the summation determines the number of additional logical links that share an NIC with link (n,m) on node n.

E. Total Flow on a Logical Link

For efficient network and capacity planning, a statistical model for network traffic needs to be available. Let γ^{sd} denote the average packet arrival rate between source and destination pair (s,d), where $s,d\in N$. We assume that the information γ^{sd} for all source and destination pairs is given.

We first define the binary variables:

$$a_{mn}^{sd} \in \{0,1\}, \qquad \forall\, m,n,s,d\in N,\ \ e_{mn}\in E \tag{7}$$

The variable a_{mn}^{sd} is equal to 1 when the traffic from source s to destination d is being routed via the logical link (m,n) *in the direction from node m to node n*, and is equal to 0 otherwise. Note that $a_{mn}^{sd}\neq a_{nm}^{sd}$ in general. In addition, if link (m,n) does not exist in the logical topology, then no packets will be sent over that link. Thus, we have the constraint

$$a_{mn}^{sd} \leq \mathbf{1}^T\bar{\mathbf{x}}_{mn}, \qquad \forall\, m,n,s,d\in N,\ \ e_{mn}\in E \tag{8}$$

Let λ_{mn}^{sd} denote the traffic between source and destination pair (s,d) that is being routed via the logical link (m,n) *in the direction from node m to node n.*

$$\lambda_{mn}^{sd} = a_{mn}^{sd}\,\gamma^{sd}, \qquad \forall\, m,n,s,d\in N,\ \ e_{mn}\in E \tag{9}$$

Let λ_{mn} denote the total traffic from all source and destination pairs that is routed over logical link (m,n). We have

$$\lambda_{mn} = \sum_{s,d\in N} \lambda_{mn}^{sd} + \lambda_{nm}^{sd}, \qquad \forall\, m,n\in N,\ \ e_{mn}\in E \tag{10}$$

F. Flow Conservation at Each Node

The flow conservation requires that for $s,d,m\in N$,

$$\sum_{n\in N}\lambda_{mn}^{sd} - \sum_{n\in N}\lambda_{nm}^{sd} = \begin{cases} \gamma^{sd}, & \text{if } s=m \\ -\gamma^{sd}, & \text{if } d=m \\ 0, & \text{otherwise.} \end{cases} \tag{11}$$

In (11), the term on the left-hand side is the *net flow* out of node m for the flow between source and destination pair (s,d). The net flow is the difference between the outgoing flow and the incoming flow. The term on the right-hand side is equal to 0 if node m is neither the source nor the destination for that specific flow. If node m is the source of the flow (i.e., $s=m$), then the net flow will be equal to γ^{sd} (the average departure rate for those packets). On the other hand, if node m is the destination (i.e., $d=m$), then the net flow will be equal to $-\gamma^{sd}$.

The constraint in (11) also guarantees that there is at least one routing path available between each source and destination pair (s,d). Thus, the obtained topology is always connected. In other words, there is no isolated node or an isolated group of nodes.

G. Hop Count Constraint

Let S_G^{sd} denote the hop count for the minimum hop path between the source and destination pair (s,d) in the physical topology graph $G(N,E)$. The hop count constraint is:

$$\sum_{m,n\in N,\ e_{mn}\in E} a_{mn}^{sd} \leq S_G^{sd} + \Gamma, \qquad \forall\, s,d\in N \tag{12}$$

where Γ is a positive integer and a tunable parameter. The above constraint guarantees that for each source and destination pair (s,d), there exists at least one routing path with the hop count to be less than or equal to $S_G^{sd}+\Gamma$. Note that the hop count for the minimum hop path between source and destination pair (s,d) cannot be less than S_G^{sd}. The constraint in (12) guarantees that it cannot be greater than $S_G^{sd}+\Gamma$ either.

H. Effective Capacity and Link Utilization

Consider the logical link (m,n) with a given nominal capacity of c_{mn}. We implicitly assume a power control algorithm that maintains a constant data rate in the presence of fading and other channel imperfections. This assumption simplifies the problem and has been used in other studies (e.g., [11]).

Let $\hat{c}_{mn}$ denote the effective capacity of the logical link (m,n). The effective capacity depends on the number of additional logical links that are sharing the same NIC with each side of the link. For all $m,n \in N$, and $e_{mn} \in E$, the effective capacity can be modeled as:

$$\hat{c}_{mn} = \frac{c_{mn}}{1 + \sum\limits_{\substack{k \in N \\ k \neq m}} \bar{\mathbf{x}}_{nm}^T \, \bar{\mathbf{x}}_{nk} + \sum\limits_{\substack{k \in N \\ k \neq n}} \bar{\mathbf{x}}_{mn}^T \, \bar{\mathbf{x}}_{mk}} \tag{13}$$

From (4)-(6), at least one end of the logical link uses an exclusive NIC. Thus, in (13), at least one of the summations in the denominator is equal to zero.

For all $m,n \in N$, and $e_{mn} \in E$, the *utilization* on logical link (m,n), denoted by u_{mn}, is defined as the total traffic load λ_{mn} divided by the effective link capacity $\hat{c}_{mn}$. That is,

$$u_{mn} = \frac{\lambda_{mn}}{c_{mn}} \, (1 + \sum_{\substack{k \in N \\ k \neq m}} \bar{\mathbf{x}}_{nm}^T \, \bar{\mathbf{x}}_{nk} + \sum_{\substack{k \in N \\ k \neq n}} \bar{\mathbf{x}}_{mn}^T \, \bar{\mathbf{x}}_{mk}) \tag{14}$$

Based on the results from queueing theory, when the link utilization is close to 1, the queueing delay tends to be very large [12]. Thus, it is necessary that

$$u_{mn} < 1, \qquad \forall\, m,n \in N, \;\; e_{mn} \in E \tag{15}$$

I. Objective Function

Let u_{max} denote the maximum utilization across all the links in the logical topology. That is,

$$u_{\text{max}} = \max_{m,n \in N, \;\; e_{mn} \in E} u_{mn} \tag{16}$$

Since a small value of the link utilization tends to provide a small queueing delay, it also implies that the network is less prone to congestion. Thus, our objective function is to minimize the variable u_{max}.

We now state the problem formally as a mixed integer constraint optimization problem. Given $G(N,E)$ and the parameters $I, \Delta, \Gamma, \gamma^{sd}, S_G^{sd}, c_{mn}$, for $m,n,s,d \in N$,

minimize u_{max}

subject to

$$\begin{aligned}
&\mathbf{1}^T \, \bar{\mathbf{x}}_{mn} = \mathbf{1}^T \, \bar{\mathbf{x}}_{nm} \leq 1, \\
&\sum_{k \in N \; k \neq n} \bar{\mathbf{x}}_{mn}^T \, \bar{\mathbf{x}}_{mk} \leq \Delta, \\
&\delta_{mn} + \delta_{nm} = \mathbf{1}^T \bar{\mathbf{x}}_{mn}, \\
&a_{mn}^{sd} \leq \mathbf{1}^T \bar{\mathbf{x}}_{mn}, \\
&\lambda_{mn}^{sd} = a_{mn}^{sd} \, \gamma^{sd}, \\
&\lambda_{mn} = \sum_{s,d \in N} \lambda_{mn}^{sd} + \lambda_{nm}^{sd}, \\
&\sum_{n \in N} \lambda_{mn}^{sd} - \sum_{n \in N} \lambda_{nm}^{sd} = \begin{cases} \gamma^{sd}, & \text{if } s = m \\ -\gamma^{sd}, & \text{if } d = m \\ 0, & \text{otherwise.} \end{cases} \\
&\sum_{m,n \in N} a_{mn}^{sd} \leq S_G^{sd} + \Gamma, \\
&u_{mn} = \frac{\lambda_{mn}}{c_{mn}} (\sum_{\substack{k \in N \\ k \neq m}} \bar{\mathbf{x}}_{nm}^T \, \bar{\mathbf{x}}_{nk} + \sum_{\substack{k \in N \\ k \neq n}} \bar{\mathbf{x}}_{mn}^T \, \bar{\mathbf{x}}_{mk} + 1), \\
&0 \leq u_{mn} \leq u_{\text{max}} < 1,
\end{aligned} \tag{17}$$

where

$$\bar{\mathbf{x}}_{mn} \in \{0,1\}^I, \;\; b_{mn}, \delta_{mn}, a_{mn}^{sd} \in \{0,1\}, \quad \forall\, m,n,s,d \in N \;\; , e_{mn} \in E$$

Solving problem (17) not only provides the solutions for the logical topology design and interface assignment problems, but it also determines which end node on each logical link is responsible for channel allocation.

The exact solution of problem (17) can be obtained by either the branch and bound or cutting plane methods; however they are *NP*-hard in general [13]. The alternative is to use some simple and efficient heuristic methods. In this paper, we use the fast greedy algorithm [14].

The traffic patterns γ^{sd} are usually time-variant in practice. However, it is possible to determine an *upper bound* by estimating the traffic demands in current WMN deployments. In addition, the value of the nominal link capacity c_{mn} depends on the channel allocation. We can assume that the channel allocation guarantees a *lower bound* on each logical link capacity. This lower bound depends on the *worst-case* signal to interference plus noise ratio and is a function of the number of channels [15]. The aforementioned bounds can be used instead of the exact values to achieve a *robust* solution.

III. Performance Comparison

In this section, we compare the performance between our proposed *TiMesh* architecture and the *Hyacinth* architecture [3]. We consider both TCP (Transmission Control Protocol) and UDP (User Datagram Protocol) traffic. Simulations are conducted by using the *ns-2* simulator. In the simulation model, the size of the network field is 1000 m $\times$ 800 m. The MC-WMN consists of 30 wireless mesh routers. Four of them also serve as gateways. The gateways are located at the four corners in the field. Each router is equipped with three NICs. Nine 802.11a orthogonal channels with 54 Mbps nominal data rate are used. The communication range and the carrier sensing/interference range are 250 m and 450 m, respectively.

Ten different random physical topologies are generated. In each topology, there are 40 flows: half of them are internal flows and the others are external flows. For each internal flow, two nodes are randomly selected to be the source and destination access points. Each external flow is assigned between

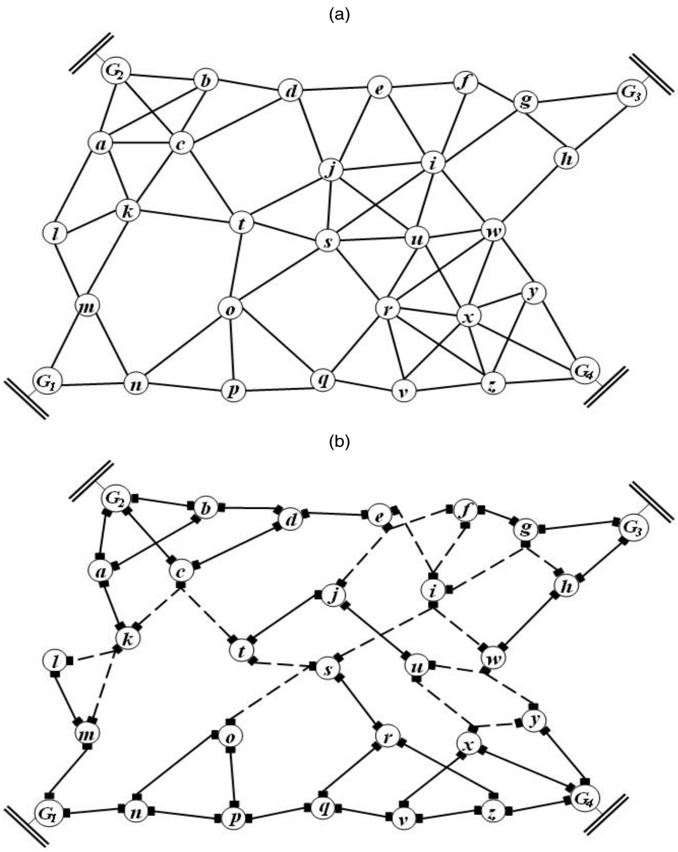

Fig. 2. A random topology with 30 routers (4 of them also serve as gateways). Each router is equipped with 3 NICs. (a) Physical topology, (b) Logical topology and interface assignment. Solid lines are wireless links that use only exclusive (not shared) NICs. Dashed lines are the wireless links that share an interface with some other links.

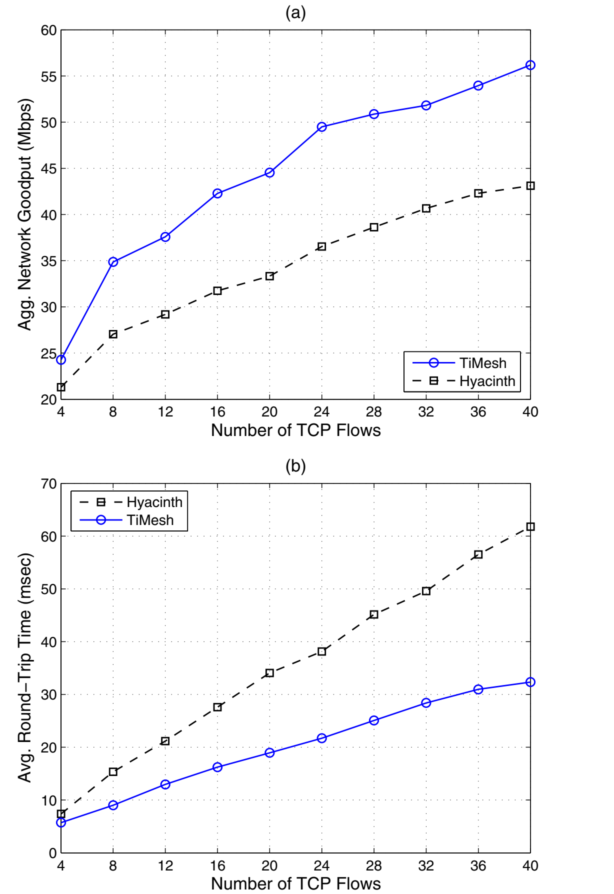

Fig. 3. Comparison between the *TiMesh* and the *Hyacinth* MC-WMN architectures in presence of TCP traffic, (a) Aggregated goodput, (b) Round-trip time.

a randomly selected node (either as a source or destination access point) and the the nearest gateway to the Internet. The simulation time is 300 sec and the channel allocation algorithms are invoked every 60 sec.

For each physical topology, the optimization problem in (17) is solved only for full traffic load (i.e., the upper bound) when all 40 flows are active. The obtained logical topologies are then simulated for the cases of 4, 8, 12, $\cdots$, 40 flows, respectively. The parameter Δ is set to 2. The parameter Γ is set to 1. We use the optimal solutions a_{mn}^{sd} to determine the routing path between the source and destination pair (s, d).

Fig. 2(a) shows a sample physical topology, and the corresponding logical topology and interface assignment solution are shown in Fig. 2(b). The physical topology graph in Fig. 2(a) consists of 70 links (i.e., $|E| = 70$) with an average node degree and the maximum node degree of 4.7 and 7, respectively. The logical topology in Fig 2(b) has 48 logical links. The average node degree is 3.2 and the maximum node degree is 5. We observe that each interface is shared by at most two links. The sharing of logical links in each NIC do not happen occur as it reduces the corresponding effective link capacities. The hop-count inequality constraint set in (12) is active only for source and destination pairs (b, G_2) and (a, e). In the optimal solution, the 1-hop route $\{b, G_2\}$ is replaced by the 2-hop route $\{b, a, G_2\}$ to take the advantage of the unused link (b, a). It also reduces the load burden on thebottleneck link (b, G_2). Route $\{a, b, d, e\}$ is also replaced by route $\{a, k, c, d, e\}$ to reduce the load on link (d, b).

A. TCP Traffic

We first consider the presence of TCP traffic. TCP Vegas protocol is being used and the packet size is 1 kByte. The Congestion-Aware [8] *distributed* channel allocation algorithm is used to allocate the frequency channels for TCP traffic. In our comparison we consider two performance metrics: 1) *Aggregated goodput*: total number of correctly received packets (in bits) at the destinations divided by the total simulation time. 2) *Average round-trip time*: average time delay between sending a TCP segment and receiving its acknowledgement.

Fig. 3 shows the results of the aggregated goodput and the average round-trip time when there are different number of TCP flows established in the network. In this figure, each point is the average of measurements for all 10 simulated topologies. It is observed that the proposed *TiMesh* architecture achieves a higher aggregated goodput and lower packet round-trip time. Considering the full traffic load scenario (i.e., presence of 40

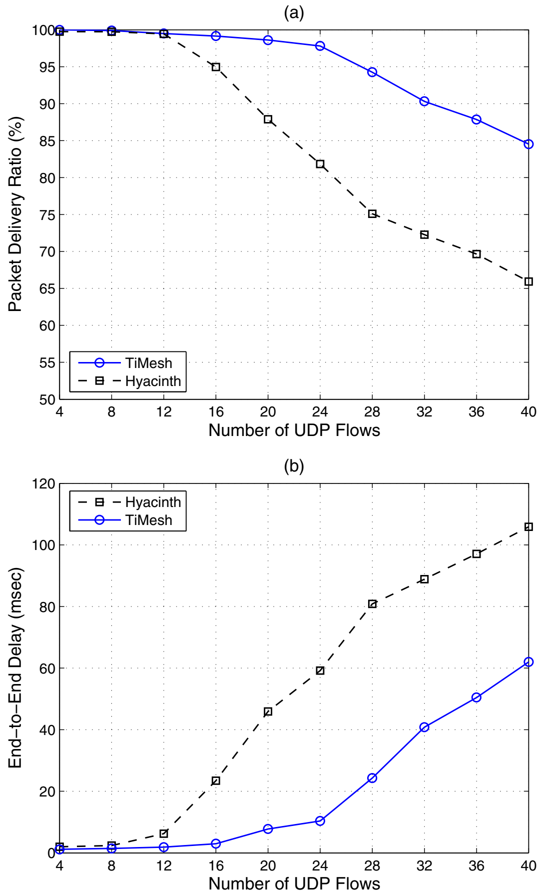

Fig. 4. Comparison between the *TiMesh* and the Hyacinth MC-WMN architectures in the presence of UDP traffic, (a) Packet delivery ratio, (b) End-to-end delay.

flows), the aggregated goodput is increased by 30% and the average round-trip-time is decreased by 48%.

B. UDP Traffic

In this experiment, we consider the presence of UDP traffic. The Load-Aware [3] *distributed* channel allocation algorithm is used to allocate the frequency channels for UDP traffic. For each UDP source, the data rate is 500 kbps. In our comparison we consider two performance metrics: 1) *Packet delivery ratio*: the ratio (in percent) of total number of packets received by all destinations to the total number of packets transmitted by all sources. 2) *Average end-to-end delay*: the average time it takes for a packet to traverse the network from a source to a destination.

Fig. 4 shows the results of the packet delivery ratio and the average end-to-end delay. In this figure, each point is the average of measurements for all 10 simulated topologies. Considering the full load scenario, the delivery ratio is increased by 28% and the end-to-end delay is decreased by 41%.

IV. Conclusions

In this paper, we proposed *TiMesh* MC-WMN architecture by formulating the logical topology design and interface assignment as a joint optimization problem. Our model formulation takes into account the number of available NICs in routers, the channel dependency among the nodes that share a common NIC, and expected traffic load between different source and destination pairs. Our proposed algorithm also prevents the *ripple effect* among channel dependent wireless logical links. We conducted extensive *ns-2* simulation experiments to evaluate our algorithm and compared it with Hyacinth MC-WMN architecture. Simulation results show that in *TiMesh* architecture, the aggregated network goodput is higher, and the end-to-end delay is lower for both TCP and UDP traffic.

For future work, we plan to consider assigning more than one logical link between a pair of nodes in order to increase the effective capacity. We shall also improve the effective link capacity model by taking into account the expected interference among the logical links.

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