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Integrated Design and Performance Analysis for Multi-Channel Wireless Mesh Networks
多通道無線網狀網路整合設計性能分析

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Abstract

Wireless mesh networks (WMNs) have emerged as a key technology for next generation wireless broadband networking. A WMN consists of a number of stationary wireless mesh routers forming a wireless backbone. Equipping wireless mesh routers with multiple channels simultaneously can improve the capacity by transmitting over multiple radio simultaneously using orthogonal channels. Efficient channel assignment schemes can relieve the interference effect of close-by transmissions. Effect routing schemes can alleviate potential congestion on any gateways. In this paper, we use the TiMesh multi-channel wireless mesh network (MC-WMN) architecture proposed by A. H. Mohsenian-Rad and V. W. S. Wang [1] and AIMMS-optimization software for operations research applications [2] to integrate design of logical topology, interface assignment, channel allocation and routing for MC-WMN. Ns-2 [3] simulations are conducted to evaluate the design performance. We investigate the network performance by varying the number of network interface cards (NICs), the available orthogonal channels, the nominal link-layer data rate and the user datagram protocol (UDP) traffic flows. The analysis and simulation results show that the TiMesh can provide fairness among the logical links due to its own capability of load balancing and congestion-aware capacity planning. When the number of the UDP traffic flow increases, the packet delivery ratio decreases and the average end-to-end delay increases and therefore degrades the network performance. This phenomenon can be significantly improved by increasing the number of NICs, the number of orthogonal frequency channels and the nominal link-layer data rate.

Key Words: Wireless mesh networks, multi-channel, multi-interface, routing, optimization.

摘 要

無線網狀網路為下一代無線寬頻連網之關鍵技術。一個無線網狀網路是由數個形成無線骨幹之固定無線網狀路由器所組成。使用多通道無線網狀路由器，以正交頻道同時傳輸，可增加容量。高效率之通道分配，能減輕相鄰傳輸間之干擾效應；而高效能之路由方案，則可有效舒解閘道器上潛在之擁塞瓶頸。本文使用 A. H. Mohsenian-Rad 與 V. W. S. Wong 發展之 TiMesh 架構[1]，利用 AIMMS 作業研究型最佳化軟體[2]，整合設計無線網狀網路之邏輯拓樸、介面指定、通道分配以及路由設定。整合設計結果以 ns-2 網路模擬器[3]驗證。分析不同數量網路介面卡、可用正交頻道、連結層資料率及用戶資料報協定流對網路性能之影響，結果顯示 TiMesh 具負載平衡及擁塞知覺能力，能達成邏輯連結間之公平化；當用戶資料報協定資料流增加時，封包交付比降低，平均端點間延遲增加，網路性能降低，此現象可由增加網路介面卡數，可用正交頻道及連結層資料率有效獲得改善。

關鍵詞：無線網狀網路、多通道、多介面、路由、最佳化。

1. Introduction

Wireless mesh networks (WMNs) were originally developed for military applications. Recently, many applications of WMNs such as metropolitan area networking, enterprise networking, community and neighborhood networking, transportation system and broadband home networking have become practical due to continuously improved technologies. With the extensive applications of WMNs, the IEEE802 standards organizations have been committed to promoting the development of WMNs technologies. The existing wireless networking technologies such as IEEE 802.11, IEEE 802.15, IEEE 802.16, and IEEE 802.20 are used to implement WMNs. The IEEE has set up a task group 802.11s to set proper mesh networking standard [4].

WMNs are an alternative technology for last-mile broadband internet access. WMNs can integrate with other existing networks through the gateway and bridging functions in the mesh routers [5-6].

The performance of WMNs can be increased by using multiple channels [7]. However, the available channel resources are limited. In order to avoid adjacent-channel interference, generally, only 3 and 12 orthogonal channels can be used in IEEE 802.11b/g and IEEE802.11a networks respectively. This implies that some logical links may operate on the same channels.

Multi-channel wireless mesh network (MC-WMN) is composed of a number of fixed wireless mesh routers. Each mesh router is equipped with multiple network interface cards (NICs) to increase the capacity. Each NIC has its specific operating frequency. If the NIC of each of the two neighboring routers operates on a common channel, a logical link can be established between these two routers. In addition to the channel resources, the number of available NICs is also limited. This implies that some logic links in a router may need to share a common NIC.

2. TiMesh MC-WMN architecture

2.1 Problem formulation

An MC-WMN is modeled by a physical topology graph *G* (*N*, *E*) where *N* is the set of all nodes and *E* is the set of all unidirectional edges. Each node $n \in N$ represents a fixed wireless mesh router. For any two nodes $m,\ n \in N$, if node *n* is within the communication range of node *m*, then there exists a link $e_{mn} \in E$ from node *m* to node *n*. The link is assumed to be symmetric, i.e., $e_{mn} \in E$ if and only if $e_{nm} \in E$. Assume that each wireless mesh router is equipped with *I* NICs, and there are *C* orthogonal channels available.

For a link $e_{mn} \in E$ and a frequency channel $i \in \{1,...,C\}$, a link channel allocation variable x^i_{mn} is defined as $x^i_{mn} = 1$ if node *m* communicates with node *n* over the *i*th frequency channel; otherwise, its value is 0. Node *m* and *n* should use the same frequency channel to communicate with each other, therefore:

$$x^i_{mn} = x^i_{nm}, \quad \forall m,n \in N,\ \ e_{mn} \in E,\ \ \forall i = 1,...C. \tag{1}$$

To increase the effective capacity,

multiple links operating over distinct frequency between the same pair of nodes is allowed for the MC-WMN. Even there exists a physical link between two nodes, a corresponding logical link may not exist due to traffic and interference constraints, i.e., it's possible that $x^i_{mn}=0$ for any $i\in\{1,...,C\}$.

The node channel allocation variable y^i_m is defined as follows:

$$y^i_m=\begin{cases}1, \text{ if } \exists n\in N \text{ and } e_{mn}\in E, \\ \quad \text{such that } x^i_{mn}=1. \\ 0, \quad \text{otherwise.}\end{cases} \quad (2)$$

Because each NIC operates on a distinct frequency, $\sum_{i=1}^{C} y^i_m$ satisfies:

$$\sum_{i=1}^{C} y^i_m \le I, \qquad \forall m\in N. \quad (3)$$

(3) shows that the total number of channels used by node m to set up logical links with its adjacent nodes is less than or equal to the total number of available NICs on node m. For all nodes $m\in N$ and all channels $i\in\{1,...,C\}$, y^i_m also satisfies

$$0\le y^i_m \le \sum_{n\in N, e_{mn}\in E} x^i_{mn}, \quad (4)$$
$$x^i_{mn}\le y^i_m \le 1, \ \forall n\in N, \ e_{mn}\in E$$

2.2 Effective capacity

Let c^i_{mn} denote the effective capacity of the logical link from node m to n over frequency channel i. c^i_{mn} satisfies

$$0\le c^i_{mn}\le c^0, c^i_{mn}\le x^i_{mn}c^0, \quad (5)$$
$$\forall m,n\in N, \ e_{mn}\in E, \ \forall i=1,...C.$$

where c^0 is the nominal link-layer data rate in the corresponding 802.11 standard. Note that $c^i_{mn}=0$, if $x^i_{mn}=0$.

A set of potential interfering links $F_{mn}\subset E$ is defined as a set that consists of all $e_{pq}\in E$ such that node p or q or both are within the interfering range of node m or n or both. The IEEE 802.11 based RTS-CTS-DATA-ACK model gives the following relationship [8]:

$$\frac{c^i_{mn}}{c^0}+\sum_{p,q,e_{pq}\in F_{mn}}\frac{c^i_{pq}}{c_0}\le 1, \quad (6)$$
$$\forall \ m, \ n\in N, \ e_{mn}\in E \ \ \forall \ i=1,...,C$$

where c^i_{mn}/c^0 represents the ratio of time that logical link (m, n) is being used for packet transmission from node m to n over frequency channel i.

2.3 Total flows on a logical link

A binary routing variable is defined as $a^{sd}_{mn,i}$ =1, if the traffic from source s to destination d is being routed through link (m, n) over channel i, otherwise, $a^{sd}_{mn,i}$ =0. To avoid packets arriving out of order, only one of the multiple logical links between a pair of neighboring nodes can be used to route the packets of each flow. We have

$$\sum_{i=1}^{C} a^{sd}_{mn,i}\le 1, \quad (7)$$
$$\forall s,d,m,n\in N, \ \ e_{mn}\in E.$$

If γ^{sd} denotes the expected traffic rate to be delivered between source s and destination d, then λ^i_{mn}, the aggregate traffic from all source and destination pairs that is routed via logical link (m, n) over channel i can be expressed by the following equation.

$$\lambda^i_{mn}=\sum_{s,d\in N} a^{sd}_{mn,i}\gamma^{sd}, \quad (8)$$
$$\forall m,n\in N, \ e_{mn}\in E, \ \forall i=1,...C$$

That λ^i_{mn} can not exceed c^i_{mn} gives the following constraint

$$\lambda_{mn}^{i} \le \Lambda c_{mn}^{i}, \quad \forall m,n \in N, \quad e_{mn} \in E, \forall i = 1...C \qquad (9)$$

where $0 < \Lambda \le 1$ imposes an upper bound on the expected link utilization $\lambda_{mn}^{i} / c_{mn}^{i}$. The higher the link utilization, the longer the queuing delay. Λ is set to 8 due to the fact that an access link is considered overloaded when its average utilization exceeds 80% [9].

2.4 Conservation of flow at each node

For $s, d, m \in N$, conservation of flow constraints at each node can be expressed as [10]

$$\sum_{\substack{n\in N,\\ e_{mn}\in E}} \sum_{i=1}^{C} a_{mn,i}^{sd} \gamma^{sd} - \sum_{\substack{n\in N,\\ e_{mn}\in E}} \sum_{i=1}^{C} a_{nm,i}^{sd} \gamma^{sd} = \begin{cases} \gamma^{sd}, & if\ s=m, \\ -\gamma^{sd}, & if\ d=m, \\ 0, & otherwise. \end{cases} \qquad (10)$$

The term on the LHS of the above equation is the net flow out of node *m* for the flow from source *s* to destination *d*. If *s*=*m*, the net flow is γ^{sd}. If *d*=*m*, the net flow is -γ^{sd}. If node *m* is neither the source nor the destination, then the net flow is 0, i.e., the outgoing flow is equal to the incoming flow at node *m*. Equation (10) guarantees that there exists at least one routing path for each traffic flow coming from source *s* and going to destination *d*.

2.5 Feasible region and the objective function

Given the network resources including *C* orthogonal channels, *I* NIC and nominal link-layer data rate c^0, (1)-(10) form the feasible region of all logical topologies capable of satisfying the expected traffic demand γ^{sd}. The feasible region can be enlarged by setting Λ to a higher value. Nevertheless, the feasible region may not exist even by setting Λ to its maximum value of 1 in case that the network resources can not support the expected traffic demand. This problem can be resolved either by increasing the network resources or by reducing the traffic demand.

Let $\delta_{mn}^{i} = \Lambda c_{mn}^{i} - \lambda_{mn}^{i}$ and define $\delta_{\min}$ as the minimum value of δ_{mn}^{i} among all channels and all links existing in the logical topology.

$$\delta_{\min} = \min_{\substack{m,n\in N, e_{mn}\in E. \\ i\in\{1,\dots C\}, x_{mn}^{i}=1}} (\Lambda c_{mn}^{i} - \lambda_{mn}^{i}) \qquad (11)$$

$\delta_{\min}$ corresponds to the most congested logical link across the network. The objective of the problem is to maximize the variable $\delta_{\min}$. It can be achieved by increasing c_{mn}^{i} or decreasing λ_{mn}^{i} or both on the most congested logical link. Increasing c_{mn}^{i} means the congestion-aware capacity planning while decreasing λ_{mn}^{i} means load balancing. The maximization of $\delta_{\min}$ leads to the fairness across the existing logical links. Eq. (11) can be rewritten as

$$\delta_{\min} \le (\Lambda c_{mn}^{i} - \lambda_{mn}^{i}) + \Lambda c^{0}(1 - x_{mn}^{i}), \quad \forall m,n \in N, e_{mn} \in E, \forall i = 1,\dots.C. \qquad (12)$$

If $x_{mn}^{i} = 1$, the above equation is simplified to $\delta_{\min} \le (\Lambda c_{mn}^{i} - \lambda_{mn}^{i})$. If $x_{mn}^{i} = 0$, then eq. (12) becomes $\delta_{\min} \le \Lambda c^{0}$.

2.6 Hop count constraint

The hop count along the designated routing path between source *s* and destination *d* is calculated from

$$\sum_{m,n\in N,\ e_{mn}\in E.} \sum_{i=1}^{C} a_{mn,i}^{sd} \qquad (13)$$

If h_{sd}^{G} denotes the smallest hop count corresponding to the minimum hop path between source s and destination d in the physical topology $G(N,E)$, then the stretch factor for the routing path between source s and destination d is defined as

$$\sum_{m,n\in N,\ e_{mn}\in E.} \sum_{i=1}^{C} a_{mn,i}^{sd} / h_{sd}^{G} \ge 1 \quad (14)$$

The hop count constraint is defined as

$$\sum_{m,n\in N,\ e_{mn}\in E.} \sum_{i=1}^{C} a_{mn,i}^{sd} \le \Gamma h_{sd}^{G}, \quad \forall s,d \in N \quad (15)$$

where Γ represents an upper bound on the routing stretch factor used to control the trade off between shortest-path routing and load- balancing routing by varying its value from one to infinity.

2.7 Optimization problem

Given the physical topology $G(N,E)$ and the following parameters: the number of orthogonal channels C, the number of NICs I, the upper bound on the routing stretch factor Γ, the upper bound on the expected link utilization Λ, the nominal link-layer data rate in the corresponding 802.11 standard c^0, the set of potential interfering links of node m or n or both F_{mn}, the expected traffic rate to be delivered between source s and destination d γ^{sd}, the smallest hop count corresponding to the minimum hop path between source s and destination d in the physical topology $G(N,E)$ h_{sd}^{G}, the joint problem formulation is summarized as follows.

$$\underset{x,y,c,a,\lambda,\delta_{\min}}{\text{Maximize}}\ \delta_{\min}$$

Subject to：

$$x_{mn}^{i} = x_{nm}^{i},$$

$$x_{mn}^{i} \le y_{m}^{i},$$

$$y_{m}^{i} \le \sum_{n\in N, e_{mn}\in E} x_{mn}^{i},$$

$$\sum_{i=1}^{C} y_{m}^{i} \le I,$$

$$c_{nm}^{i} \le x_{mn}^{i} c^{0},$$

$$c_{mn}^{i} + \sum_{p,q,e_{pq}\in F_{mn}} c_{pq}^{i} \le c^{0},$$

$$\sum_{\substack{n\in N\\ e_{mn}\in E}} \sum_{i=1}^{C} a_{mn,i}^{sd} - \sum_{\substack{n\in N\\ e_{mn}\in E}} \sum_{i=1}^{C} a_{nm,i}^{sd} = \begin{cases} 1, & \text{if } s = m, \\ -1, & \text{if } d = m, \\ 0, & \text{otherwise.} \end{cases}$$

$$\sum_{i=1}^{C} a_{mn,i}^{sd} \le 1,$$

$$\lambda_{mn}^{i} = \sum_{s,d\in N} a_{mn,i}^{sd} \gamma^{sd},$$

$$\lambda_{nm}^{i} \le \Lambda c_{mn}^{i},$$

$$\delta_{\min} \le \left(\Lambda c_{mn}^{i} - \lambda_{mn}^{i}\right) + \Lambda c^{0}\left(1 - x_{mn}^{i}\right),$$

$$\sum_{\substack{m,n\in N\\ e_{mn}\in E}} \sum_{i=1}^{C} a_{mn,i}^{sd} \le \Gamma h_{G}^{sd},$$

where

$$x_{mn}^{i}, a_{nm,i}^{sd} \in \{0,1\},$$

$$y_{m}^{i}, c_{mn}^{i}, \lambda_{mn}^{i}, \delta_{\min} \ge 0, \quad y_{m}^{i} \le 1,$$

$$c_{mn}^{i} \le c^{0},$$

$$\forall m,n,s,d \in N,\ e_{mn} \in E,\ \forall i = 1,\ldots,C. \quad (16)$$

Let W denote the number of source and destination pairs. Also let $|N|$ and $|E|$ represent the cardinality of sets N and E respectively. Eq. (16) is a mixed-integer linear problem (MILP) having $|E|C(1+W)$ integer variables and $C(2|E|+N)+1$ real variables as well as $1.5|E|C+|N|W$ equality constraints and $|E|(5C+W)+|N|(C+1)+W$ inequality constraints. This MILP is described in AIMMS language [11] and is solved with GUROBI solver [12].

3. Integrated design and performance analysis

We consider a 500 m x 400 m MC-WMN as shown in Fig. 1. This network is composed of eight routers. Each router has *I* NICs and there are *C* orthogonal channels available. Two routers *G1* and *G2* located at diagonal corners also serve as gateways to the internet via high-speed wired link

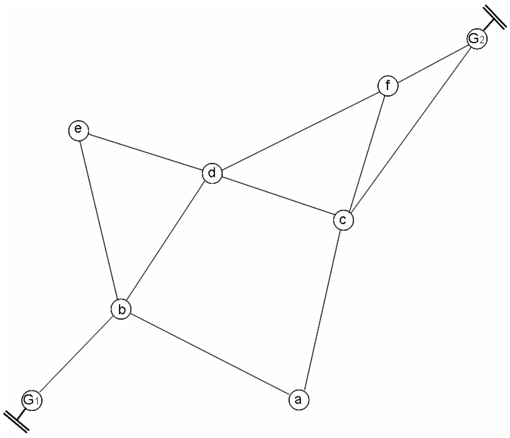


Fig. 1 The physical topology of a MC-WMN with eight nodes.

The communication and interference range are 250 m and 450 m respectively. The interference range is typically twice as large as the transmission range [13].

We consider UDP traffic, half of which is internal flow, while the other half is external flow. Internal flow refers to a traffic flow where neither its source node nor destination node is a gateway. External flow is established between a node and a gateway. Both the source node and the destination node are selected randomly for each internal and external flow. The UDP packet size is 1000 bytes and the transmission rate is 0.5 Mbps.

The integrated design includes logical topology creation, interface assignment, channel allocation and routing. The design configuration and related parameters are shown in Table 1.

Table 1 Integrated design configuration and related parameters

Parameter	Symbol	Configuration	
		Ⅰ	Ⅱ
Number of channels	C	3	5
Number of NICs	I	2	3
Nominal link-layer data rate	c^0	11 Mbps	54 Mbps
Expected traffic rate	γ^{sd}	0.5 Mbps	
Upper bound on the expected link utilization	Λ	0.8	
Upper bound on the routing stretch factor	Γ	2	

3.1 Program verification

The summarized equation (16) is described in AIMMS language. Let $< s, d >$ denote the traffic flow from source s to destination d. We input two traffic flows $< f, d >$ and $< c, G1 >$ for configuration Ⅰ to verify the correctness of the source program written in AIMMS programming language. The above source program solved with GUROBI solver generates 198 integer variables, 157 real variables, 115 equality constraints and 408 inequality constraints. The results are in accordance with the theoretical predictions. The calculated values of the variables are as follows.

1. The link channel allocation variable

$$x_{bd}^{1} = x_{bG1}^{3} = x_{cd}^{2} = x_{db}^{1} = x_{dc}^{2} = x_{df}^{2} = x_{fd}^{2} = x_{G1b}^{3} = 1$$

2. The node channel allocation variable
$y_b^1 = y_b^3 = y_c^2 = y_d^1 = y_d^2 = y_f^2 = y_{G1}^3 = 1$
3. The binary routing variable
$a_{bG1,3}^{cG1} = a_{cd,2}^{cG1} = a_{db,1}^{cG1} = a_{fd,2}^{fd} = 1$
4. The aggregate traffic
$\lambda_{bG1}^3 = \lambda_{cd}^2 = \lambda_{db}^1 = \lambda_{fd}^2 = 0.5\text{Mbps}$
5. The effective capacity
$C_{bd}^1 = C_{dc}^2 = C_{df}^2 = C_{G1b}^3 = 2.4375\text{Mbps}$
$C_{bG1}^3 = C_{cd}^2 = C_{fd}^2 = 3.0625\text{Mbps}$
$C_{db}^1 = 8.5625\text{Mbps}$
6. The optimum solution of $\delta_{\min}$ =1.95

The calculated results for the binary routing variable show that the routing paths for the two traffic flows < *c*, *G1*> and < *f*,*d* > are $c \xrightarrow{2} d \xrightarrow{1} b \xrightarrow{3} G1$ and $f \xrightarrow{2} d$ respectively. They are both shortest paths. The number on the arrow denotes the channel number for the corresponding logical link.

From the calculation results of the link channel allocation variable, we know that there are four bi-directional logical links. However, only three channels are available, and therefore one frequency channel (channel 2) is used repeatedly. Both active logical links (*f*, *d*) and (*c*, *d*) share a NIC assigned channel 2 on node *d*. The above phenomenon is also shown in the calculation results of the node channel allocation variable.

There is only one traffic flow for each of the four active unidirectional logical links; as a result, the aggregate traffic is equal to the expected traffic rate. This represents load balancing.

The effective capacity for the active unidirectional logical link is always greater than the other idle one in opposite direction between the same pair of nodes. This reveals that the network has the capability of congestion-aware capacity planning.

The values of δ_{mn}^i of the eight unidirectional logical links are all equal to 1.95 except $\delta_{db}^1 = 6.35$. The results of maximization of $\delta_{\min}$ show that the network has the capability of achieving fairness among the existing logical links.

The summarized equation (16) is fully satisfied by substituting the above calculated values into that equation. The correctness of the program written in AIMMS language to describe (16) is thus verified.

3.2 Optimal integrated design

We use the verified program to integratedly design the logical topology, interface assignment, channel allocation and routing for a MC-WMN with different UDP flows. The physical topology and the configuration of this MC-WMN are shown respectively in Fig. 1 and Table 1.

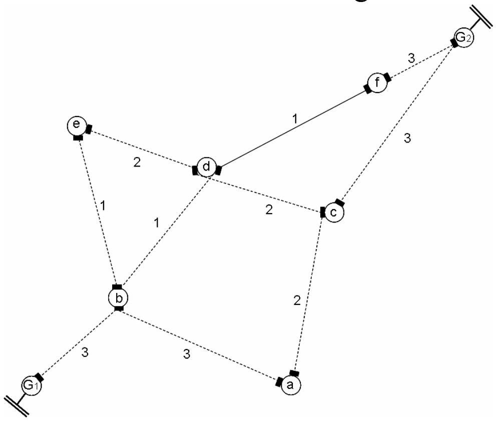
The results of the optimal integrated design for configuration Ⅰ and Ⅱ with 24 UDP flows are shown in Fig. 2.

There are twenty pairs of logical links established between two neighboring nodes for both configuration Ⅰ and Ⅱ. One of the differences between the physical topology shown in Fig. 1 and the logical topology shown in Fig. 2 is that no logical link is established between node *f* and node *c*. This may increase the number of hops. For example, the path of the traffic flow < *a*, *f* > in configuration Ⅰ and Ⅱ are $a \xrightarrow{3} b \xrightarrow{1} d \xrightarrow{1} f$ and $a \xrightarrow{3} c \xrightarrow{4} G2 \xrightarrow{4} f$ respectively. However, it can reduce the co-channel interference.

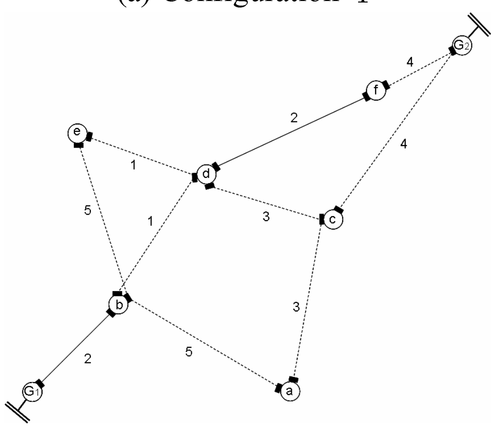
The co-channel interference refers to the interference among logical links operating over the same frequency channel within the interfering range. This includes the interference among adjacent logical links sharing a common NIC on a router. The dashed lines in Fig. 2 represent this kind of logical links. There are only one and two pairs of logical links not sharing NIC for configuration Ⅰ and Ⅱ respectively. For configuration Ⅱ, there are two nodes d and b, each of which uses three NICs. The interference for configuration Ⅰ is apparently more severe than that for configuration Ⅱ. Eq. (6) indicates that the co-channel interference leads to a decrease in the effective capacity for the corresponding logical link.

Table 2 shows the logical links and their corresponding aggregate traffics as well as effective capacities obtained from the optimal integrated design for configuration Ⅰ and Ⅱ with the same set of 24 UDP flows. In Table 2, (m n, i) denotes the logical link corresponding to $x_{mn}^{i}=1$.

From the variation of the values of λ_{mn}^{i} and C_{mn}^{i} in Table 2, we know that TiMesh can balance the traffic load among different logical links using proper logical topology formation and routing schemes. We also know that TiMesh can provide higher effective capacity for more congested logical links using proper logical topology formation, interface assignment and channel allocation scheme. The values of δ_{mn}^{i} show that the maximization of $\delta_{\min}$ leads to the similar level of congestion for most existing logical links. Measured with Jain's fairness index [14], the fairness among the existing logical links for configuration Ⅰ and Ⅱ are 0.9163 and 0.9994 respectively. The calculated value of $\delta_{\min}$ is equal to 0.133 and 9.55 for configuration Ⅰ and Ⅱ respectively. The former is much smaller than the latter. This result is due to two facts: 1) The co-channel interference for configuration Ⅰ is more severe than that for configuration Ⅱ; 2) The nominal link-layer data rate is smaller for configuration Ⅰ. It is expected that the performance for configuration Ⅰ will be much worse than that for configuration Ⅱ.



(a) Configuration Ⅰ



(b) Configuration Ⅱ

Fig. 2 Logical topology, interface assignment and channel allocation obtained from the optimum integrated design.

Table 2 Aggregate traffic and effective capacity obtained from the optimum integrated design

(a) Configuration Ⅰ

(*m n*, i)	λ^i_{mn} (Mbps)	C^i_{mn} (Mbps)	δ^i_{mn}
(*cd*,2)	2.5	3.2917	0.1334
(*bd*,1)(*dc*,2)(*de*,2)	2.0	2.6667	0.1334
(*bG1*,3)(*cG2*,3)(*db*,1) (*df*,1)(*eb*,1)(*G1b*,3)	1.5	2.0417	0.1334
(*ab*,3)	1.0	1.6667	0.3336
(*fd*,1)(*G2c*,3)	1.0	1.4167	0.1334
(*ac*,2)(*ba*,3)(*be*,1) (*ca*,2)(*ed*,2)(*fG2*,3)	0.5	0.7917	0.1334
(*G2f*,3)	0.0	0.2083	0.1666

(b) Configuration Ⅱ

(*m n*, i)	λ^i_{mn} (Mbps)	C^i_{mn} (Mbps)	δ^i_{mn}
(*cG2*,4)(*de*,1)	2.0	14.4375	9.55
(*ab*,5)(*bd*,1)(*bG1*,2) (*cd*,3)(*dc*,3)(*G1b*,2)	1.5	13.8125	9.55
(*eb*,5)	1.5	14.4375	10.05
(*ac*,3)(*ba*,5)(*ca*,3) (*db*,1)(*df*,2)(*fd*,2)	1.0	13.1875	9.55
(*G2c*,4)	1.0	14.4375	10.55
(*be*,5)(*ed*,1)(*fG2*,4) (*G2f*,4)	0.5	12.5625	9.55

In Fig. 2, all the logical links between two nodes are two opposite unidirectional links, each of which operates over a common channel. The two opposite unidirectional links are regarded as a single bidirectional link between a pair of nodes. For other different UDP traffic flows (e.g. 12 UDP flows), it is possible to generate two bidirectional logical links each of which operate independently over distinct frequency channel between the same pair of nodes as a result of the optimum integrated design.

Using GUROBI solver, we are able to get optimal solutions for all the MILP optimization problems encountered in configuration Ⅰ. As for configuration Ⅱ, we get near-optimal solutions, of which the optimization errors are 2.6%, 5.8% and 13.1% for 10, 16 and 24 UDP flows respectively.

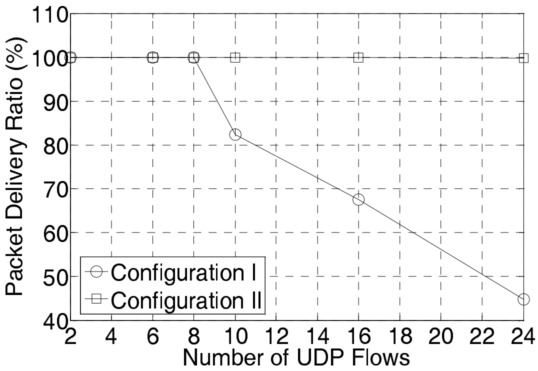
4. Performance evaluation

The optimal integrated design is evaluated by ns-2 simulator. The simulation parameters are presented in Table 3. The performance evaluation metrics are: 1) packet delivery ratio: the total number of packets received by all destinations divided by the total number of packets transmitted by all sources; 2) average end-to-end delay: the total time spent by all packets transmitted by all sources to traverse the network to their corresponding destinations divided by the total number of packets received by all destinations.

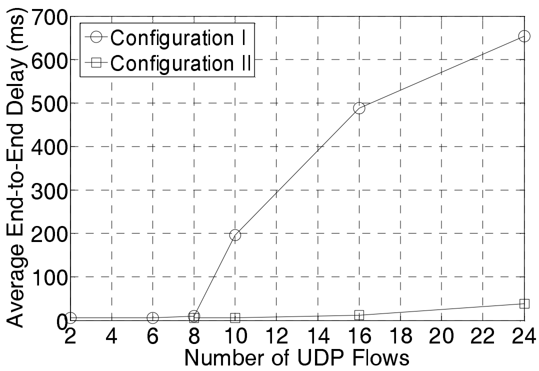
Table 3 ns-2 simulation parameters

Parameter	value
Transmission power	0.2818 W
Communication range	250 m
Carrier sensing range	450 m
Receive threshold	3.652×10^{-10} W
Carrier sensing threshold	1.559×10^{-11} W
IEEE802.11b data rate	11 Mbps
IEEE802.11a data rate	54 Mbps
Queue type	Drop-Tail
Queue size	50 Pkts
UDP packet size	1000 bytes
UDP transmission interval	0.016 s

The ns-2 simulator itself does not provide multi-channel multi-interface model. We refer to [15-17] and modify [18] to support the simulations. The routing agent is configured manually in the modified script according to the optimal routing design results. The simulation time is 100 seconds.



(a)



(b)

Fig. 3 The impact of UDP traffic on network performance, (a) Packet delivery ratio, (b) Average end-to-end delay.

The impact of varying the number of UDP flows from 2 to 24 on network performance is shown in Fig. 3. When the number of UDP flows is less than or equal to 8, the packet delivery ratio can be maintained beyond 99.99%, while the average end-to-end delay can be limited under 10.18ms. The network becomes congested as the number of UDP flows increases. Owing to lack of congestion control mechanism for UDP, the packet delivery ratio decreases and the average end-to-end delay increases as the number of UDP flows increases. This phenomenon is significant for configuration Ⅰ (the number of NIC I=2, the number of orthogonal channels C=3, the nominal link-layer data rate c^0=11Mbps) when the number of flow is greater than 8. The performance can be significantly improved by increasing I, C and c^0 to 2, 3 and 54Mbps respectively (configuration Ⅱ). When the number of UDP traffic flows is up to 24, the packet delivery ratio can still reach 99.86% and the average end-to-end delay is only 38.46ms.

5. Conclusions

In this paper, we use the TiMesh MC-WMN architecture to formulate the logical topology creation, interface assignment, channel allocation and routing as a MILP optimization problem. The optimization problem is described in AIMMS language and solved with GUROBI solver. Given a physical topology, the corresponding optimal logical topology, interface assignment, channel allocation and routing are obtained by varying the number of UDP flows. The optimal design results show that TiMesh owns the capability of load balancing and congestion-aware capacity planning and therefore can achieve fairness among the logical links. The optimal design results are evaluated by a modified ns-2 simulator. The performance evaluation shows that the packet delivery ratio decreases and the average end-to-end delay increases as the number of UDP flows increases. The performance can be significantly improved by increasing the number of available NICs, the number of available orthogonal frequency channels and the nominal link-layer data rate.

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