A Distributed Channel Assignment for 802.11-based Multi-Radio Wireless Mesh Networks

Deepesh Man Shrestha
Graduate School of Information and Communication
Ajou University, Korea
Email: deepesh@ajou.ac.kr

Arun Ranjitkar
Graduate School of Information and Communication
Ajou University, Korea
Email: arun@ajou.ac.kr

Young-Bae Ko
Graduate School of Information and Communication
Ajou University, Korea
Email: youngko@ajou.ac.kr

***Abstract*—In this paper we propose a distributed channel assignment protocol (*DCAP*) for topology formation in the IEEE 802.11 based wireless mesh network. The non-overlapping channels are assigned to the network interfaces according to the simple heuristics (such as *degree* and *node-ID*) with the goals to enable connectivity and reduce interference in the network. Ns-2 simulation results are presented and compared with the solutions from integer linear programming (ILP) and the common channel assignment (CCA) algorithm. We measured the number of concurrent links, average throughput and the end-to-end latency. We showed that the DCAP produces optimally connected topology and performs better in all cases compared to CCA.**

I. Introduction

Wireless multi-hop mesh networks based on the IEEE 802.11s is different from the IEEE 802.11 WLAN. The traditional IEEE 802.11 WLAN is architecturally similar to the cellular networks. Access points (AP) like base stations are connected to the wired gateways for the services such as Internet, while they provide wireless access to client stations that are one hop away. In contrary, the current IEEE 802.11s draft [1] defines a multi-hop WLAN mesh of wireless routers (named *mesh points* or *MPs*) that form a wireless infrastructure backbone. For increasing the network capacity, nodes can be equipped with multiple interfaces to use extra channels. Moreover, MPs in such a WLAN mesh are expected to be self-configuring when forming the backbone topology.

The problem of channel selection in the WLAN mesh is known to be non-trivial with the nodes having multiple interfaces and channels [2]. The problem is similar to the well-known 'edge-coloring problem', which is NP-complete. Along with that, network partitions can be expected due to a channel mismatch among neighbors and co-channel interference might cause disruption in communication due to use of same channels. However, even if we find one optimum solution, it is not possible to fix the same channels throughout the lifetime of network because of potential changes in the topology. Due to the limitation of resources, channel assignment protocols themselves can cause a rippling effect [3] over the entire topology. For example, when a node assigns a specific channel to its own interface, its neighbors might be enforced to change their previously assigned channel to preserve connectivity. Propagation of such changes throughout the network that does not arrive at any converging point is called a ripple effect. Thus, a proper channel assignment algorithm is a key requirement to generate a self-configuring network topology of high performance in a distributed mesh networks.

We consider a static channel assignment for topology formation where the channel assigned to a particular radio interface is tuned for a significant time period. In general, such channel assignment strategies can be classified into traffic dependent and independent algorithms. Traffic dependent algorithms such as [4]–[6] use some predefined traffic profiles. [4] proposes centralized interference-aware topology control and QoS routing in the IEEE 802.11 based mesh networks. This algorithm produces k-connected network by assigning channels to minimize interference, upon which QoS routing is performed. [5] considers availability of traffic profiles at each node before assigning channels and suggests a hierarchical architecture having gateway node as a root of the tree. In [6], the distributed channel assignment algorithm jointly co-ordinate with the route selection based on the measured traffic information. However, availability of routing information and traffic profiles *a priori* are not always feasible due to a time varying traffic demand and a wide range of communication pattern [7].

The notion of traffic-independent static channel assignment for the topology formation in wireless mesh network is first proposed in [7]. They propose a centralized adaptive priority based channel assignment using algorithm similar to depth first search (DFS) and compare it with a common channel assignment (CCA) protocol. In the CCA protocol, the radio interfaces of each node is assigned with the same set of channels. For example, if the number of available interfaces in a node is two, all nodes are assigned channel 1 and 2. Clearly, CCA leads to the poor channel utilization when the number of interfaces per node is fewer than the number of channels. [8] proposes a channel assignment for topology formation with two radio access point. Each AP is assigned two channels: one for inter-cluster and another for the intra-cluster communication. Each intra-cluster nodes shall have

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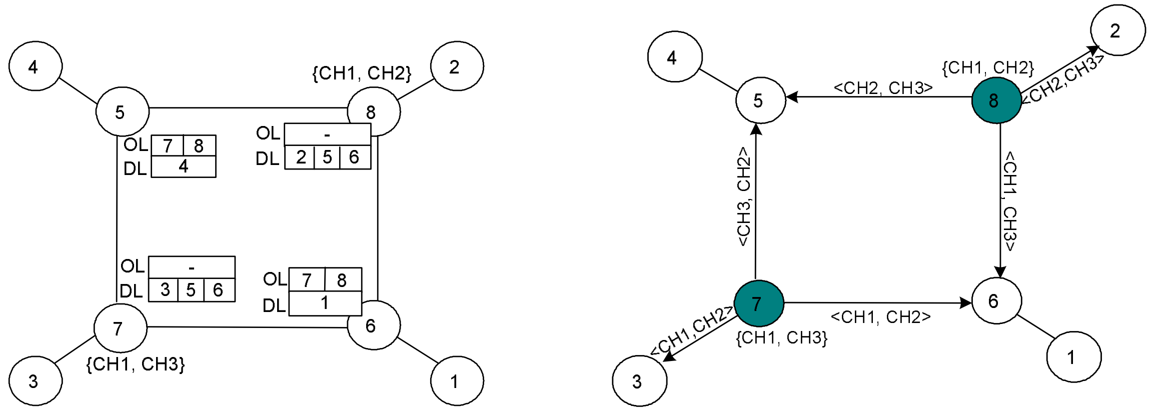


(a) Nodes with ordered list (OL) and dependent list (DL) values

(b) Seed Nodes 7 and 8 transmit priority channel list (PCL, shown in angle brackets) to neighbors

Fig. 1: Example network with 8 nodes having 2 interfaces each and 3 channels {CH1, CH2, CH3}

same channel to enable communication with each other. Some optimization model for static channel assignment in wireless mesh networks with multiple radios is developed in [9]. They propose an ILP based formulation to generate optimal channel assignment solutions. The objective is to maximize the number of *concurrent links* constraints on the number of interfaces and channels. Maximizing concurrent links increases the traffic carrying capacity of the network. Finally, [2] proposes distributed channel assignment method similar to our protocol. It proposes two algorithms, first for the nodes with the number of interfaces twice more than the number of channels and the second with an opposite condition. For the first case, channels are randomly selected while in second case channels are selected from the broadcasted set of channels from the neighbors. While the objective of our paper is similar in the sense that, we take a different approach driven by a priority to ensure connectivity with all neighbors using assigned channels.

In this paper, we propose a new distributed channel assignment protocol, DCAP that induces the association between neighboring nodes for generating a backbone topology. Our scheme meets both ends of assigning common channel to each neighboring pair of MPs for enabling connectivity and reducing co-channel interference. We compare our scheme with the CCA and the results from [9].

II. Network Model and Problem Description

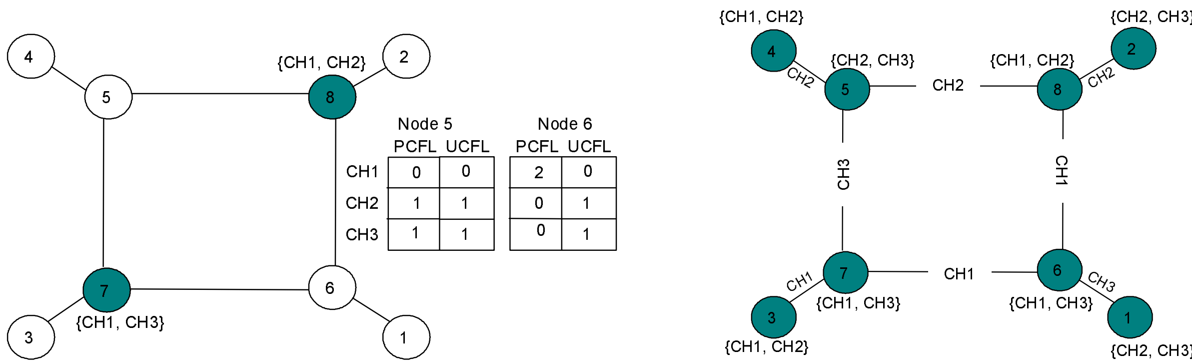
We consider n wireless static nodes. Each node represents MP in the WLAN mesh with I interfaces with the fixed number of available orthogonal channels. We consider two interfaces for each node and three non-overlapping channels as defined in the IEEE 802.11b radios [10]. Transmission range is uniform for all nodes. It is defined as a range in which a transmitted packet by the sender can be decoded by the receiver. If other node pairs that are within the transmission range initiate communication using a same channel, they interfere with the communicating nodes and might cause a transmission failure.

In a network with multi-interfaces, at least one interface of a node in a node-pair must be tuned to a common channel for data communication. Thus, a channel assignment strategy should assign a common channel to each neighboring pair. Such a strategy would guarantee network connectivity and generate a feasible network topology. In the other hand, repeatedly assigning a same channel in the entire network decreases spatial reuse and increases interference. Again a given strategy should minimize interference by using different channels while maintaining a feasible network. Hence this problem is defined as a connectivity preserving interference bounded problem and proved to be NP-complete [7].

In this paper, we develop a distributed solution for channel assignment based on heuristics such as node degree and ID. The degree of a node, henceforth referred only as the degree is a total number of its one-hop neighbors. By exchanging this information in a one-hop neighborhood we prioritize the nodes for the systematic channel assignment that attempts to increase simultaneously operating links by utilizing all available non-overlapping channels. Our scheme is independent of any specific traffic demands and can facilitate different adaptation modes including the dynamic or hybrid channel switching schemes. Since the focus is to generate a network topology which requires channel assignment for a longer time period, other approaches such as a dynamic channel assignment is considered beyond the scope of this paper.

III. Distributed Channel Assignment Protocol (DCAP)

Initially, degree and ID information of the neighbors are collected to prioritize nodes before the actual multi-channel assignment. For this purpose each node should have at least one of its interface assigned to a common channel for the entire network achieved by Simple Channel Unification Protocol in the IEEE 802.11s [1]. Our channel assignment protocol is described in 2 phases as follows:



(a) Preferred channel frequency list (PCFL) and Unused channel frequency list (UCFL) table maintained by Nodes 5 and 6

(b) Selected channels for the interfaces and links

Fig. 2: Channel selection for the non-seed nodes

A. First Phase: Channel Selection for the Seed Node

This process is initiated after network discovery process, where vital information are collected. The collected information, node degree and the ID information of the neighbor nodes, are used to determine the seed node. Each node maintains an *ordered list* (OL) that contains ID of its neighbors with higher degree compared to itself. If the degree is equivalent, the nodes with the greater ID is inserted in the OL. Rest of the neighbors with the lesser degree and same degree with smaller IDs are stored in the *dependent list* (DL). For example, in Fig. 1(a), consider a network with 8 nodes each equipped with two interfaces. The OL for Node 8 is empty because the ID and the degree of its neighbors (Nodes 2, 5 and 6) are smaller than itself. These nodes are instead inserted in the DL. The node with an empty OL determine itself to be of the highest order and to become a 'seed node'.

Each seed node first allocates candidate channels for its own interfaces. This is achieved by randomly choosing channels among all the available orthogonal channels. Again referring to the Fig. 1(a) the seed Nodes 7 and 8 randomly select two channels from the channel set {CH1, CH2, CH3}. Node 7 assigns CH1, CH3 and Node 8 assigns CH1 and CH2 in their respective interfaces.

The seed nodes then construct a *priority channel list*(PCL) with *connecting* and the *unused* channels. *Connecting channel (CC)* is the one among the candidate channels alternatively assigned for each node in the DL. *Unused channel (UC)* is the one that are not among the candidate channels of the seed node. As shown in Fig. 1(b), Node 7 sends PCL $< CH1, CH2 >$ with CH1 as the CC and CH2 as the UC to Node 6. In the same PCL, it sends CH3 as the CC and CH2 as the UC to Node 5 and 3. Similarly, node 8 also transmit its PCL with CH1 for node 6, CH2 for Nodes 1 and 5 as CC with CH3 as the UC.

B. Second Phase: Channel Selection for the Non-seed Node

In this phase, nodes with the non-empty OL start a wait timer and expect PCL from all nodes in OL before it expires. They maintain two lists, namely a *preferred* and *unused channel* frequency lists (PCFL and UCFL) that contain the frequencies of the connecting and unused channels obtained from the PCL. The frequency of the received CC channels are recorded in PCFL and the UC in UCFL. In our case, Node 5 receives CH2 and CH3 as the connecting channels from Node 8 and 7, respectively their frequencies are updated in PCFL as shown in Fig 2(a) . Similarly the count of the unused channels is updated in the UCFL. After the PCL from all nodes in its OL are received, the candidate channels are selected based on the following three cases:

- **Best case** occurs when $|N_{CC}| < |N_{IFS}|$ where $|N_{CC}|$ denotes the number of connecting channels and $|N_{IFS}|$ denotes the number of interfaces in a node. In this case we have a flexibility of choosing unused channels for better spatial reuse, including the connecting channels for preserving the connectivity. Thus, both CC and UC are included in the candidate set for maximizing channel utilization. Refer to Fig. 2(a), Node 6 has a best case where it receives CH1 from both Nodes 7 and 8 as its CC. Thus it selects CH1 to connect with its higher order nodes and uses CH3 for another interface associated to the Node 1. In the network with more channels, we select an unused channel with higher frequency.
- **Good case** occurs when $|N_{CC}| == |N_{IFS}|$. In this case, we assign all the channels in PCLF with frequency more than 1 to the candidate set balancing the connectivity and interference. In the Fig. 2(a), Node 5 has a best case where two connecting channels CH2 and CH3 in its PCFL, both of which are assigned to its candidate set. Note that we cannot use unused channels that might cause network partition.
- **Worst case** occurs when $|N_{CC}| > |N_{IFS}|$. In this case the number of connecting channels is greater than the number of interfaces. In this case, a node searches for a common set of channels from all the candidate sets that are assigned to its seed nodes' interfaces for preserving the connectivity. This is performed by listing all the channels in PCL sent by the nodes in OL to its neighbors. Since PCL is broadcasted, each node receiving

TABLE I: Number of concurrent links

Topology	Total links	DCAP	CCA	Optimal [9]
4x4	24	12	8	12
5x5	40	18	14	18
6x6	60	27	18	27

this message can know the CCs sent to another node. For example, in Fig. 1(b) Node 5 can decode the preferred channel for Node 5 and 2 from the same PCL.

After selecting the candidate channels, a node constructs and transmit PCL to its DL nodes if it is nonempty. The PCL arriving from the nodes in its DL are ignored. If the DL is empty, node need not further transmit the PCL. Thus our algorithm terminates when such nodes finally receive the PCL. Fig. 2(b) shows the final channel assignment of the entire network.

IV. Performance Evaluation

We implemented the proposed solution, DCAP and CCA protocol in ns-2 simulator version 2.29 [11]. We modified *ns-2* to support multiple interfaces and channels based on.

A. Simulation Environment

N static wireless nodes in *grid* and *random* topology are placed in 1000x1000m^2. A grid topology has a fixed 200m distance between nodes and the network size is changed by increasing number of nodes from 3x3 to 6x6 grid. In random topologies, nodes are randomly distributed however, forming a connected graph with 10 15, 20, 25 and 30 nodes. The transmission range for all nodes is fixed to 250*m* and interference range to 550*m* [5]. Based on the IEEE 802.11b specifications, we set three channels and two interfaces at each node. We generated traffic for 50s with different inter-arrival time from 0.0001s to 0.1s. Data packet size is 1024 bytes. First, we computed the number of concurrent links to compare with the optimal solutions obtained from [9]. In the next set of simulations, we randomly selected one node as a source and flood data packets in the network after assigning channels. Flooding is used in common routing protocol for finding destination. In case of multi-interface network, instead of flooding in all channels, we transmit packet in the channels assigned to each interface [2]. We performed each simulation five times to measure throughput and end-to-end latency when the network is saturated with the traffic. Throughput is computed at each receiving node by summing the total number of bytes received during the simulation time. Similarly, we measure latency by reducing a received time of a packet at a particular node by its generated time at source. The results are compared with the CCA protocol. CCA as explained earlier has a same pair of channels assigned to each node interfaces.

B. Simulation Results

We first present the results obtained on the number of concurrent links in the grid topologies. The total number of available links are 24, 40 and 60 in the 4x4, 5x5 and 6x6 grid respectively. Table I shows the results obtained from [9], CCA and our proposed scheme. Since our scheme and [9] uses all three available channels for the network, more concurrent links can co-exist for multiple transmission as compared to CCA.

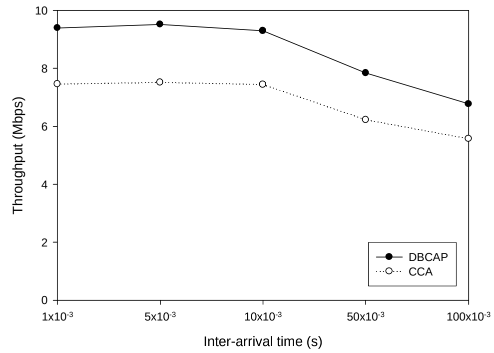


Fig. 3: Average throughput in a random topology across traffic load

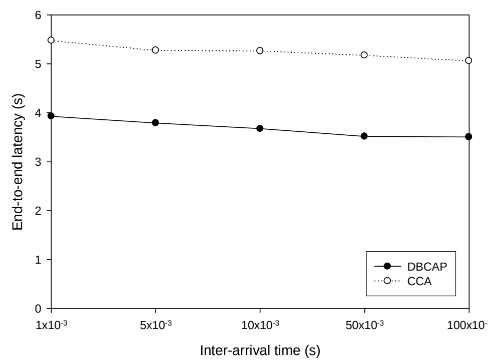


Fig. 4: Average end-to-end latency in a random topology across traffic load

Even though CCA does not require extra overhead for assigning channels, achieving higher network capacity by using optimal channel assignment protocol such as DCAP has a long term benefit. 50% and 45% of links can be concurrently active in 5x5 and 6x6 grid respectively. We observe that this reduction is due to the limited number of available channels for the larger networks. Moreover, when the number of interfaces in all nodes are equal to the number of channels, our protocol generates same topology as CCA. Thus, one additional channel increases the concurrent links by 14% in average.

We next describe the performance of the DCAP and CCA with respect to the traffic flow in random topologies. In random topology, higher degree nodes face more interference due to excessive channel reuse. Such links become a potential bottleneck for the flow in the network.

Following observations are made from our simulation results. Our DCAP scheme performs best in all cases. With respect to the inter-arrival time, DCAP shows 25% more throughput gain than CCA as shown in Fig. 3 in the topology of 30 nodes. This is because our scheme uses more concurrent links to carry traffic. As the inter-arrival rate increases, more

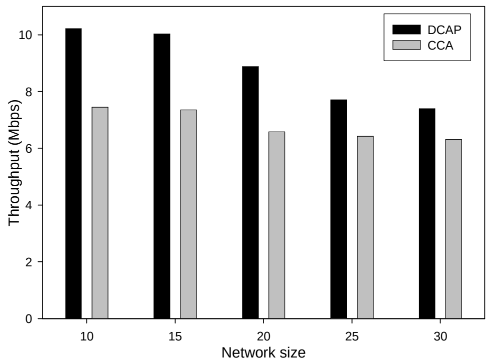


Fig. 5: Average throughput in random topologies across network size

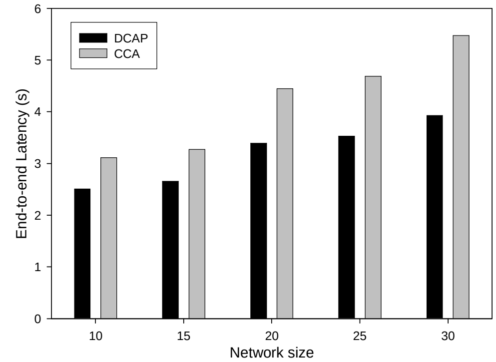


Fig. 6: Average end-to-end latency in random topologies across network size

number of packets drop in CCA due to the saturation of available links for forwarding packets in the network. Fig. 4 shows the end-to-end latency measured in the same topology with respect to the traffic inter-arrival rate. DCAP shows 30% decrease in average latency compared to CCA. Due to the repeated use of same channels in CCA that causes interference, packets generated at a source might take longer route to reach distant destinations. Increase in latency with more traffic in the network is expected in both schemes. As the concurrent link gets saturated, the packet gets forwarded to the destination nodes through the longer paths.

In the next simulation, we describe the results on throughput and the latency across the increasing number of nodes (network size) in the random topologies. Network size increases the density of nodes and links. New links using new channels are constructive and increase throughput whereas the ones that uses same channels are destructive as they increase the collision probability of packets. We use maximum traffic inter-arrival rate of 0.0001s in the following cases.

Fig. 5 shows the throughput across the network size in the random network. We observe that the DCAP shows 30% average increase over CCA. With the increasing network size throughput gradually decreases as a result of increasing co-channel interference. Limitations in the number of channels create more destructive links as described earlier. In Fig. 6 we see the consistent performance of DCAP over CCA. In average, the latency of the DCAP is 3.2s and CCA is 4.1s. In random topology, packet delivery is often unsuccessful due to collision in the nodes with high degree. In case of CCA, this gets worst with limited use of channels and thus takes longer path to reach the destination. We also observe that the latency steadily increase with the network size. The results are as expected because of lesser spatial reuse in larger networks.

V. Conclusion

We present the distributed channel assignment protocol in multi-interface and multi-channel wireless mesh networks. Our method is based on simple but effective heuristics such as neighbor degree and node identification. We showed that the priority based selection of the channels can be performed in a distributed manner for forming the wireless mesh network topology with minimum interference. We also showed that our channel assignment algorithm produces similar number of concurrent links as generated by the ILP based protocol [9].

Our results show 30% of increased network throughput compared to CCA and also reduces per-packet latency by 3s in best cases. In general, we conclude that the advantage of being selective in channel selection offers better network capacity. For the network in which channel switching can be costlier in terms of delay, channel assignment such as this proves to be better alternative for the network with multiple interfaces and channels. In future, we will investigate the performance of our protocol in the network with mixed number of interfaces. We will also study other topology control aspects such as transmission power control with the channel assignments.

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