On the Channel Usability of Wireless Mesh Networks –When Stability Plays With You

Abstract— **In distributed wireless mesh networks, highly reliable channels are typically preferred and thus suffer from heavy contentions; on the other hand, unreliable channels are often discarded, leading to bandwidth waste. Indeed, each node, in contributing to overall network performance, should balance between utilization on reliable channels and unreliable channels. Stability plays an important role, either on each node or the whole network. We propose a distributed Multi-phase Maximum Weighted Matching algorithm, making use of both reliable and un-reliable channels. We prove that the algorithm will achieve maximized overall network throughput with relatively high stability in a distributed manner. We also apply channel bundles to effectively improve stability in the network, and the problem proves to be $\mathcal{NP}$-hard. The approximate ratio and complexity of the algorithm are also analyzed in a structural manner. The time complexity is $O(\triangle^3+(\log^* n)^2)$, and overhead complexity is $O(\triangle\times(\triangle+n)+n^\alpha+\log n)$, with $\triangle$ denoting maximum number of node degree in a n nodes network. Simulation results show that p-stable design effectively improves network stability, especially upon the existence of large number of unreliable channels.**

I. Introduction

The emergence of wireless mesh network (WMN) proves to be effective in providing last-mile Internet access ability for mobile devices. Wireless channels, however, depend largely on radio propagation which are sensitive with magnetic environments, terrestrial characters, and even weather conditions. Communication quality in WMN varies among roaming routers from time to time [7] [29]. Differing cellular networks, WMN usually works in a distributed manner, where each node makes decision by itself. As illustrated in Fig. 1, a WMN is deployed with multiple channels and multiple radios (*MCMR*) equipped on each node. Previous works [7] [**?**] [21] have shown that, in wireless network, reliability varies on different wireless channels as well as different radio links. With moderate channel coordination among nodes, reliability of end-to-end communication [?], and network throughput could improve for both multi-hop network [21] and infrastructure based networks [7]. Many efforts have been made in maintaining a stable and reliable network communication paradigm. For example, L. Tassiulas and A. Ephremides [23] [24] investigate the finite queue model, aiming at keeping the system queue size in a stable state with stochastic packet arriving process.

Considering the reliability between wireless channels, a receiver-side threshold is usually employed in evaluating the probability on correct packet reception. As shown in right part of Fig. 1, according to the packet receiving principle in wireless communication [28], channels with reliability lower than threshold should be prohibited from transmitting packets.

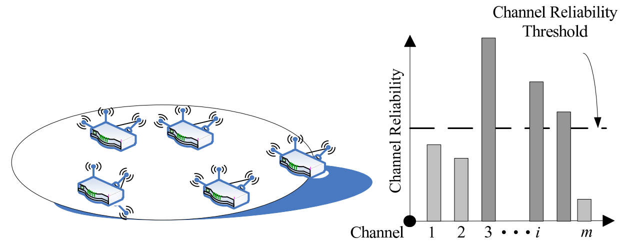

Fig. 1. Distributed Multichannel Communication Models

In network scenarios with much noise or severe interferences, the number of admitted transmission channels turns to be accordingly small, degrading overall throughput. In [?], S. Jain. *et al*, have proposed an optimal traffic allocation method with unreliable paths, while no efficient algorithm on optimal utilization among channels exists, especially in terms of the entire network.

Highly reliable channels are preferred by each node, which often leads to severe congestion and contention due to simultaneous selections on same channels. Considering the right part of Fig. 1, it is actually a waste if we simply discard channels with low reliability unconditionally, instead we should make use of them. With sufficient number of channels bundled, the transmission reliability would be increased right above the threshold. For example, given a channel i, if the probabilistic based reliability p_i is lower than threshold, that is $p_i < p_{thre}$, we can bundle it with other poor channels together, and then let them transmit the same packet so as to increase overall reliability. We calculate the bundle probability that, $P_B = 1 - \prod_{i\in U}(1-p_i)$, where as cardinality of channel set U goes to infinity, that is $\|U\| \to \infty$, and accordingly, the bundling reliability $P_B \to 1$.

G. Sharma [21] *et al.*, unfortunately, have proved that, an optimal interference-free coordination in wireless network with RTS/CTS interference model is $\mathcal{NP}$-hard. We thus need a distributed heuristic which avoids contention on high reliability channels as well as organizing low reliable channels effectively. The major challenge of such a design is that we typically assume channel reliability is a static measurable parameter. Actually such a dynamic reliability parameter varies and changes depending on other nodes in the network. Indeed, in a full distributed network, "*what you see locally is NOT what you get*". As shown in Fig. 2, channel C_1 is a highly reliable channel ($p(C_1) = 0.9$), while C_2 is low reliability channel ($p(C_2) = 0.3$). However, effective bandwidth of channel C_1

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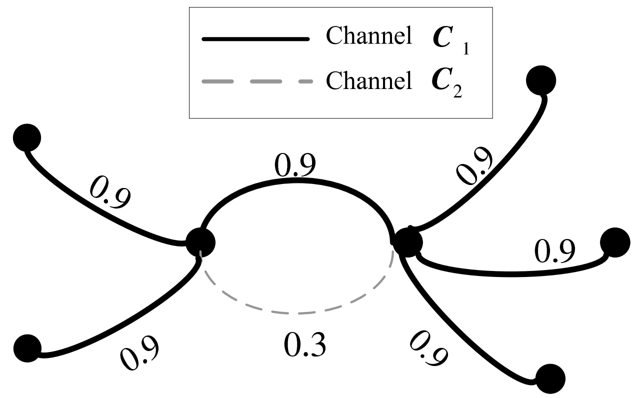

Fig. 2. Illustration on high reliability channel congestion

will be shared by five links. Since these five links are in the contention zone, transmission on any link would interference that of others, and a fair and interference-free schedule is needed. In this case, C_2 should be favored instead of C_1, because transmission opportunity on channel C_2 is five times to that of channel C_1, and accordingly, effective bandwidth can be $B_w \cdot 0.3 > B_w \cdot (0.9/5)$, as B_w denotes link bandwidth if channel is error-free. There should be a balanced utilization among high reliable and low reliable channels. As unilateral utilization on any channel set, reliable or unreliable, would degrade overall network performance, a stable point exists if the usability of wireless channels in network is maximized. In *MCMR* WMN, when stability plays with each node, there should be an algorithm to explore a "stable point vector" in network, so that each node would transmit at its stable point rate respectively between different level of reliable channels.

The main contributions of this paper are listed as follows:

1) Different from methods that simply drop the channels below the acceptable threshold, we propose a bundle transmission model, making use of both reliable and unreliable ones. We show that to find an optimal solution is $\mathcal{NP}$-hard. A heuristic algorithm is then introduced to solve this problem, where the channels with low reliability are effectively used.
2) Specifically, we propose a channel assignment algorithm based on maximum weighted matching problem and a scheduling algorithm based on coloring problem. We prove that, if maximum weighted matching (MWM) and coloring algorithms will achieve an optimal result with value $\|\mathcal{M}^*\|$ and $\|\mathcal{S}^*\|$, the overall network stability is maximized.
3) Our p-stable algorithm is distributed, which is important to WMN. We conduct analysis and simulation to evaluate the correctness and effectiveness of our proposed scheme.

To the best of our knowledge, this work is the first attempt in achieving the maximized stability in a *MCMR* WMN. Rest of this paper is organized as follows. In section II, we present the related work of throughput optimization and network stability issues. In section III, we present *MCMR* WMN model with a probabilistic reliability on wireless interfaces and channels. In section IV, we form the stability maximization problem into a multi-phase maximum weighted matching problem. In section V, an understanding of the stability issue is made according to different type of transmitting models. In section VI, we propose a distributed algorithm in maximizing stability in network. In section VII, algorithm analysis on time complexity and network message overhead are discussed. In section VIII, we evaluate our p-stable algorithm. Conclusions and future research works are presented in section IX.

II. Related Work

An efficient scheduling algorithm based on synchronized TDMA network is introduced in [1], under the context of single-channel wireless networks, where coloring algorithm is applied to interference-free network schedule. V. Li [27] [26] proposed efficient scheduling algorithm in wireless network, reducing both network interference and congestion. Different from research works on globally throughput maximization, a max-min fairness based capacity calculation algorithm is proposed in terms of collision domains' throughput and computation overhead [12]. Capacity upper bound and lower bound for *MCMR* WMN are estimated according to the static and dynamic link channel assignment [4]. Seminar works mentioned above are concerning on single-channel scheduling, routing, and the capacity region estimation respectively, they however suffer from unilateral considerations on one or more aspects in network separately. Joint considerations on those aspects are also studied by M. Alicherry *et al.* [5], who propose a joint channel assignment and routing optimization algorithms. Unlike our work, it focuses on the infrastructure based mesh networks, without providing a distributed algorithm. In [10] [11], Kyasanur and Vaidya present the capacity of multi-channel wireless networks scaling with the number of orthogonal channels. Since the radio interface and channels are not available as theoretical results have assumed, it would not be applicable to *MCMR* WMN with a limited number of available channels.

Most of the research works on network throughput maximization approaches are based on ideal error-free wireless channels, where optimum value is rather a theoretical value instead of practical utilization in networks. In real WMN deployments, communication quality varies with spatial and temporal conditions. In many cases, reliable channels suffer from heavy contention, while low reliability are often dropped without being utilized. A distributed algorithm is proposed in [9] for spectrum allocation, power control, routing, and congestion control in wireless networks. Given a feasible spectrum allocation, the algorithm can effectively control the transmission power. It is also assumed in [9] that the spectrum can be divided into sufficient number of sub-channels. Those designs are different to our models in the sense that we do not assume every mesh router adopts optimal power transmission protocol and has sufficient channels. An interference-aware channel assignment is also proposed in mesh routers and co-located wireless networks [6], called BFS-CA, which is a dynamic, interference-aware channel assignment algorithm. Scheduling of wireless data in transmitting queue is also considered in multi-carrier wireless data systems [7]. Since different carriers have separate channel rates, a scheduling algorithm is needed in order to enhance the performance of WiMax access point. Unlike ours, they only consider the one-hop scenario, and it is a centralized data scheduling algorithm. Ours is a similar work to [1], we are applying algorithm in a *MCMR* WMN, where channel assignment and scheduling are jointly considered instead of scheduling algorithm only in single channel wireless network [1].

A. Brzezinski *et al.* [19], propose a distributed throughput maximization algorithm in wireless mesh networks based on network decomposition. They also study the stable zone in achieving a 100% throughput, which relies on the queuing size of each node. G. Sharma, N. B. Shroff, *et al.* [21] map the wireless interference constraints on the utility maximization. In their work [21], the authors propose a Maximum Weighted K-Valid Matching problems (MWKVMP) for scheduling on interference-free transmissions in multi-hop wireless systems, and the complexity of this problem is evaluated. However, there is no scheduling algorithm introduced in [21]. J. H. Hoepman *et al.* [22], propose a sequential greedy algorithm, in which at most a factor 2 away from the optimum result. In [22], a tree graph is considered in solving maximum matching problem, where coloring algorithm by tree decomposition are combined in solving the matching problem. The general graph is not considered [22]. M. Wattenhofer and R. Wattenhofer [20] propose fast and distributed algorithms for matching in weighted trees and general weighted graphs, where the work suffers large amount of information overhead.

III. System Model

In this section, we build our system model in describing the stable channel assignment problem. We firstly introduce the multi-channel multi-interface system as a foundation for our proposed model. Secondly, we use the threshold model for transmission, which is fundamental to channel utilization model. Considering the threshold value on receiver side, introduce different transmission mode for reliability. Finally, we build the extended graph and present the interference constraints for network communications.

A. Multi-channel Multi-interface System

As heterogeneity widely exists in WMN [25], we assume that, the number of available interfaces on each router varies. For each mesh router v_i, the number of radio interfaces is $Q(v_i)$. And we denote $O(v_i, \vartheta_k)$ as the number of orthogonal channels employing the interface ϑ_k on node v_i. Also, the total number of orthogonal channels on node v_i can be denoted as the sum of radio channels for all wireless interfaces.

Orthogonal transmissions are achieved if and only if either of the two conditions is satisfied:

1) Two transmissions t_r^i and t_r^j are not using the same radio interfaces, which is denoted by $I(t_r^i) \neq I(t_r^j)$.
2) If $I(t_r^i) = I(t_r^j)$, then the orthogonal channels should be different, that is $OC(t_r^i) \neq OC(t_r^j)$

where $I(t_r^i)$ denotes the wireless interface of the transmission for node i and $OC(t_r^i)$ is orthogonal channel of the data transmission for node i. As mentioned above, interfaces and channels are labeled with number, the notion $a \neq b$ stands for different identity between a and b.

As the reliability varies between channels and interfaces, we denote $p_{ij}(\vartheta_k, \chi_r)$ as the reliability of link $l_{i,j}$, where ϑ_k and χ_r are the interface and channel used for transmission respectively. That is to say, we use the success rate of the data packet transmission for the reliable probability of link $l_{i,j}$.

In this model, we assume identical bandwidth between channels, where stability is a measurement of available network throughput, that is, the sum of channel usability can be achieved. Our system model can also be used in heterogeneous wireless environments, where bandwidth on different channels are not identical, where the bandwidth can be normalized combining with the successful transmission rate.

B. Threshold Model

In wireless communications, threshold values are important to successful data receptions. Threshold values however, due to the various transmission mode, are categorized into two types. The first type is single-channel oriented, where packets are transmitted on one channel, and the probability on correct receival should be kept above the threshold value. As shown in Fig. 3, at the receiver side, if the probability satisfies $p > p_{thre}$, the packets can be correctly received, where p_{thre} is the threshold value of a channel. If the channel reliability is below p_{thre}, the packets are simply dropped.

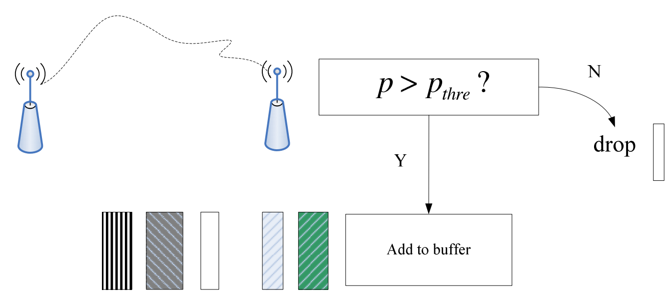

Fig. 3. Illustration on Single Channel Packet Receival

Another type of packet receival is multi-channel oriented, where packets are transmitted on multiple channels independently. As redundancy mechanism is applied, packets buffering at the receiver side can be error-prone if the redundancy factor $r = \frac{L_r}{L_o} > r_{thre}$, where r_{thre} is the redundancy threshold, L_r and L_o are the coded packet length and the original packet length respectively. The redundancy factor determines the redundancy degree, for example, if redundancy factor $r = 2$, it means that if at least 50% coded blocks are received, the messages can be decoded.

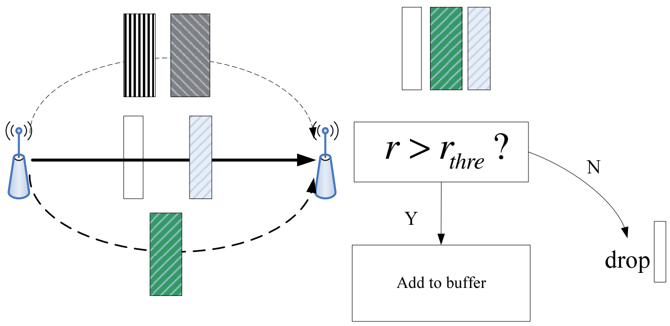

Fig. 4. Illustration on Multi-Channel Packet Receival

Algorithm p-stable Algorithm
1: Graph Conversion Process $(G) \rightarrow$ directed tree $\overrightarrow{\mathfrak{T}}$
2: Tree Decomposition $\rightarrow F_1, F_2, ...F_\triangle$
3: **while** $E \neq \emptyset$ OR $\nexists v_i, k, r$ that $C_{v_i}(k, r)$ is assigned **do**
4: Weighted Maximum Matching Process on Decomposed Trees Set $(\mathcal{F}) \rightarrow \mathcal{S}^i$.
5: $i++$
6: **end while**

Fig. 5. p-stable algorithm pseudo-code

C. Network Model

We assume a set V of mesh routers deployed in the plane. Each node $v_i \in V$ is a mesh router in the network $G = \{V, E^T\}$. For a conventional single channel graph, given the edge set E, the link l_{ij} indicates that, node v_i and v_j can directly communicate with each other. In our network model, the extended edge set E^T is for multi-graph, where multiple edges might exist between nodes, and the edge between node v_i and v_j on channel χ_r of interface ϑ_k can be denoted as $l_{i,j}(\vartheta_k, \chi_r)$.

Interference models fall into three categories, which are protocol interference model (PrIM), fixed power protocol interferences model, and RTS/CTS model [1]. For easy understanding, we mainly use the RTS/CTS model, which is widely used in WMN. Indeed, this design is independent to interference model, and nothing restricts to the model we use for discussion. An easy extension to our selected interference models can be workable for other models. We will present this work in the following section.

IV. Distributed Algorithm

In this section, we make an introduction to the p-stable algorithm. Firstly we have an overview on the p-stable algorithm. Also, we present the distributed algorithm on MWM step by step. Finally, the bundling algorithm and the effects of tree construction are also introduced respectively. We first generate a directed tree T from the original graph G, in order to realize the distributed algorithm in matching which is based on tree structure. Since our input parameters are the original graph, we are partitioning network graph with consideration of the lost weight (probabilistic reliability of channels), that is why we use the network partition approach instead of tree decomposition approach. We will discuss this problem in the later subsection. Pseudo code of the algorithm is listed in Fig. 5. Since our algorithm is to achieve a maximized overall network stability, and bases on probabilistic model, we name our algorithm p-stable in showing these characteristics.

Our algorithm is based on the work of [16], with moderate modification in order to fully schedule all the edges in multi-graph $G = \langle V, E^T \rangle$ and multiple channels are shared effectively by edges in network with proper transmission schedule. Conversion process and tree decomposition algorithms are referred to similar works in [16] [20], which assume different ID should be assigned to each router. But in real network, especially WMN, it is very hard to make this kind of network management in highly dynamic network. Ours need not assign each node with different IDs. In order to void loop, modify the $\mathcal{N}(v)$ value with a moderately small factor ϵ, where $\epsilon \ll 1$. Our tree decomposition algorithm is based on the number of neighbors and give a ranking among them; so that, each induced link is assigned a candidate "color" in partition the tree into set of trees from F_1 to $F_\triangle$, where $\triangle$ is the maximum degree of nodes in network.

V. Performance Evaluation

We evaluate our p-stable algorithms by series of simulations on random network. Simulation program is written in C++ language, and the multi-channel multi-radio wireless communication is designed according to definitions on concurrent transmissions in section III. In our simulation works, nodes are uniformly placed in network with 10×10 unit region. On different radio interfaces, the transmission range is randomly selected from 0.8 to 1.2 unit, and there are totally five levels of transmission ranges, the step between different levels is set to 0.1 unit. Number of channels is ranges from 5 to 10, while the number of radio interfaces would uniformly range from 2 to 4. We vary the node number n in network, from 50 to 400. Channel reliability are uniformly distributed from low reliability to high reliability. In our simulations, we set the lower bound to 0.4, and upper bound to 0.99. The throughput values are computed in a steady state, i.e. they are derived after the distributed algorithms running in the simulated network have converged.

Simulation is done with two transmission modes: threshold based mode and non-threshold based mode. In threshold based modes, the threshold value should be set to different levels so as to see its effects on network performance. In our simulation work, we set threshold value to 0.5 and 0.7 respectively. We are aiming at evaluating metrics such as number of scheduling rounds, messages overhead, and network overall average network stability (throughput). According to the simulation results, it could be shown that, with the increasing number of nodes, scheduling rounds would increases in dealing with conflictions in network. Therefore, the messages overhead would increase also. Simulation results also show that, with the increasing threshold value, network performance would drop

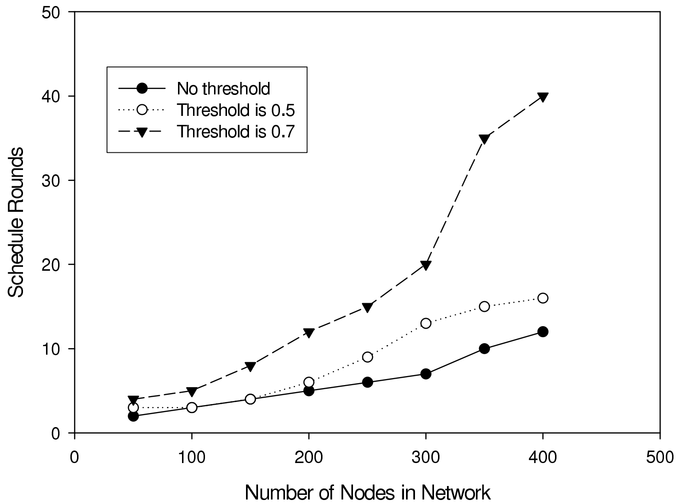

Fig. 6. number of nodes in network versus number of schedule rounds

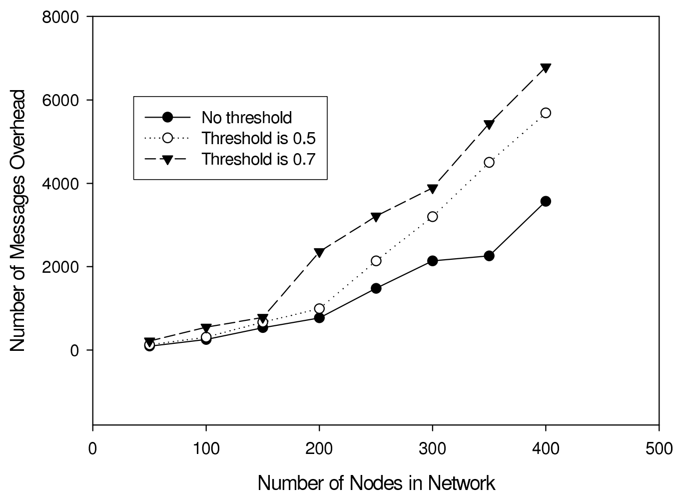

Fig. 7. number of nodes in network versus message overhead

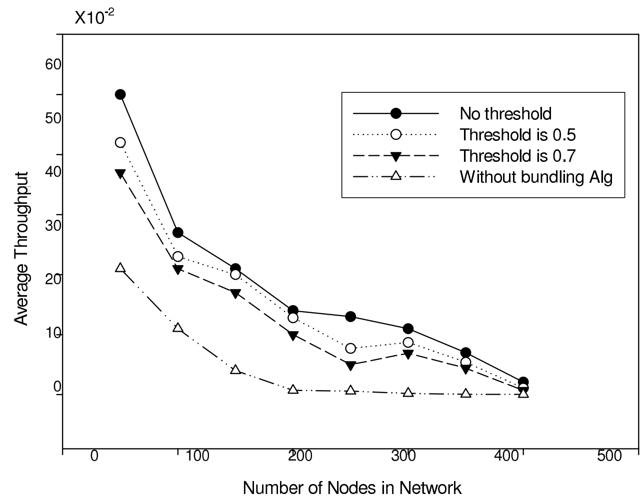

Fig. 8. number of nodes in network versus throughput

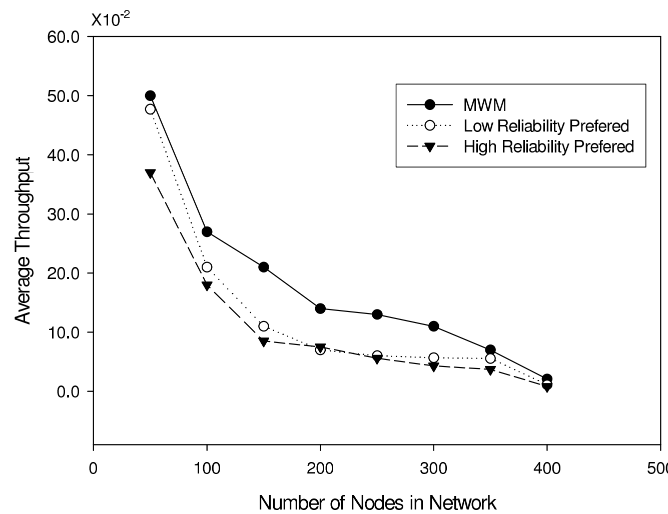

Fig. 9. number of nodes in network versus throughput on stable point respect

accordingly, where a fraction of channels with low reliability would be filtered out. Even with bundling methods, the bundle transmission can only improve the network throughput a constant factor as threshold increases linearly.

Although simulations have been done to prove the efficiency of p-stable algorithm, there are two extra works need to do. One is to illustrate the bundling efficiency; the other is to illustrate effects on high reliable congestions avoidance.

In the first simulation work, we compare two schemes on network reliability, one is the algorithm using proposed heuristic bundling algorithm and the other is not, simulation results in Fig. 8 have shown that algorithm with bundling method outperform that without bundling on average network throughput.

In order to illustrate the congestion avoidance effects, we need a modification on our simulation test, and a newly built method is needed to evaluate the performance. Considering the "stable point" character. As we know, if the MWM is achieved, any modification on channel assignment would degrade network performance, since our proposed MWM with the schedule scheme is a stable point vector for each node in network. Our simulation test works as follows: We firstly use our matching algorithm to get the optimized throughput, then based on the transmission schedule, we make modifications on some links. The modification scheme can be categorized into two types: One is to select some of the low reliability channels to avoid the contention on high reliability channels, which is denoted as "low reliability preferred". The other is to do the same process, and the only difference is to choose high reliability channels, which is characterized as "high reliability preferred". We do simulations based on both of the modification schemes, in order to prove that, our algorithm can approximately achieve the stable point vector, we intuitively accept high reliability channels with reliability p from 0.7 to 0.9, and the low reliability p is from 0.5 to 0.7. The number of links enduring modifications is also uniformly distributed from 10 to 100.

According to simulation results shown in Fig. 9, our p-stable algorithm outperforms "low reliability" and "high reliability" modifications on average network throughput. We also find that, in small network scale (< 200 nodes in network), "low reliability preferred" scheme outperform "high reliability preferred" scheme. The reason is that, as network is not densely deployed, coordination and schedule would be effective in case that some of nodes choose low reliability channels. Choosing some of the low reliability channels would also improve the usability of high reliability channels. While in densely deployed network, channels with different level of reliability are all contented seriously, coordination effects are limited in small scale, which leads to throughput reduction.

From Fig. 9, we can find that, there is no obvious gap between MWM and its modifications. We can explain this phenomenon as follows: On one hand, our algorithm is heuristic, which is not an optimal "stable point vector". On the other hand, reliability distribution on channels has low variance and topology affects overall performance seriously. We will make a further research on this problem in future work.

VI. Conclusions

Based on the observations in most of previous designs, highly reliable channels often suffer from heavy contentions, while unreliable channels are simply discarded. In this work, we study stability maximization in heterogeneous *MCMR* WMNs. We form the problem, prove its NP-hardness, and propose a distributed weighted maximum algorithm. The time complexity is $O(\triangle^3 + (\log^* n)^2)$, and overhead complexity is $O(\triangle \times (\triangle + n) + n^{\alpha} + \log n)$, the best among existing works to our knowledge. Simulation results prove the algorithm's efficiency and illustrate the stability achieved by the algorithm.

There are still number of challenging issues left for future study. We will further improve the reliability model, as well as conduct prototype implementations to explore better solutions. The recent papers on wireless measurements find out that, most wireless links have either very high reliability or very low reliability. We will make further research on this topic. For example, considering the spatial and temporal channel state dynamics, opportunistic routing techniques and network coding mechanisms can be employed in dealing with these difficulties.

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