# A Maximum Fair Bandwidth Approach for Channel Assignment in Wireless Mesh Networks

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*Abstract*—**Multi-Channel Multi-Radio WMNs are promising solutions for overcoming the limited capacity problem in multi-hop wireless networks. In these WMNs, each mesh router is equipped with multiple radios and each radio operates in a distinct frequency band. Channel assignment is the key issue that should be addressed in these networks. In this paper we propose a channel assignment scheme with the objective of maximizing per-flow bandwidth with fairness consideration to equalize the bandwidth assignment of flows. A novel problem formulation as multi-objective non-linear optimization problem is developed. We propose a heuristic randomized channel assignment algorithm, MFPFB, to obtain an approximate solution. The MFPFB assigns channels based on the interference level experienced by each flow, which is derived from the given traffic pattern and the proposed interference model, DWIG. For a given channel assignment, a simple algorithm allocates bandwidth for each flow. We used numerical and ns-2 simulations to compare our algorithm against others, investigate effect of routing mechanisms and to validate our model. The result indicates an improvement of up to 20% in the effectiveness of bandwidth assignment.**

***Keywords-Multi-Channel, Multi-Radio, Wireless Mesh Networks, Channel Assignment, Fairness.***

## I. Introduction

Wireless Mesh Networks (WMN) is the emerging technology for the next generation wireless networks [1]. In WMNs, nodes are comprised of mesh client and mesh router. Mesh routers don't have mobility in WMN. The mesh routers construct a static multi-hop wireless backbone, which is the distinguishing feature of WMNs.

Due to multi-hop topology of the backbone, the end-to-end throughput on a route drops as the number of hops increases. Interference between multiple nodes is the primary reason for the throughout degradation. Capacity of wireless networks and impact of interference on multi-hop wireless network are extensively investigated in literature [6], [9], [12]. It is shown that the single channel multi-hop wireless networks cannot be scaled up to large number of nodes. Multi-Channel Multi-Radio networking is one of the approaches to reduce the interference and hence improve the network throughput [19], [20]. In current wireless network standards, IEEE 802.11 a/b/g, there is an orthogonal subset of channels in each band, e.g. there are 12 orthogonal channels in IEEE 802.11a. The orthogonal channels can be used simultaneously (concurrent transmission without interference) to enhance the network throughput. In Multi-Radio WMNs, each mesh router is equipped with $R>1$ radios [2]. A pair of radios can communicate with each other if they are assigned to the same channel and are within the transmission range of each other.

The channel assignment is a key issue that should be addressed in Multi-Channel Multi-Radio networks. A channel assignment is a mapping between links and the channels. Minimizing the interference level is the overall objective in channel assignment. Each channel assignment algorithm works based on a specific interference model. Section II reviews some prevalent optimization objectives and interference models. The constraints in the channel assignment problem are as follows: (i) The number of available channels is limited, (ii) Network connectivity should be maintained, and (iii) The number of radios per-node is limited and is less than the number of the orthogonal channels. It is proved that different version of the channel assignment problem is *NP* hard [4], [17], [19], and due to the constraints, none of graph (vertex or edge) coloring algorithms can be used as a channel assignment algorithm directly [19].

In this paper, our goal is maximizing per-flow bandwidth with fairness consideration. The objective in the fairness model is equalizing bandwidth assignment of flows. It is assumed that, the network topology, the number of orthogonal channels, the number of radios per-node, and routing of each flow are given. We propose a distributed static channel assignment algorithm to maximize per-flow bandwidth while maintaining fairness in allocated bandwidths.

A few research papers studied fairness in WMNs, [11], [24]. These works assume that channel assignment is given and studied bandwidth allocation with the objective of maximizing the network throughput and enhancing fairness. In this paper, however, we address channel assignment and maximizing per-flow bandwidth fairness as join optimization problem. Besides, an extended version of the interference graph, the Directed Weighted Interference Graph (DWIG), is used to model the interference between links.

Remainder of this paper is organized as follows: Related works are discussed in Section II. This Section provides a classification of channel assignment algorithms and reviews the interference models. In Section III, our interference model and formulation of the Maximum Fair Per-Flow Bandwidth problem are presented. We propose our algorithm in Section IV. Numerical and simulation results are presented in Section V and Section VI concludes this paper.

## II. RELATED WORKS

Channel assignment in Multi-Channel Multi-Radio network has been extensively studied in recent years. Previous works can be classified according to the following criteria.

**Channel allocation duration:** Channel assignment can be (quasi)static, fast switching or hybrid [10]. In the static assignments, channels are assigned to radios for long time period or permanently [4], [7], [14], [17], [18], [19], and [22]. When the fast switching is used, the radio interfaces should switch between channels per-packet or per-flow [3], [21], [23]. In the hybrid methods, some interfaces are statically assigned and the rest of interfaces switch between channels [10]. Current MAC protocols and their implementation don't support the fast switching [10].

**Load dependency:** Channel assignment can be load aware or load unaware. In former algorithms, the traffic matrix is given [8], [19], [20], and [22]. But in latter algorithms [4], [7], [14], and [17] there is not any assumption about traffic matrix.

**Distributed/Centralized:** Most researchers focus on centralized algorithms [14], [17], [18], [19], some other proposes distributed algorithms [7], [20], [22].

**Objective function:** In [4], channel assignment is modeled as four different optimization problems: (i) Maximize one-hop capacity, (ii) Minimize maximum collision domain size, (iii) Minimize average collision domain size, and (iv) Minimize channel diversity. In addition to these graph theoretical objectives, other objective functions are used, such that maximizing the aggregate bandwidth [19], [22], maximizing the cross-section goodput [20], minimizing the maximum interference [14], minimizing the total interference [17], [25], dynamically minimizing WMN and co-located networks interference [18], minimizing the maximum link utilization[15] and maximizing the wireless spectrum utilization [7].

**Interference models:** Usual interference models are *Protocol* model and *Physical* model. The protocol model assumes interference to be an all-or-nothing phenomenon and the physical model considers the impact of interfering transmissions on the signal-to-noise ratio at receiver [6]. In link-centric models, interference range of both sender and receiver are considered [17]. The Amount of load on each link can also be accounted to compute the interference [19].

## III. PROBLEM FORMULATION

In this section we will formally define the optimization problem we are going to study. To model the interference and estimate the available bandwidth, we propose the DWIG. Clearly traffic source and destination are required for resource allocation. We decouple routing and channel assignment; hence, in addition to source and destination. We assume that routing of flows is given. In addition to the routing information, it is assumed that the physical topology of network, the number of orthogonal channels, the number of radios per-node, the transmission range $T$ , and the interference range $I$ are given as inputs.

### *A. Directed Weighted Interference Graph*

The WMN is modeled by undirected graph $G = (V, E)$, where $V$ is the set of $n$ vertices and $E$ is the set of $m$ edges. Each $a \in V$ corresponds to a node in WMN and $(a,b) \in E$ iff $d(a,b) \le T$. Where $d(a,b)$ is the distance between $a$ and $b$. It is assumed that the set of flows $F = \{\alpha_1, \alpha_2, ..., \alpha_q\}$ and routing of the flows are given, where $\alpha_k = (s_{\alpha_k}, d_{\alpha_k})$ and the $s_{\alpha_k}$ and $d_{\alpha_k}$ are the source and destination of $k^{th}$ flow respectively.

The assigned channel to a link is specified by the *link channel allocation vector*:

$$X_{ab} = [x_{ab,1}, x_{ab,2}, ..., x_{ab,K}]$$

$$x_{ab,k} = \begin{cases} 1, & \text{if channel } k \text{ is assigned to } (a,b) \\ 0, & \text{others} \end{cases} \quad (1)$$

Where $C$ is the set of channels and $K$ is the number of available channels, $K = |C|$.

Using the given routing information, we have path of each flow $\alpha$ : $p_\alpha = \{(s_\alpha, j_1)(j_1, j_2)...(j_l, d_\alpha)\}$ and the number of flows on each link $(a,b)$ : $f_{ab}$ .We use the routing information and *link-centric protocol model* to construct the Directed Weighted Interference Graph (DWIG). Link-centric interference model reflects on both sender and receiver, which is suitable model for 802.11 DFC operations when the RTS/CTS mechanism is enabled. For each link $(a,b)$ , the interference set $I_{ab}$ is defined as follows:

$$I_{ab} = \{(x,y) \in E \mid d(x,a) \le I \textbf{ or } d(x,b) \le I \textbf{ or } d(y,a) \le I \textbf{ or } d(y,b) \le I\} \quad (2)$$

Total interference from a link to its neighbors depends on the load of the link [19]. The load isn't known before bandwidth allocation. Therefore, we use the *number* of routed flows on a link as the load of the link. Obviously, if the number of flows on link $(a,b)$ and $(x,y)$ are different, imposed interference by link $(a,b)$ on $(x,y)$ isn't equal to interference imposed by $(x,y)$ on $(a,b)$. The Interference Graph model is generalized to account the load dependency and the asymmetric nature of interference. The DWIG is a directed weighted graph $G_I = (V_I, E_I)$. $V_I$ is the set of $m$ vertices and $E_I$ is the set of $o$ edges. Each $v_{ab} \in V_I$ corresponds to $(a,b) \in E$ . If two links $(a,b)$ and $(x,y)$ interfere with each other, $(a,b) \in I_{xy}$ and $(x,y) \in I_{ab}$ , there would be two directional edges $(v_{ab}, v_{xy}, f_{ab}) \in E_I$ and $(v_{xy}, v_{ab}, f_{xy}) \in E_I$ . Where $f_{ab}$ and $f_{xy}$ are the number of routed flows on links $(a,b)$ and $(x,y)$ respectively.

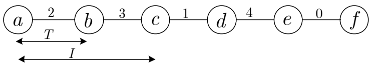


Figure 1. Sample chain topology. I = $2T$

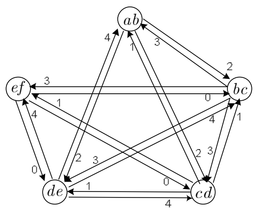


Figure 2. The DWIG of the topology in Fig. 1

Fig. 1 and Fig. 2 depict a sample network and the correspond DWIG. In Fig. 1, all links are assigned to the same channel and the label of each links is the number of flows on the link. In Fig. 2, the label of each edge is the link weight.

### *B. Problem Formulatoin*

In the following, we will use these definitions: *Neighbors of link* $(a,b)$:

$$N_{ab} = \{v_{xy} \in V_I \mid (v_{xy}, v_{ab}, f_{xy}) \in E_I\} \tag{3}$$

and *Interference number of flow* $\alpha$ *on link* $(a,b)$:

$$I_{ab,\alpha} = \sum_{\{xy \in N_{ab} \mid X_{xy} = X_{ab}\}} f_{xy} + f_{ab} \tag{4}$$

In this paper, maximizing fair per-flow bandwidth is the objective of channel assignment. Obviously the end-to-end bandwidth $b_\alpha$ depends on available bandwidth for the flow on its path as follows:

$$b_\alpha = \min_{(a,b) \in p_\alpha} b_{ab,\alpha} \tag{5}$$

Where $b_{ab,\alpha}$ is the normalized available bandwidth for the flow $\alpha$ on link $(a,b)$. Using $I_{ab,\alpha}$, $b_{ab,\alpha}$ is *estimated* as

$$b_{ab,\alpha} = \frac{1}{I_{ab,\alpha}} \tag{6}$$

Bandwidths of all flows are summarized in the vector $B = [b_{\alpha_1}, ..., b_{\alpha_q}]$.

Fairness is the second aspect of our channel assignment. Allocating *equal* bandwidth for all flows is the objective of the fairness model. Hence, we attempt maximizing $b_{\alpha_i}$ while minimizing the variation between every $b_{\alpha_i}$ and $b_{\alpha_j}$. The Standard Deviation of vector $B$, $SD(B)$, is used to measure the *fairness quality*. Lower $SD(B)$ means more fairness and vice versa.

Network connectivity and the radio constraints should also be maintained in channel assignment. Our channel assignment is a *topology preserving* scheme. To preserve the topology, one channel should be assigned to each link. If $\bar{I}$ denotes a $K \times 1$ vector with all entries equal 1, topology is preserved iff

$$X_{ab}\, \bar{I} = 1 \qquad \forall (a,b) \in E \tag{7}$$

To derive the radio constraint, we use the *node channel allocation vector*, which is defined as

$$Y_a = [y_{a,1}, y_{a,2}, ..., y_{a,K}]$$

$$y_{a,k} = \begin{cases} 1, & \sum_{(a,b) \in E} X_{ab}\, \bar{e_k} \geq 1 \\ 0, & \text{others} \end{cases} \tag{8}$$

Where $\bar{e_k}$ denotes a vector $K \times 1$ with $k^{th}$ entry equals 1 and remain entries equal 0. $y_{a,k} = 1$ means that the channel $k$ is assigned to at least one of the links of the node $a$.

Putting (5), (6), (7), and (8) altogether, the **Maximum Fair Per-Flow Bandwidth** problem is formally described as:

$$\begin{aligned} &\text{Objective: } \textbf{Maximize}\, B \text{ while } \textbf{Minimize}\, SD(B) \\ &\text{s.t.} \\ &X_{ab}\, \bar{I} = 1 \qquad \forall (a,b) \in E \\ &Y_a\, \bar{I} \leq R_a \qquad \forall a \in V \end{aligned} \tag{9}$$

Where $R_a$ denotes the number of the radios of the node $a$. Last equation in (9) satisfies the radio constraint. The formulation (9) is a multi-objective non-linear mixed-integer optimization problem. It is known that it is *NP* problem. Therefore, achieving optimal solution for MFPFB is not straightforward. In next section, a heuristic randomized greedy algorithm will be proposed to find an approximate solution.

## IV. PROPOSED ALGORITHM

To maximize $b_\alpha$, we should maximize *bottleneck bandwidth* ($\min_{(a,b) \in p_\alpha} b_{ab,\alpha}$). However, the bottleneck bandwidth of each flow cannot be determined before assigning channels. Therefore, we try to maximize $b_{ab,\alpha}\ \forall (a,b) \in p_\alpha, \forall \alpha \in F$. Due to (6), we should minimize $I_{ab,\alpha}\ \forall (a,b) \in p_\alpha, \forall \alpha \in F$. According to (4), channel assignment should assign channels in such way that the $\sum_{\{v_{xy} \in N_{ab} \mid X_{xy} = X_{ab}\}} f_{xy}$ is minimized.

(10) defines parameters of the proposed algorithm. The $\varphi_{ab}^{X_{ab}}$ denotes the imposed interference level on flows on link $(a,b)$ by the flows on other links that have the same assigned channel. The $\phi_{ab}^{X_{ab}}$ indicates the interference level on the most interfered link in the $N_{ab}$ for given allocation vector $X_{ab}$.

$$\begin{aligned} \varphi_{ab}^{X_{ab}} &= f_{ab} \sum_{\{v_{xy} \in N_{ab} \mid X_{xy} = X_{ab}\}} f_{xy} \\ \phi_{ab}^{X_{ab}} &= \max(\varphi_{ab}^{k}, \max_{v_{xy} \in N_{ab}} (\varphi_{xy}^{X_{xy}})) \\ \gamma_{ab}^{X_{ab}} &= \frac{f_{ab}}{\sum_{\{v_{xy} \in N_{ab} \mid X_{xy} = X_{ab}\}} f_{xy}} \\ \Gamma_{ab}^{X_{ab}} &= \gamma_{ab}^{X_{ab}} + \sum_{v_{xy} \in N_{ab}} \gamma_{xy}^{X_{xy}} \end{aligned} \tag{10}$$

The $\gamma_{ab}^{X_{ab}}$ specifies available bandwidth on link $(a,b)$, when channel allocation vector $X_{ab}$ is assigned to the link.

$\Gamma_{ab}^{X_{ab}}$ is the total available bandwidth in the $N_{ab}$ .To prevent *network connectivity* or *ripple* problem [5], [15], in proposed algorithm, as in [17], an initial channel is assigned to all links. The assigned channels are subsequently modified according to our optimization criteria while maintaining the radio constraint. The approach provides necessary guarantees that one cannel is assigned to each link.

At each round of channel assignment, we change channel of the most interfered link, it provides maximum reduction in the $\phi_{ab}^{X_{ab}}$ . If we cannot reduce $\phi_{ab}^{X_{ab}}$ , we improve available bandwidth while maintaining maximum interference by changing the channel that provides maximum increment in the $\Gamma_{ab}^{X_{ab}}$ . If it isn't possible too, the assigned channel does not change. Because selecting the best channel for each link $(a,b)$ depends on assigned channels to other links in the $N_{ab}$ , which may be changed later, the MFPFB algorithm rescans edges multiple times. Our simulations show that rescanning links at most $K$ times is sufficient to ensure that no future improvement is possible. In each round, links are selected in random manner to offer equal priority for all links. The MFPFB channel assignment is listed in Fig. 3. The **Available Channels** $(a,b)$ in MFPFB finds a set of channels which can be assigned to the link $(a,b)$ , while maintaining the radio constraint. Fig. 4 depicts the algorithm. After channel assignment is done, the **Allocate Bandwidth** algorithm indicates the feasible bandwidth for each flow according to the (4), (5) and (6). As mentioned, the obtained bandwidth is not max-min fair, but we compare its effectiveness against ns-2 simulations in section V. The algorithm is depicted in Fig. 5, where the $C_{one-hop}$ is the one-hop-capacity.

MFPFB scans each link $K$ times and in each scan, at most $K$ channels are available for the link. Total computing per-channel for each $(a,b)$ depends on $|N_{ab}|$ . It is known that the average node degree increases almost linearly with the number of nodes [13], therefore $|N_{ab}| = O(n)$ . Putting altogether, the complexity of MFPFB is $O(K^2 mn)$ .

It should be noted that only local information are used to select the best channel for links. Therefore, while we presented a centralized algorithm in Fig. 3, the MFPFB algorithm can run completely as a distributed algorithm. The extra considerations should be attended in distributed version are: (i) Which node is responsible to change the channel of a link? This issue can be solved simply using a unique ID for each node. For each link, a node with lower ID is responsible to change the channel. (ii) Prevent changing channels of multiple links in an interference region simultaneously (to avoid inconsistency in the information that used to select the best channel). To do this, each node informs all other nodes in its interference range that it wants to change channel of a link, `change_channel_req`. Other nodes in interference range confirm the request, `confirm_change_req`, which also contains required information (assigned channel to links and the number of flows on each link). After receiving the `confirm_change_req`, the node selects the best channel and grants to other nodes to change channels of their links by `change_channel_done`.

**ALGORITHM:** MFPFB Channel Assignment

**Input:** $G = (V,E), G_I = (V_I, E_I), f_{ab}\ \forall (a,b) \in E$
$C = \{0, 1, ..., K\}$

**Output:** $X_{ab}\ \forall (a,b) \in E$

$X_{ab} = [1, 0, ..., 0]\ \forall (a,b) \in E$
**for** $k$ **from** $1$ **to** $K$ **do**
  **Randomize** $E$
  **for** $\forall (a,b) \in E$ **do**
    $A$ = Available-Channles $(a,b)$
    **for** $\forall X_{ab}^i \in A$ **do**
      $\Delta_\phi^{X_{ab}^i} = \phi_{ab}^{X_{ab}} - \phi_{ab}^{X_{ab}^i}$
      $\Delta_\Gamma^{X_{ab}^i} = \Gamma_{ab}^{X_{ab}^i} - \Gamma_{ab}^{X_{ab}}$
    **If** $\max_{X_{ab}^i}(\Delta_\phi^{X_{ab}^i}) > 0$
      $X_{ab}^j = \arg\max_{X_{ab}^i}(\Delta_\phi^{X_{ab}^i})$
    **else If** $\max_{X_{ab}^i}(\Delta_\phi^{X_{ab}^i}) = 0$ **and** $\max_{X_{ab}^i}(\Delta_\Gamma^{X_{ab}^i}) > 0$
      $X_{ab}^j = \arg\max_{X_{ab}^i}(\Delta_\Gamma^{X_{ab}^i})$
    **Change-Channel** $(a, b, X_{ab}^j)$

Figure 3. MFPFB Channel Assignment

**ALGORITHM:** Available Channels

**Input:** $(a,b) \in E$

**Output:** $A = \{X_{ab}^1, X_{ab}^2, ..., X_{ab}^l\}$

**if** $Y_a \bar{I} < R_a$ **and** $Y_b \bar{I} < R_b$
  $A$ = all possible $X_{ab}$
**else if** $Y_a \bar{I} = R_a$ **and** $Y_b \bar{I} < R_b$
  $A = \{X_{az} \mid (a,z) \in E\}$
**else if** $Y_a \bar{I} < R_a$ **and** $Y_b \bar{I} = R_b$
  $A = \{X_{bz} \mid (b,z) \in E\}$
**else if** $Y_a \bar{I} = R_a$ **and** $Y_b \bar{I} = R_b$
  $A = \{X_{az} \mid (a,z) \in E\} \cap \{X_{bz} \mid (b,z) \in E\}$

Figure 4. Available Channels Algorithm

**ALGORITHM:** Allocate Bandwidth

**Input:** $F,\ p_\alpha\ \forall \alpha \in F,\ X_{ab}\ \forall (a,b) \in E,$
$f_{ab}\ \forall (a,b) \in E,\ C_{one-hop}$

**Output:** $b_\alpha\ \forall \alpha \in F$

**for** $\forall (a,b) \in E$ **do**
  $I_{ab,\alpha} = \sum_{\{xy \in N_{ab} \mid X_{xy} = X_{ab}\}} f_{xy} + f_{ab}$
**for** $\forall \alpha \in F$ **do**
  $b_\alpha = \min_{(a,b) \in p_\alpha} \left(\frac{C_{one-hop}}{I_{ab,\alpha}}\right)$

Figure 5. Allocate Bandwidth Algorithm

## V. Results

In this section, numerical and simulation results of MFPFB are presented. Performance of MFPFB is compared against the Greedy [17] and the Random [22] algorithms. The Greedy minimizes the total network interference. In [22], it is shown that the Random assignment achieves fairly high network throughput, but fails to maintain network connectivity. We therefore repeat the Random channel assignment until a connected graph is reached. To evaluate the algorithms, following parameters are measured:

- Average per-flow bandwidth, $\bar{b} = (\sum_{\alpha \in F} b_\alpha) / \mid F \mid$. This parameter should be maximized.
- Standard deviation of allocated flows, $SD(B)$. This parameter is minimized to achieve the fairness.
- Effectiveness of algorithm, $1/CV(B) = \bar{b}/SD(B)$. Where $CV(B)$ denotes the coefficient of variation. Obviously this parameter should be maximized.

The MFPFB, Greedy and Random channel assignment are applied on a random network. The network is composed of 40 nodes which are randomly placed in $1000 \times 1000m^2$ area. The transmission range is 220m, the interference range is 350m and the one-hop-capacity is 3.55 Mbps.

### A. *Effect of Channel Assignment Algorithm*

Fig. 6 and Fig. 7 depict $\bar{b}$ and $1/CV(B)$, for various number of flows. After run of each channel assignment algorithm, per-flow bandwidths are allocated by the **Allocate Bandwidth**. For each number of flows, 10 different random traffic patterns are generated and the results in the figures are average of the 10 different patterns. The *Minimum Hop Count* routing is used in MFPFB algorithm. Fig. 6 depicts that MFPFB allocates more average bandwidth, especially when there are few flows in the network. As the number of flows increases, difference between achievable bandwidth by MFPFB and Greedy reduces. When there are many flows in the network, the network is saturated. It is shown that there is little difference between saturated throughput of the Greedy and an analytical bounds obtained by SDP [17]. Thus, in this case, MFPFB cannot do better than the Greedy.

In addition to more average bandwidth, MFPFB achieves lower *SD(B),* which leads to better effectiveness. The effectiveness of different algorithms is shown in Fig. 7. It depicts that the MFPFB enhances effectiveness while the Random and the Greedy have comparable performance. The Greedy algorithm attempts maximize the *aggregated* bandwidth and not *per-flow* bandwidth. The Random algorithm, distributes interference almost uniformly between links that leads to less variation in achievable per-flow bandwidth. But it cannot improve the available bandwidth, which Fig. 6 depicts that. The MFPFB uses traffic pattern and distributes interference between links in such way that minimize the variation of bandwidth while maximizing the amount of bandwidth.

### B. *Effect of Routing Algorithm*

As mentioned, according to (4) the $I_{ab,\alpha}$ and consequently per-flow bandwidth depends on $f_{ab}$, which is determined by routing. In addition to $f_{ab}$, routing influences the inter-flow and intra-flow interference [25]. If a routing algorithm selects long hop path for a flow instead of congested short path, the $\max(f_{ab})$ will be minimized but the longer path causes that the flow interferes with many other flows and therefore inter- and intra-flow interference to growth.

We compare the Min Hop Count (MHC), the Shortest Widest Path (SWP) and the Widest Shortest Path (WSP). Fig. 8 and Fig. 9 depict average bandwidth and *SD(B)* for different algorithms respect to various number of flows. Fig. 8 and Fig. 9 indicate that the MHC and WSP are the two extreme cases. MHC does not reflect on the current number of flows in the path selection for new flow, and always select the shortest path. WSP tries to spread flows in network to avoid congestion on some links. These two different strategies show their effects on the average bandwidth and the standard deviation. WSP provides less standard deviation, on the other hand, the path spreading increases the intra- and inter- flow interference and leads to less average bandwidth. But MHC provides more average and more standard deviation. SWP is an intermediate strategy. It provides average bandwidth more than WSP while less standard deviation than MHC.

### C. *Model Validation*

In this subsection, we evaluate our model using ns-2 simulation. In this paper we use the protocol interference model, generate the DWIG, assign channels and give out bandwidth according to the **Allocate Bandwidth** algorithm. The real networks are more complicated; interference model is the physical model and per-flow bandwidth may not exactly obey the (6).

To validate our model, we measure $\frac{\text{Drop Rate}}{\text{Aggregate Throughput}}$, respect to various per-flow offered load. The per-flow offered load is scaled by the obtained bandwidth from the **Allocate Bandwidth**. Given a channel assignment, we used the **Allocate Bandwidth** algorithm to compute the $b_\alpha$ for each flow. Then different scale of the $b_\alpha$ was used as offered load in ns-2 simulation and the drop rate and the aggregate throughput were measured. Fig. 10 depicts that when there are 10 flows in network, per-flow offered load can be scaled up to $1.1b_\alpha$ while the $\frac{\text{Drop Rate}}{\text{Aggregate Throughput}}$ is less than 0.05. But in 40 flows case, offered load should be scaled down to $0.85b_\alpha$ to maintain $\frac{\text{Drop Rate}}{\text{Aggregate Throughput}}$ less then 0.05.

Fig. 10 depicts that our model is almost accurate model, especially when the number of flows is less than the number of nodes. But when network is crowded and any node simultaneously acts as source and destination of some flows, the obtained $b_\alpha$ should be considered as *unfeasible* upper bound. The inaccuracy is related to operation of DCF; previous studies [12], [16] showed that in heavy loaded networks, DCF operation does not follow the simple model such as the (6).

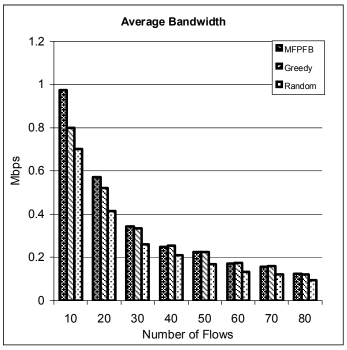


Figure 6. Average bandwidth for different channel assignments

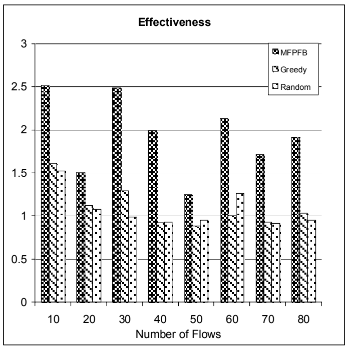


Figure 7. Effectiveness of channel assignment algorithms

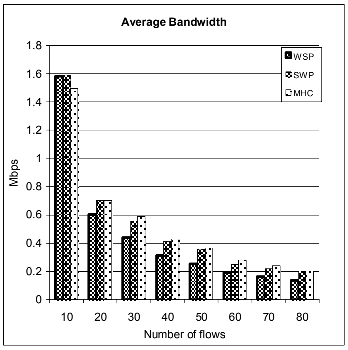


Figure 8.Average bandwidth using different routing algorithms and MFPFB

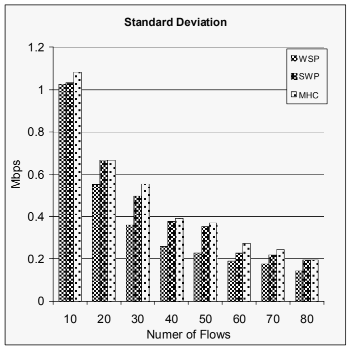


Figure 9. Standard deviation using different routings and MFPFB

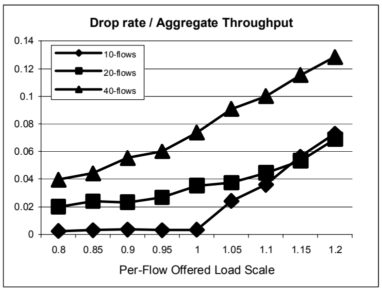


Figure 10. Loss rate using different per-flow offered load scale

## VI. CONCLUSION

In this paper, for first time, we formulated per-flow maximum fair channel assignment problem in WMNs. The fairness is measured by standard deviation of the allocated per-flow bandwidths. Based on proposed interference graph, Directed Weighted Interference Graph, it was shown that the maximum achievable per-flow bandwidth depends on the number of routed flows on each link and the number of interfering flows, which are routed in the interference range of that link. The former is specified by routing algorithm while channel assignment can control the latter. We presented the NLIP form of the Maximum Fair Per-Flow Bandwidth problem, a randomized greedy algorithm (MFPFB channel assignment) and simple bandwidth allocation algorithm. Using numerical and simulation results, we validated the proposed algorithm, compared it against others algorithms and investigated the impact of routing algorithm.

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