國立交通大學

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碩 士 論 文

針對無線網狀網路介面卡的角色與頻道選派之最佳化研究

Role and Channel Assignments for Throughput Optimization in Wireless Mesh Networks Using Hybrid Approach

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摘　　要

在無線網狀網路中，網路容量是個相當重要的議題。可以透過使用多天線的裝置和多個不重疊的頻道來增加網路容量。因此如何有效的去安排頻道給各介面卡就被廣泛的討論。在混合式無線網狀網路中，每個裝置至少有兩個介面卡。依介面卡功用又可分為可切換式介面卡和固定式介面卡。網路的傳輸主要是由可切換式介面卡和固定式介面卡之間的連線來達成的。在文獻[15]中，作者討論了裝置的介面卡數量大於二時，多出來的介面卡所可能產生的角色問題。對於多出來的介面卡要當做可切換式介面卡或固定式介面卡，作者稱為角色指派問題，且提出了連結層指標-平均衝突連線來評估網路效能。在此論文中，我們專門討論在混合式無線網狀網路上的指派問題。我們會驗證平均衝突連線和網路吞吐量之間的關係且提出兩個演算法來降低網路平均衝突連線以改善網路吞吐量。最後我們會將現有的方法和我們的演算法做一個比較。

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Abstract

The capacity problem is an important issue in wireless mesh networks (WMNs). It can be enhanced by using multi-radio devices and non-overlapping channels. Therefore, how to efficiently arrange the non-overlapping channels is widely investigated. In the hybrid WMNs, each device has at least two radios, and the radios are divided into two disjoint sets, switchable radio and fixed radio. Transmissions are mainly through the link between the switchable radio and fixed radio. In [15], the authors considered an assignment problem for WMNs that the number of radios per node is more than two. This problem is called role assignment problem. They also propose a link-layer metric: average conflicted links (ACL) for the assignment problem. In this thesis, we will validate the correlation between ACL and the throughput of network. We also propose two approximation algorithms to minimize ACL as well as to enhance the network throughput. Finally, we will compare our algorithms with other existing methods.

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兩年裡的日子中，實驗室裡的學長姐(世昌、安凱、嘉泰、蕙如、福文、苑瑩、祐慈、奕叡、依璇)、同學(佑笙、宇翔、俊傑、允琳)以及學弟妹們(志賢、淑盈、子興)的共同努力以及共同生活的點點滴滴，不管是在學術上的討論或者言不及義的閒扯，讓我的這兩年的研究生生活變得絢麗多彩，尤其是實驗室的共同出遊更讓我留下美好的回憶。

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Chapter 1

Introduction

The IEEE 802.11-based Wireless Mesh Network (WMN) is a fully wireless network. It uses multi-hop ad hoc techniques to extend the Internet access to last mile. The architecture of WMNs consists of mesh routers and mesh clients which are equipped with one or multiple IEEE 802.11 interfaces. In recent years, the importance of wireless mesh networks has increased. The reasons the WMNs have become more popular lie in not only the self-organized and self-configured properties of the WMNs, but also the low-cost of its deployment. In the sparse population area, the wireless mesh network is the best way to provide the network access to little inhabitant and saving the cost of line deployment.

In wireless mesh networks, the capacity of networks is a key issue. The number of channels has crucial effect. The more available channels often lead to better performance. With *k* available channels, the throughput of network can be improved at most *k* times than single channel. IEEE 802.11b/g provides three orthogonal channels in the 2.4 GHz spectrum and IEEE 802.11a provides 12 orthogonal channels in the 5 gigahertz (GHz) spectrum. The radios on different channels can avoid the interference due to the co-channel. So the multiple channels scheme brings the chance to enhance the capacity of networks. However, if every mesh node only has single radio, it cannot transmit and receive simultaneously and each node only can exploit one channel. The devices with multiple radios can use different channels on separate radios to improve channel reusability and the throughput of network. Due to the finite number of available channels, how to assign the channels to radios to achieve better channel reusability and avoid interference becomes a problem. Only with proper arrangement the node just might receive and transmit on different channels simultaneously. The problem of arranging the radios as possible as on different channels is called *channel assignment* problem. On the other hand, the communication between the radios builds on two radios on a common channel. The nodes must communicate through some mechanism to rendezvous to common channel to make transmission successful. Among the better channel reusability, avoiding interference, and communication requirement, how to exploit the finite channels and keep the ability of communicating between nodes is widely discussed. Enormous works have been delivered under the multiple channels multi radios architecture. According to the frequency of the radios changing the channel, the works about channel assignment can be categorized into three approaches: static approach, dynamic approach, and hybrid approach.

In the static approach [1-4], each radio stays on a channel for a long time, the mesh nodes can use the channel where the radio stays. Because the radios are fixed on the channel, the nodes only need to broadcast its status to the neighbors once per period of long time. No extra communication cost is required. However, the mesh nodes only can use the assigned channels, even the assigned channel is in bad situation and the other channels are idle. The channel utilization of static approach is not good.

On the contrary, in dynamic approach, each radio changes its channel frequently. The radios could use different channels in short times; According to various constraints such as load [5], the nodes may switch to the newly assigned channels instead of the previously assigned channels. Radio may use any available channel, so the channel utilization is much better than static approach. However, when mesh nodes changed its occupied channels, they must inform its neighbors. The more frequently channel switching happened, the more communication overhead is needed.

In order to improve the drawbacks of two above approaches, Kysanur and Vaidya recently proposed a hybrid approach [7-8] which combines the benefits of static approach and dynamic approach. In hybrid approach, each node has least two radios. One radio is fixed on a channel for a long time as radios in static approach; therefore we called it fixed radio. And the other radio switches its channel frequently as radios in dynamic approach; it is called switchable radio. Every mesh node needs at least one fixed radio and at least one switchable radio. The primary mission of fixed radio is to wait for transmission request RTS and data from the channel. On the other hand, if a node wants to start a transmission, it will tune its switchable radio to the channel which receiver's fixed radio is on to send RTS. In other words, node can communicate with each neighbor on different channels through the switchable ability of switchable radios, the channel utilization is much better than the static approach. And the mesh nodes in hybrid WMNs need less coordination due to low frequency of changing the channel of fixed radio. So the communication cost is much less than the dynamic approach. Overall, the hybrid approach* alleviates the shortcomings and owns the part of the advantage of the two previous approaches. Due to the above mentioned advantages, in my thesis, the discussion is under the multi-channel multi-radio hybrid approach WMNs. Related to hybrid approach WMNs, there are two major challenges.

- Channel assignment problem:

  The channel of switchable radios is changeable and dependent on the receivers' fixed radios. But the fixed radios stay on a channel for a long period of time. Therefore, the interference between the fixed radios must be considered.

- Role assignment problem:

  How to determine the radios besides the basic fixed and switchable radio on the mesh nodes should be fixed or switchable. It is rarely mentioned. This is called *role assignment problem* in [15]. The effects of the role assignment and channel assignment are concerned in the thesis.

*In [6], another similar protocol Dynamic Channel Assignment (DCA) is proposed. The nodes negotiate the channel to transmit data through a specific radio and a control channel. Then the other radios start the transmission on the reserved channel.

According to above challenges, our design principle should adapt the variance of environments and the assignment is only needed once. In order to investigate the special challenges in hybrid approach, a recent work [15] proposes a set of problems to feature the challenges, named MAX *SL*, MIN *TCL*, and MIN *ACL*. We introduce briefly here:

- MAX *SL*:

  In hybrid approach, the transmission is mostly beginning from the switchable radio of the sender sending RTS to the fixed radio of the receiver, the links of switchable radio and fixed radio are called switchable links (*SL*). MAX *SL* problem tries to find a role assignment to make the number of switchable links in the network maximized.

- MIN *TCL*:

  The collisions are mainly caused by co-channel and co-interface problems between the radios. The switchable links which conflicted with the specific switch link due to co-channel problem are called interfered links (*IL*) and due to co-interface problem are called blocked links (*BL*). The sum of the number of interfered links and the number of blocked links is called total conflicted links (*TCL*). MIN *TCL* tries to find a channel assignment to minimize the total number of conflicted links.

- MIN *ACL*:

  Due to solving the role assignment and channel assignment in sequence does not guaranteed the global optimum with respect to minimum *TCL* [15]. So authors jointly consider the two problems to obtain an integrated solution. The authors try to maximize *SL* and minimize *TCL*. So they define the average number of conflicted links (*ACL*), i.e.

$$ACL = TCL / SL$$

However, [15] does not design any explicit algorithm for the problems, and the metric ACL about the optimized problems is not yet verified. In this thesis, we will show the correlation between the metric *ACL* and the throughput of network is highly related. The result showed that we can make the performance better through minimizing the *ACL*. Due to the properties of hybrid WMNs, the low changing frequency of fixed radios and switchable radios, to design a centralized algorithm to optimize the performance is possible but the optimization problem might be more complex than WMNs in other approaches. So we will propose the centralized algorithms focus on the role assignment and the channel assignment in hybrid WMN to minimize the *ACL* and get better throughput.

Chapter 2

Related Works

Link-layer protocols have great effects to the throughput of WMNs. With the different purposes the designs styles of link-layer protocols are varied. A link-layer protocol, Hybrid Multi-Channel Protocol (HMCP), is presented in [11]. This is the basic architecture of hybrid approach WMNs mentioned in the previous chapter. And through the exchange of Hello packet, the link-layer protocol manages the fixed radio on each node by maintaining a NeighborTable and a ChannelUsageList containing the channel status within two-hop neighborhood. The node will change the channel of its fixed radio when the number of two-hop neighbor nodes using the same channel is too large. The new routing metric, Multi-Channel Routing (MCR) which selects path with better channel diversity, is proposed according the principle of WCETT [12] and the property of hybrid WMNs. MCR is a weighted sum of two components. The first component is the sum of expected transmission time and switching cost along the path. This component presents the total resource consumed along the path. The second component is maximum ETT cost of all channels. This component is used to make sure the path will have good channel diversity. The metric measures the tradeoff between the path length by first component and the channel diversity by second component. Overall, the architecture of hybrid WMNs is completed through [11] and [8]. But some problems caused by multi-channel scheme are not solved, such as the multi-channel hidden terminal problem, etc on.

Li et al. [13] proposed an improved MAC protocol HMCMP for MCMR WMNs based on hybrid MAC protocol [8]. To solve the multi-channel hidden terminal problem, the authors used a waiting time scheme for updating network allocation vectors (NAVs). Waiting for a proper period of time after the switchable interface switches to another channel for checking the channel current state to prevent the hidden terminal problem without sacrificing the efficiency under MCMR environment.

However, the above mentioned papers less discussed about the channel assignment problem in hybrid WMNs. Only one general method is proposed. But the channel assignment problem is widely discussed in WMNs. With proper arrangement, the limited available resource, channel frequency, will be used efficiently. Under different assumptions, some papers focused on the distributed channel algorithms based on different goals such as the maintenance of the network connectivity [2], with limited local information [2, 5], or trying to minimize interference cost [16]. They use the distributed algorithms to assign channel to avoid using centralized entity. But they often do not consider the global optimum of network.

Some channel assignment methods mainly concerned about the static WMNs. The property of the radios fixed on a channel for a long period of time makes the optimization of the network is possible. The authors of [9] mathematically formulated the joint channel assignment and routing problem by considering interference constraints, the number of available radios and channels. And [9] also proposed an approximation algorithm to maximize the network throughput. But [9] only consider infrastructure WMNs. For hybrid approach WMNs due to the low changing frequency of fixed radio, the centralized algorithm may be suitable to obtain the optimal performance. Through the switchable radios on the mesh node in hybrid WMNs, mesh nodes can transmit to the every neighbor within the transmission range. It means the hybrid architecture can adapt the dynamic traffic patterns without changing the channel of the fixed radios occupied. Because of the part of the switchable radios in the network is changing its channel very often, the optimization in hybrid WMNs is more different and may be complicated than the optimization in static WMNs.

Jeng and Jan noticed an undiscovered problem in MCMR WMNs using hybrid approach [15]. Based on the hybrid WMNs approach, the role assignment problem is proposed. When the number of radios on a node is more than two, the effects of extra radios is rarely mentioned. So the authors investigated the optimization problems in hybrid WMNs. Due to the architecture, the traditional channel assignment problem happened on the fixed radios in hybrid WMNs. And if the role assignment problem on the radios of nodes combines with channel assignment problem, the problem becomes more complex. A series of problem transformations, analyses and results is showed. The new metric, *average conflicted links* (*ACL*) is proposed to be the benchmark of the link-layer throughput in of networks. However, there is no verification about *ACL* and no algorithm is proposed in [15]. After the above discussions, we will target the distinctions of hybrid WMNs on the basis of [15] to propose the algorithms to achieving the goals: the centralized algorithm providing nearly optimal solution to assignment problems and it is traffic independent.

We will discuss the detail network model and problem definitions in the next chapter. And we try to propose algorithms for the above assignment problems on the basis of theorem in [15].

Chapter 3

Network Model and Assignment Problems

3.1 Network Model

In this section, we introduce the network model [15] which is used through this thesis. There are H available orthogonal channels in the network. A set of $V = \{V_1, V_2, \ldots, V_N\}$ presents N static wireless mesh nodes. Each mesh node has R_i radios, see Fig. 3.1. The transmission range of each radio may be different. We present the network topology as $G_T = (V_I, E_T)$, $V_I = \{u_{ir} \mid i=1, 2,\ldots, N, r=1, 2,\ldots, R_i\}$, $E_T=\{u_{ir}u_{jt} \mid u_{jt}$ is in the transmission range of $u_{ir}\}$. V_I is corresponding to all radios on every node in the network and E_T is corresponding to the directed links i.e. the end radios are covered by the starting radio. And G_T is called as a *transmission graph*.

However in the graph G_T, there are the edges between the radios in the same node and the unidirectional links due to unequal transmission ranges of two end radios. In practical WMNs, the radios within a node communicate through hardware circuit and unidirectional links cannot handle RTS-CTS-DATA-ACK sequence. Therefore, *communication graph* (G_C), subgraph of G_T, is presented as $G_C = (V_I, E_C)$. $E_C = \{u_{ir}u_{jt} \mid u_{ir}u_{jt} \in E_T, u_{jt}u_{ir} \in E_T$ and $i \neq j\}$. To see Fig. 3.2, we show the transmission graph and the communication graph.

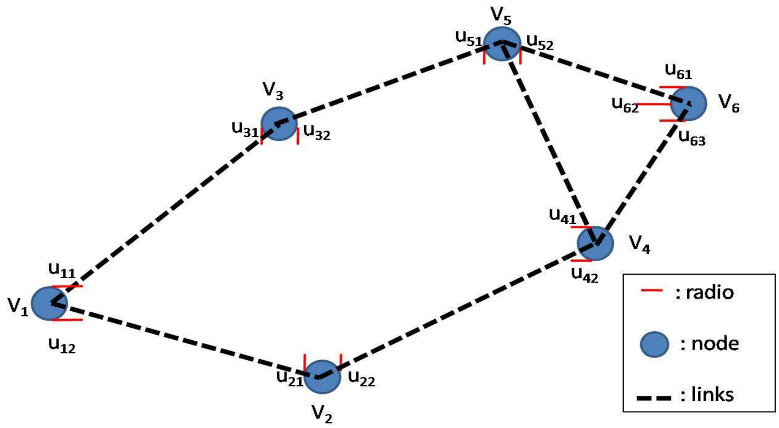
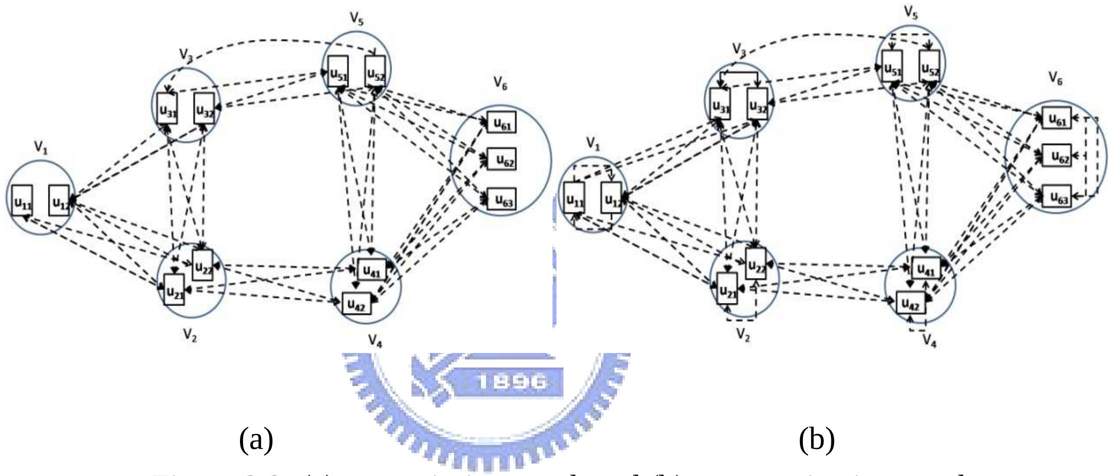


Figure 3.1 Network topology



(a) (b)

Figure 3.2: (a) transmission graph and (b) communication graph.

In hybrid approach WMNs [7-8], each radio should be either fixed or switchable. The property of the radio is called *the role* of radio. The role of each radio in the network is called *the role assignment of network*. Therefore we try to model this phenomenon as a graph. Given a set V_I of interfaces, a role assignment $\rho = (V_F, V_S)$ is a disjoint partition of V_I. V_F is the set of fixed radios which stay on a channel for a long period of time. V_S is the set of switchable radios which can transmit the data to its neighbors by tuning to different channels which neighbors' fixed radio is on. Each radio should belong to either V_F or V_S, and each mesh node must have at least one fixed radio and at least one switchable radio. For any two radios u_{ir} and u_{jt}, u_{ir} can switch to channels which u_{jt} is on, if u_{ir} is switchable radio and u_{jt} is fixed radio. Because the transmission is based on the interaction between the switchable radio and the fixed radio, the links between the switchable radios and fixed radios is a main factor to the transmission routes in hybrid WMNs. We named the links as *switchable links* (SL). Then the *switchability graph* (G_S) is presented as $G_S = (V_I, E_S)$. $E_S = \{u_{ir}u_{jt} \mid u_{ir}u_{jt} \in E_C$, and $u_{ir} \in V_S, u_{jt} \in V_F\}$, see Fig. 3.3.

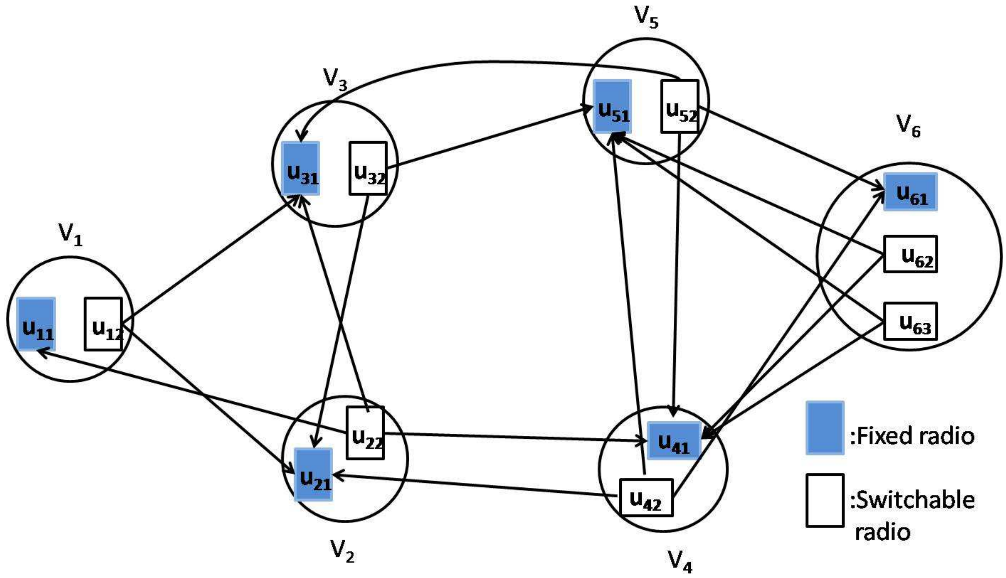


Figure 3.3 Switchability graph

Due to the links G_S in are directional, we must consider the connectivity of the network. Therefore, the role assignment $\rho = (V_F, V_S)$ is called *feasible* if and only if the whole network is strongly connected, for the convenience, the following graphic terms is used through the thesis:

- $E_{ir}^+(G)$ ($E_{ir}^-(G)$) : the out-going edge (in-coming edge) adjacent to u_{ir}
- $N_{ir}^+(G)$ ($N_{ir}^-(G)$) : the adjacent vertices of u_{ir} linked by $E_{ir}^+(G)$ ($E_{ir}^-(G)$)
- $E_{ir}(G)$: $E_{ir}^+(G) + E_{ir}^-(G)$
- $N_{ir}(G)$: $N_{ir}^+(G) + N_{ir}^-(G)$

After the basic definitions of network model of the hybrid WMNs, there are some issues and problems we will discuss below.

3.2 Assignment Problems

- **Problem 1 – role assignment:**

In hybrid WMNs, the transmissions are mostly started by the switchable radio of nodes tuning to the channel which receivers' fixed radios on. Therefore, it is intuitive that the number of switchable links, i.e. $|E_S|$, seriously affects the performance of network. The larger number of switchable links of the network brings better adaptability to different traffic patterns and transmission ability, and makes transmission routes more diverse. With the above consideration, the role assignment problem is defined below:

MAX *SL*: given a communication graph $G_C = (V_I, E_C)$, find a feasible role assignment $\rho = (V_F, V_S)$ of V_I such that $|E_S|$ is maximized.

- **Problem 2 – channel assignment:**

A switchable link is active when the end radios of link are transmitting data. Assume a switchable link $e = u_{ir}u_{jt}$ is active; there are two conditions which will cause the collisions between the links.

- Co-interface collision

  When e is active, radio u_{ir} and radio u_{jt} are occupied by e. Therefore the other radio around u_{ir} and u_{jt} cannot use u_{ir} and u_{jt} to do any transmission. In other words, the switchable links which contain either u_{ir} or u_{jt} in the link cannot be active. It is named co-interface collision. And we called the switchable links which conflicted with e due to co-interface collision as *blocked links* of e. All blocked links of e are defined by

$$BL(e) = E_{ir}^{-}(G_S) \cup E_{jt}^{+}(G_S) - \{e\} \quad (1)$$

- Co-channel collision

  When e is active, all radios within the transmission range of u_{ir} and u_{jt} cannot involve any transmission on the channel which fixed radio u_{jt} is on. The set of radios within the transmission range of u_{ir} and u_{jt} is called *potential interfered* *interface* and defined by

$$PIN(e) = N_{ir}^{-}(G_T) \cup N_{jt}^{+}(G_T) - \{u_{ir}, u_{jt}\} \quad (2)$$

The switchable links adjacent to the interface in *PIN(e)* may be interfered by *e*. The switchable links may conflicted with *e* due to co-channel collision are defined by

$$PIL(e) = \{e' \mid e' \in E_{ls}(G_T), u_{ls} \in PIN(e)\} - BL(e) \quad (3)$$

In (3), *BL(e)* is subtracted to avoid doubly counting. We call *PIL(e)* as *potentially interfered links* of *e*. But in *PIL(e)*, the links actually interfered with *e* are the switchable links whose fixed radios are on the same channel as fixed radio u_{jt}. The set of *interfered links* of *e* is defined by

$$IL(e) = \{e' \mid e' \in PIL(e), \chi(e') = \chi(e)\} \quad (4)$$

We say *e*' is the *conflicted links* of *e* when *e*' is either *blocked* or *interfered* by *e*. The set of conflicted links of *e* is

$$CL(e) = BL(e) + IL(e) \quad (5)$$

So *the number of total conflicted links* of the network is the sum of conflicted links of every switchable link, i.e.

$$TCL = \sum_{e \in E_S} |CL(e)| \quad (6)$$

The number of total conflicted links, abbreviated as *TCL*, can present the collision status of network. For the network topology, the higher *TCL* means the more conflicts happened in the network. Consequently, if we try to minimize conflicts, our goal is to minimize the total number of conflicted links of the network. In this problem, we assume the roles of radios are given. Based on [15], we know that blocked links are determined by the roles of radios, so the number of blocked links is a constant when role assignment is given. The goal is transformed into minimizing *the total number of interfered links*, abbreviated as *TIL*, i.e.

$$TIL = \sum_{e \in E_S} |IL(e)| \quad (7)$$

With above mentioned conditions, the channel assignment problem can be defined as follows:

MIN *TIL:* Given a transmission graph $G_T = (V_I, E_T)$, a feasible role assignment $\rho = (V_F, V_S)$, and H channels, find a feasible channel assignment $\chi: V_F \rightarrow [H]$ such that

TIL is minimized, where an assignment is *feasible* if and only if any fixed interface is assigned exactly one channel.

■ **Problem 3 – joint role and channel assignment:**

The role assignment problem is concerned with switchability, and the channel assignment problem tackles the interference problem. Therefore, given a transmission graph G_T and H channels, we can solve the above two problems sequentially to get an integrated solution. But there is no guaranteed that the way can find global optimum with respect to minimum *TCL*. We have already discussed the role assignment affect the number of blocked links in the previous paragraph. And [15] presents the optimum of MIN *TIL* is constrained under the given role assignment.

So we should jointly consider the problems of role assignment and channel assignment to obtain the global optimum of *TCL*. The joint assignment problem is defined below:

MIL *TCL-SL*(*q*): Given a transmission graph $G_T = (V_I, E_T)$, H channels, and a positive integer q, find a joint assignment (ρ, χ), where is an feasible role assignment $\rho=(V_F, V_S)$ of V_I and $\chi: V_F \rightarrow [H]$ is a feasible channel assignment of V_F, such that *TCL* is minimized and subject to that $SL \geq q$.

The problem jointly takes the role assignment problem, channel assignment problem, and switchability above the number of switchable links q into consideration. Furthermore, we define the *average number of conflicted links*, abbreviated as *ACL*, by

$$ACL = \frac{TCL}{SL} \tag{8}$$

The problem of minimizing *ACL* is called **MIN *ACL***. Obviously there must be an optimal q such that ACL is minimized.

3.3 Complexity of the problems

The proofs are given in [15]. We only present the conclusions here.

- MAX *SL* is *NP-hard* and can be reduced from the *maximum cut problem*, abbreviated as MAX CUT, defined below:

MAX CUT: Given a graph $G = (V, E)$, find a set of vertices S that maximize the cardinality of the cut $(S, \overline{S})$, i.e. the number of edges with one end point in S and one end point in $\overline{S}$.

- MIN *TIL* is also *NP-hard* and reduced to MIN *K*-PARTITION problem which is defined below:

  MIN *K*-PARTITION: Given a $G = (V, E)$ with weight function $\omega{:}E \rightarrow N$, find a k-color assignment $\sigma : V \rightarrow [k]$ such that total weight of monochromatic edges, i.e. $\sum_{v_i v_j \in E: \sigma(v_i)=\sigma(v_j)} \omega(v_i, v_j)$, is minimized.

  In other words, it is to find an edge set of minimum weight whose removal makes the graph k-colorable.

- MIL *TCL-SL(q)* is transformed to the *NP-hard* problem: *minimum weighted independent dominating set problem*, abbreviated as MIN WIDS, defined below:

  MIN WIDS: Given a graph $G = (V, E)$ with weight functionω: $V \rightarrow N$, find an independent dominating set $\eta \in V$, such that $\sum_{v \in \eta} \omega(v)$ is minimized.

  For a graph $G = (V, E)$, independent dominating set is a subset S of V such that each vertex is either in S or adjacent to some vertex in S and the elements in S have no edges among them.

3.4 Example

Here we present an example of the role and channel assignment on the topology of Fig 3.1 with 2 available channels and shows the interference among the links. In Fig. 3.4, the role of each interface is assigned and the different colors stand for the different channel of fixed interfaces. For a link e: $u_{12}u_{21}$, the blocked links of e: $BL(e) = u_{12}u_{31}$, $u_{32}u_{21}$, $u_{42}u_{21}$, the interfered links of e: $IL(e) = u_{22}u_{31}$, $u_{52}u_{31}$, $u_{42}u_{61}$ and the number of conflicted links of e: $|CL(e)| = 3+3 = 6$.

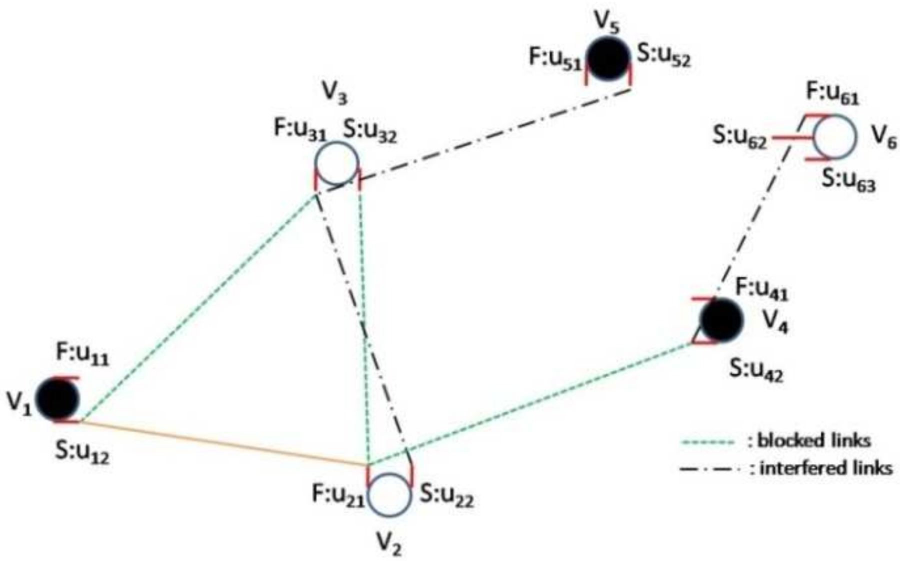


Figure. 3.4: Interfered links and blocked links of e:$u_{12}u_{21}$

Fig. 3.5 Shows *BL* and *IL* of every link, after calculating, *TCL*=141, *SL*=18.So, *ACL*=7.83, which means on average a switchable link conflicted to at most 7.83 links.

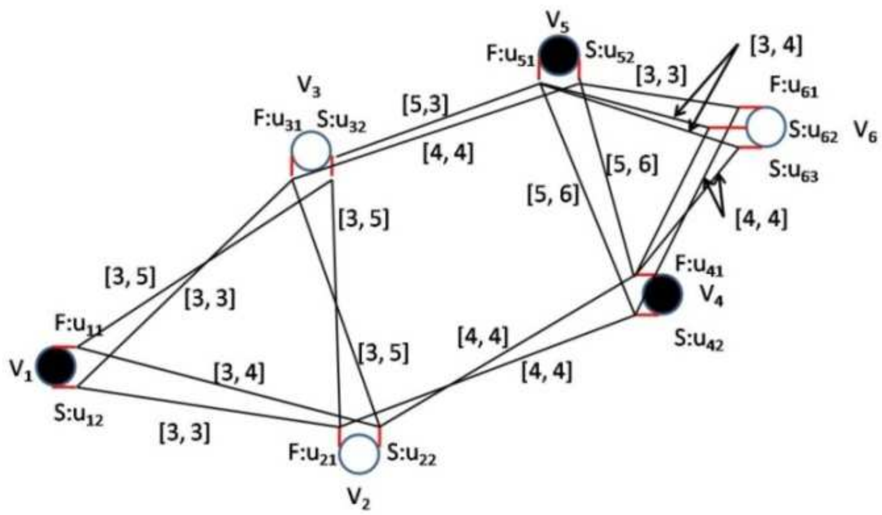


Figure. 3.5: The numbers of blocked links and interfered links
of each switchable link ([BL,CL])

Chapter 4

The Proposed algorithms

In this section, we will present algorithms for MAX CUT and MIN *K*-PARTITION problem. The role assignment problem can be reduced to MAX CUT problem. And the algorithm-*Minimum Revoking First* (MRF) for role assignment problem is based on an algorithm proposed by [14]. The algorithm in [14] is a 1/*k*-approximation algorithm for the MAX *K*-CUT problem. In my thesis, there are two disjoint sets, switchable radio set and fixed radio set. So MRF is 1/2-approximation here.

In previous chapter, we obtain reduction from MIN *TIL* to MIN *K*-PARTITION. Because MIN *K*-PARTITION problem has no polynomial time approximation with a const bound [10], we will design an efficient heuristic algorithm-*Maximal Weighted Vertex First* (MWVF) for MIN *K*-PARTITION problem. Based on MWVF, the channel assignment algorithm for MIN *TIL* named the *Maximal Interfering Interface First* (MIIF) is presented below.

However, an integration solution of sequentially solved two above problem is no guaranteed for global optimum of minimum *TCL*. Therefore, we also propose another algorithm for the joint problem. The joint problem can be transformed into minimum weighted independent dominating set problem (MIN WIDS) [15], and we briefly introduce the transformation and design an algorithm-*Joint* for MIN WIDS problem. The joint problem takes into account every possible potential interfered link and blocked links according to transmission graph G_T. By assigning the role and channel to a radio simultaneously, we try to minimize the number of total conflicted links. We will describe the algorithms below.

4.1 Algorithm for role assignment problem

Briefly speaking, the algorithm counts the weight between the radio and the set (Step 2). Then we assign the radio to the set which has the minimum weight with the radio (Step 3). Repeat the above steps until all radios belong to either switchable radio set or fixed radio set. In other words, the node always joins the set which the node has the minimum weight with.

Here are some terms below:

SL: the value of the vertex partitioning obtained.

w{i, j}: =1, if node *i* is adjacent to *j*.

=0, if node *i* is not adjacent to *j*.

SET(i): the set which node *i* belongs to.

WT(i): the weight between the nodes in set *i* and some node *j*, i.e. $\sum_{m \in S_i} w\{m, j\}$

ALGORITHM: MRF

Input:	A communication graph $G_C = (V_I, E_C)$, a weight function $w\{x, y\} \rightarrow N$
Output:	A role assignment ρ, and the number of switchable links *SL*
Step 1:	Pick 2 radios out of *K* radios on each node to each set.
Step 2:	Process edge list from E_C of vertex *j*. For each edge {*j*, *m*} on the edge list of *j*, calculating *WT(SET(m))= WT(SET(m))+w{j, m}*
Step 3:	Find the set for which $\sum_{m \in s_i} w\{j, m\}$ is minimal
Step 4:	Assign vertex to set S_i
Step 5:	Update *SL* and reset *WT*, $SL = SL + w\{j, m\}, m \notin S_i$
Step 6:	Next vertex: $j = j + 1$, back to step 2.

4.2 Algorithm for channel assignment problem

According to [15], MIN *TIL* can be solved by MIN *K*-PARTITION. So we firstly transform MIN *TIL* problem in our model into MIN *K*-PARTITION in weighted graph. Then we present a heuristic algorithm for the MIN *K*-PARTITION problem here.

A. Transformation

We construct a weighted graph G' = (V', E') as following:

(i) For any radio $u_{ir} \in V_F$, construct a vertex $V_{ir} \in V'$

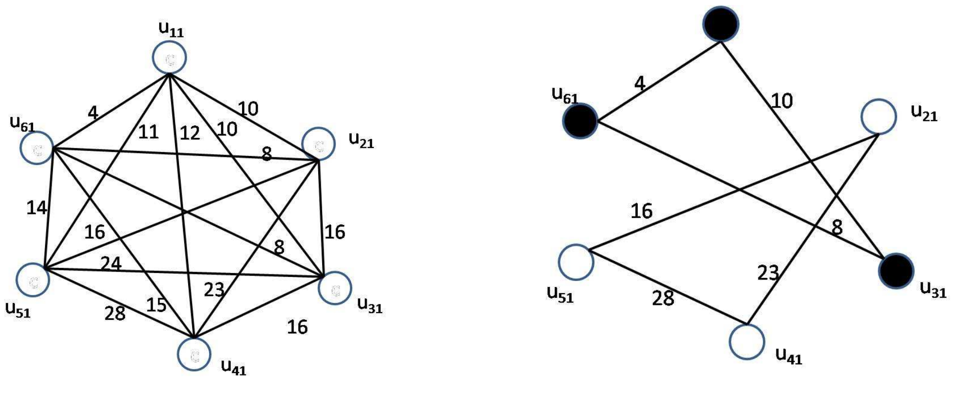
(ii)For any two radios V_{ir} and $V_{jt} \in V'$, there is an edge $e \in E'$ between them

(iii)Count weight W between the vertex pair in V':

For each vertex pair $u_{ir}u_{jt}$, the total number of switchable links of u_{jt} which might be interfered by all edges $e = u_{ab}u_{ir} \in E_S$ are presented as $w(u_{ir}, u_{jt})$and the total number of switchable links of u_{ir} which might be interfered by all edges $e = u_{ab}u_{jt} \in E_S$ are presented as $w(u_{jt}, u_{ir})$. And the weight of edge between the two vertices V_{ir} and V_{jt} in V' is the sum of all possible interfered links between the fixed radio u_{ir} and u_{jt}, i.e.

$$w(V_{ir}, V_{jt}) = w(u_{ir}, u_{jt}) + w(u_{jt}, u_{ir}) \tag{9}$$

Fig. 4.1.(a) shows the weighted graph transformed from Fig. 3.4. And Fig. 4.1.(b) shows the 2-partition of the weighted graph.



(a) (b)

Figure. 4.1: (a) transformed weighted graph (b) 2-partition of the weighted graph

B. Heuristic algorithm for MIN *K*-PARTITION

At the beginning, the total weight *W* which records generated weight and the set *S* which records colors assignment for vertices is initialized as 0 and ∅ (Step 1). The algorithm counts the weight $W(v_i)$ for all vertices (Step 2). The total weight of the edges adjacent to v_i, denoted as $W(v_i)$, is calculated for each $v_i \in V$, i.e.

$$W(v_i) = \sum_{v_i v_j \in E} w(v_i, v_j) \tag{10}$$

Choose the vertex with maximum weight $W(v_i)$ and assign it to one of the *K* color which will cause the minimal number of monochromic edges (Step 3 and 4), i.e.

$$\min_{k \in [1,2,\ldots,k]} \left\{ \sum_{v_j \in \{N_j \cap S\} : \sigma(v_i) = \sigma(v_j) = k} w(v_i, v_j) \right\} \tag{11}$$

The number of newly generated monochromic edges will be accumulated as *W* (Step 5). Then recount $W(v_i)$ of the remaining unassigned vertices (Step 2). Repeat the above procedures until all vertices have chosen its color. The final value of *W* is the weight of *K*-partition of the weighted graph G. The algorithm is called Maximal Weighted Vertex First (MWVF). And based on the MWVF, the channel assignment algorithm for MIN *TIL* is named MIIF. The algorithms are presented below:

ALGORITHM: MWVF

Input:	A graph $G = (V, E)$, a weight function w: $E \rightarrow N$, and *K* colors
Output:	A *K*-color assignment σ, and the total weight *W*
Step 1:	W:=0, S=empty set
Step 2:	For each $v_i \in V$, calculate $W(v_i)$
Step 3:	Choose a vertex $v_i \in V\text{-}S$, with the largest $W(v_i)$
Step 4:	Assign $\sigma(v_i)=k^*$
Step 5:	$W := W + W^*(v_i)$; $S := S + \{v_i\}$
Step 6:	If $S \neq V$, go back to Step 2; Otherwise, stop and return σ and *W*;

ALGORITHM: MIIF

Input:	A transmission graph $G_T = (V_I, E_T)$, a partition ρ = {V_F, V_S}, and H channels.
Output:	A channel assignment χ and the corresponding *TIL*
Step 1:	Transform the input instance into G' = (*V*', *E*'), *w*' and *K*' according the above description
Step 2:	Apply the transformed instance to the MWVF and obtain a color assignment σ' and total weight *W*
Step 3:	For any $u_{ir} \in V_F$, $\chi(U_{ir}) = \sigma'(V_{ir})$;*TIL*=*W*;
Step 4:	Stop, return χ and *TIL*

4.3 Algorithm for joint assignment problem

A. Transformation

The proof of MIN *TCL* can be formulated as any mathematic model of MIN WIDS is given in [15]. We briefly introduce the polynomial transformation here. Fig. 4.2 shows the example of the transformation. Given any $G_T = (V_I, E_T)$ and H channels, we construct a weighted graph $G_f = (V_f, E_f)$. Let $H^+ = H + \{0\}$. The construction consists of the following parts.

(i) For any $u_{ir} \in V_I$, a vertex $v_{ir,h} \in V_f, \forall h \in H^+$

(ii) For any $e \in E_C$, $e' \in PBL(e, G_C)$, a vertex $v_{e,e',0} \in V_f$

(iii) For any $e \in E_C$, $e' \in PIL(e, G_C)$, a vertex $v_{e,e',h} \in V_f$, $h \in H$

Part (i) defines all possible states of the radio u_{ir}. Part (ii) defines the all blocked links of e, where $e \in E_C$. Part (iii) defines the all interfered links of e on the same channel. For explanation, we define the following subset of V_f:

$$V_{ir} = \{v_{ir,h} \in V_f \mid h \in H^+\}, \forall u_{ir} \in V_I$$

$$V_\alpha = \bigcup_{u_{ir} \in V_I} V_{ir}$$

$$V_{e,e'} = \{v_{e,e',h} \in V_f \mid h \in H\}, \forall e \in E_C, \forall e' \in PIL(e, G_C)$$

$$V_e = \{v_{e,e',0} \mid e' \in PBL(e, G_C)\} + \bigcup_{e' \in PIL(e,G_C)} V_{e,e'}, \forall e \in E_C$$

$$V_\beta = \bigcup_{e \in E_C} V_e$$

(iv) For any $u_{ir} \in V_I$, each vertex pair in V_{ir} has an edge in E_f

(v) For any $V_i \in V_N$, the edge $v_{i_1,0}v_{i_{R_i},0} \in E_f$

(vi) For any $e \in E_C$, $e' \in PIL(e, G_C)$, each vertex pair in $V_{e,e'}$ has an edge in E_f

For part (iv), the vertices in V_{ir} will have edges among each other, because there is exactly only one state for each radio. Part (v) keeps the constraint that at least one switchable radio and at least one fixed radio are within a node to be sure. Part (vi) explains that at most one the possible interfered state of two edges which compose the vertex in $V_{e,e'}$ exists.

In addition, the vertices which generated from (i) and (iii) will have edges $v_{ir,h}v_{e,e',h'} \in E_f$ if and only if one of the following condition is satisfied. The edges of $v_{ir,h}v_{e,e',h'}$ show that the state of the conflicted links and the state of radio should be coherent. The edges which generated by the following condition ensure the regularity of the role and channel assignment of the radio. And $r(e)$ and s(e) below present ending radio and starting radio.

(vii) $h=0, h' \in H^+$, and $u_{ir} = r(e)$ or $r(e')$;

(viii) $h \in H, h' \in H^+$, and $u_{ir} = s(e)$ or $s(e')$;

(ix) $h \neq h' \in H$, and $u_{ir} = r(e)$ or $r(e')$;

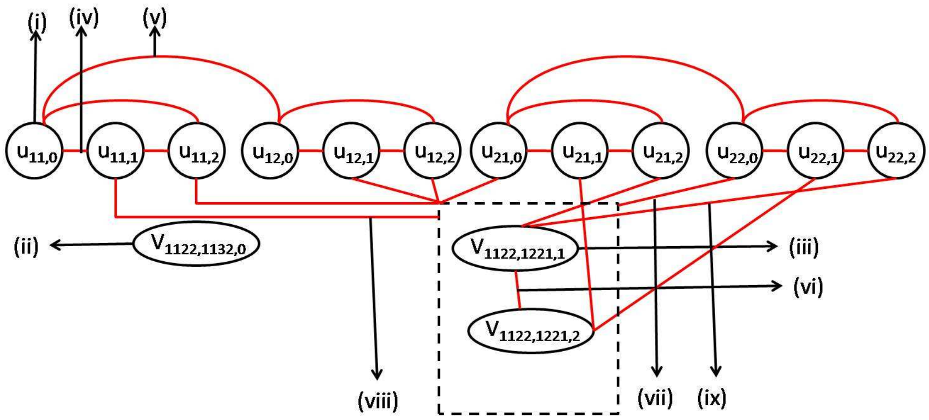


Figure. 4.2: Part of transformation from Fig. 3.2

B. Algorithm for WIDS

First, the algorithm transforms the transmission graph G_T into weighted graph G_f. All vertices in V_α and V_β have weight 0's and 1's for counting the weight of each vertex. The algorithm counts the weight of each vertex in G_f according to the total weight of the adjacent vertices of each vertex. So for each vertex only the adjacent vertices in V_β will increase the weight. The reason is the vertices in V_β stand for the conflicts that might happen in a certain role and channel assignment. So the algorithm choose the vertex with largest weight which means this assignment of the vertex will reduces the largest value of the number of possible conflicted links. Then algorithm marks the neighbors of the chosen vertex, because the algorithm targets on independent dominating set. Repeat the counting and choosing procedure until all vertices is chosen or dominated.

ALGORITHM: JOINT

Input: A transmission graph $G_T = (V_I, E_T)$, and H channels
Output: A role assignment ρ and a channel assignment χ
Step 1: Transform input instance G_T into weighted graph $G_f = (V_f, E_f)$ for WIDS
Step 2: Counting the weight of each unmarked vertex v in V_f
Step 3: Pick the maximum weight vertex V_{max} from V_f and mark the adjacent vertices of V_{max} as dominated vertices
Step 4: Repeat step 2 ~ step 4 until all vertices in V_f is chosen or dominated.

Chapter 5

Simulation

In the first-half part of this chapter, we will present the correlation between ACL and throughput under the environment with different number of channels and radios. The results show that ACL is suitable to be an objective function of an assignment of hybrid WMNs due to the fact that ACL and the throughput of network are strongly negatively correlated. And in the second-half part of the chapter, we will compare the throughput between different assignment algorithms including MCUF proposed in [8], hash algorithm, and the algorithms we proposed.

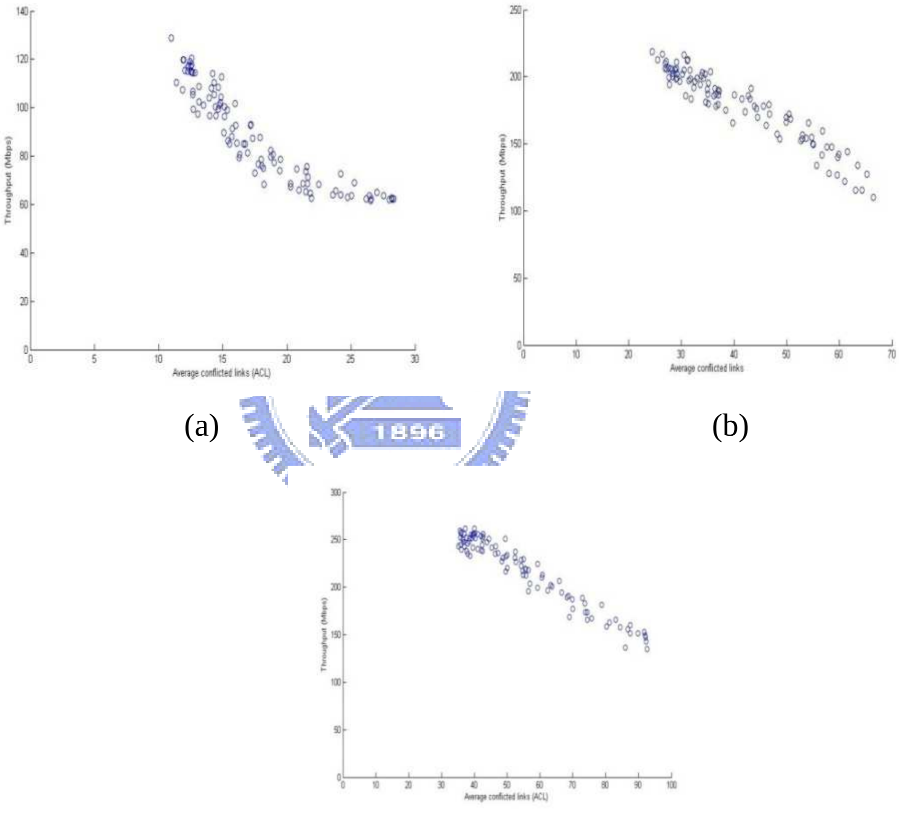
We use HMCMP [13] as our MAC lay to avoid the multi-channel hidden terminal problem in hybrid WMNs. The simulations are operated on the ns-2 network simulator [17]. There are 100 mesh nodes randomly distributed on 2000x2000 deployment region. The transmission range of each radio is 250 meters. Our simulation time duration is 50 seconds. The detailed system parameters and simulation variables are listed in the Table 5.1. Because ACL is the metric for the link-layer of network, there are 400 single-hop Poisson flows in the network. The data rate of each flow is 1Mbps. Packet size is fixed at 1024 bytes. To avoid the specific topology, we run simulations on 30 randomly distributed topologies.

Table 5.1(a) NS-2 environment setting and simulation variables

Environment Parameters	
Waiting Time(WT)	200us
Fixed Staying Time (FST)	4ms
Switching Cycle	10ms
Transmission range	250m
MAC type	HMCMP with 802.11a interfaces(12 channels)
Queue size	50 packet/channel
Switching delay	100 SIFS
Simulation Variables	
Number of nodes	100 mesh nodes
Deployment region	2000m X 2000m
Traffic pattern	Single hop Poisson flow
Number of traffic flows	400 flows
Traffic rate	1Mbps
Simulation time	50 seconds

5.1 Correlation between throughput and ACL

According to Fig 5.1 and TABLE 5.2, the correlations show a strong relationship between ACL and the throughput of network. Even the number of radio per node and the number of available channels are varied, the results show that all correlation coefficients are below -0.894. This means that ACL is strongly negatively correlated with the throughput and ACL is an excellent cost metric for measuring the performance of an assignment.



(c)

Figure. 5.1: Throughput vs. ACL under 12 channels: (a)2 radios; (b)3 radios; (c)4 radios

Table 5.2 Correlation (R) between throughput and ACL

radios \ R \ channels	3 channels	5 channels	12 channels
2radio	-0.895	-0.894	-0.901
3radio	---	-0.954	-0.953
4radio	---	-0.936	-0.969

5.2 Algorithms comparison

In this section, we compare the throughput of different algorithms in hybrid WMNs. There are four algorithms. The descriptions are as following:

1. Hash: randomly assign role and channel for the radios with two constraints due to the properties of hybrid WMNs :

   (i)At least one fixed radio and at least one switchable radio per node.

   (ii)The fixed radios on a mesh node are on different channels.

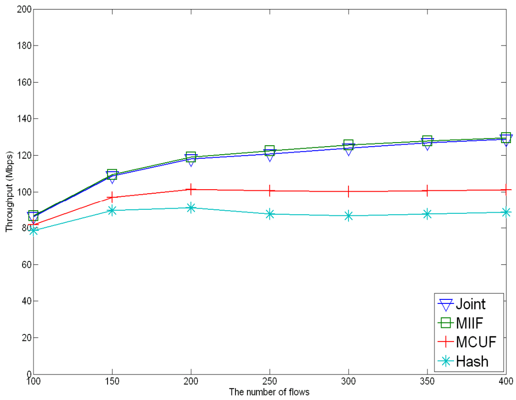
2. MRF+MCUF: role assignment is obtained from MRF, and channel assignment MCUF is based on [11]. Fixed radios will change its channel when the number of user of the channel in two-hop neighborhood is too large. For convenience, in our implemented MCUF algorithm the mesh nodes have the same number of chances to change the channel of its fixed radios as the times the nodes using MIIF to choose its best channel in centralized way.

3. MRF+MIIF: the two algorithms are designed for MAX *SL* and MIN *TIL* problem. We will get an integrated assignment through algorithm MRF and algorithm MIIF sequentially.

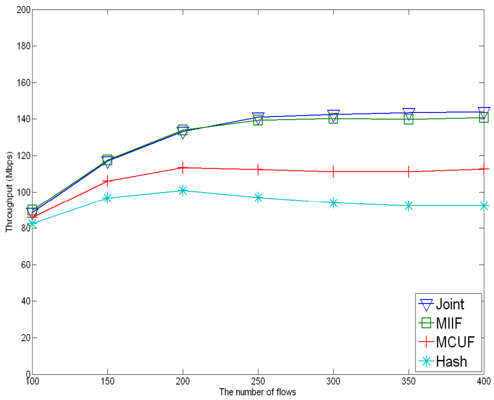
4. Joint: the Joint algorithm is designed for joint assignment problem. Through considering the role assignment and channel assignment simultaneously. We try to obtain the global optimum of *TCL* of network.

The first two algorithms are existing method for hybrid WMNs. But they are just designed for the convenience of implementation. The two algorithms do not consider the whole network situation and use limited information to determine the assignment. But our algorithms are based on the design and analysis of hybrid approach WMNs and target to different problems in [15]. In the comparison of algorithms, the number of flows is varied from 100 to 400 in order to present the change of traffic loading.

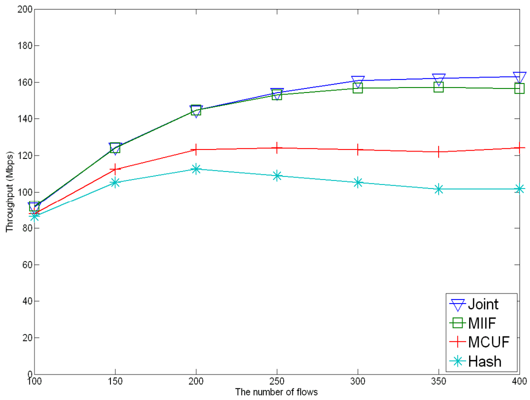
Fig. 5.2 shows the performance of the network under 2-radio mesh node environment. It is clear that both of our algorithms are much better than the remaining algorithms and the performance between MIIF and Joint algorithm are almost the same. MCUF is 22% better than Hash. The performances of our algorithms MIIF and Joint are 25% better than MCUF and 54% better than Hash. But in 2-radio environment due to the basic constraint in hybrid WMNs, at least one fixed radio and at least one switchable radio on a node, there is no necessary to choose the role of radio on the mesh nodes. So the algorithm MRF does not work here.



(a)



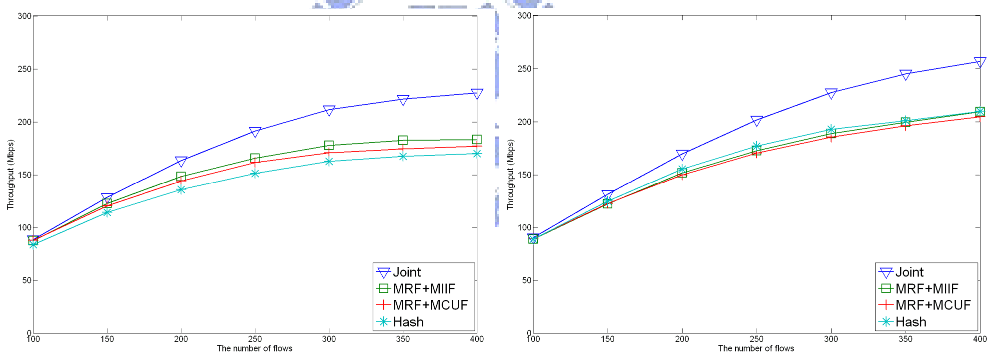
(b)



(c)

Fig. 5.2: Throughput comparison under 2 radios environment:
(a)3 channels; (b)5 channels; (c)12 channels

Fig. 5.3 represents the throughput with 12 available channels for 3-radio and 4-radio environment. Compare to the 2-radio environment result in Fig 5.2, the performances of Joint algorithm and MIIF algorithm in 3-radio and 4-radio environment the throughput have an obvious gap between Joint algorithm and MIIF algorithm. In 3-radio and 4-radio environment the performances of Joint are 22% and 24% better than MIIF. The performance of MIIF is 3% better than MCUF in 3-radio environment and almost the same as MCUF in 4-radio environment. This is because the role assignment generated from the MRF algorithm increases the number of switchable links and brings the constraint to MIIF algorithm for channel assignment. The above phenomenon presents that the integrated solution obtained from sequentially solving MAX *SL* and MIN *TIL* cannot achieve global optimum of MIN *TCL*. The joint algorithm simultaneously considers the role and channel assignment for MIN *TCL*. So the throughput of Joint algorithm is much better than other three scenarios.



(a) (b)

Figure. 5.3: Throughput comparison under 12 channels: (a)3 radios; (b)4 radios.

Chapter 6

Conclusion

In this thesis, we propose two assignment algorithms based on the theorem of [15]. We target different problems, such as MAX *SL*, MIN *TIL*, and MIN *TCL*, to design the algorithms. We have compared the performance of the proposed algorithms and other algorithms used in hybrid WMNs. The results show that our algorithm performs better without question. For the further research, we may develop the distributed algorithm for wide use.

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