Interplay between Power Control and Channel Allocation for Multi-Channel Wireless Networks

Jaeseon Hwang and Hyuk Lim

Abstract

In wireless networks, interference from adjacent nodes that are concurrently transmitting can cause packet reception failures and thus a significant throughput degradation. The interference can be simply avoided by assigning different orthogonal channels to each interfering node. However, if the number of orthogonal channels is smaller than that of interfering nodes, some adjacent nodes have to share the same channel and may interfere with each other. This interference can be mitigated by reducing the transmit power of the interfering nodes. In this paper, we propose to jointly coordinate the transmit power and the multi-channel allocation to maximize the network throughput performance by fully exploiting multi-channel availability. This coordination enables each node to use high transmission power as long as different orthogonal channels can be assigned to its adjacent nodes. Then, we propose a simple multi-channel media access control (MAC) protocol that allows the nodes on different channels to perform efficient data exchanges without interference in multi-channel networks. We show that the proposed scheme improves the network throughput performance in comparison with other existing schemes.

Index Terms

power control, channel assignment, MAC protocol, multi-channel wireless networks.

I. Introduction

Multi-channel availability can be exploited to mitigate the interference and maximize the network capacity in wireless networks. To exploit multi-channel availability, competing nodes need to use non-overlapping channels in order to guarantee that the data transmission on a

The authors are with the School of Information and Communications, Gwangju Institute of Science and Technology (GIST), Gwangju 500-712, Republic of Korea. E-mail: hlim@gist.ac.kr

channel does not interfere with those on any other channels. The number of non-overlapping and orthogonal channels is 3 and 12 in most countries as defined in IEEE 802.11b/g and IEEE 802.11a [1], respectively. Note that the channel regulation is different, depending on countries [2]. For IEEE 802.11b/g, the channels 1-11 are permitted in the United States, while most other countries use the channels 1-13. In addition, Japan supports the channel 14 in IEEE 802.11b, so that the number of orthogonal channels is 4 in Japan. For IEEE 802.11a, 10 orthogonal channels are used in Europe and Japan, while most other countries support 12 orthogonal channels. Using this multi-channel availability, multiple pairs on different orthogonal channels can concurrently perform data transmissions without any interference. Therefore, the number of transmissions can be increased, and the achievable capacity in a multi-channel network becomes larger than that in a single-channel network.

In wireless networks, interference is one of the dominant factors affecting network throughput performance. As the interference on a wireless channel increases, the signal-to-noise ratio (SNR) level at the receiver decreases and thereby disrupts successful packet reception. To improve the network throughput performance against the interference, a variety of transmission power control schemes have been studied [3]–[9].

In addition, a variety of protocols and algorithms for exploiting multi-channel availability have been reported [10]–[17]. To efficiently utilize multi-channels, a pair of nodes selects an appropriate channel for data transmission by channel negotiation. Among available multiple channels, a channel for data transmission of a sender-receiver pair can be randomly selected or decided as one that is least congested. On the selected channel, the sender-receiver pair performs either one data transmission [10], [11] or multiple data transmissions [15]–[17]. However, during the data transmissions, interference may affect neighboring nodes if there are nearby simultaneous transmissions on the same channel.

For interference mitigation, vertex coloring [18] of graph theory has been widely used for multi-channel assignment between nodes in wireless networks [19]–[25]. Using graph theory, a wireless network can be represented as a graph where *vertices* denote the nodes, and *edges* denote the links that connect the nodes. In this manner, vertex coloring can be used such that no two adjacent vertices/nodes have the same color/channel[1].

In this paper, we propose a power and channel allocation control (PCC) algorithm for multi-

[1]We will use nodes and vertices, and colors and channels, interchangeably.

channel wireless networks. The basic idea is that each node increases its transmission power as long as different orthogonal channels are assigned to its interfering nodes, in order to maintain a high data transmission rate between two nodes. Each node builds an interference graph with its current transmission power and computes the number of required channels for interference avoidance in the interference graph using channel allocation based on vertex coloring. Then, the node adjusts its transmission power as long as the available channels are fully assigned to its adjacent nodes in order to not cause interference to its neighbors. For a wireless network where each node resides on its channel assigned by the vertex coloring, we propose a simple multi-channel coordination protocol (MCC) that can efficiently coordinate data transmissions between nodes. Because the neighboring nodes use different non-overlapping channels, the node has to change its channel to that of the intended receiver for data transmission. Finally, we show that the network throughput performance is significantly improved through ns-2 simulations [26].

The main contribution of this paper is the consolidated design of the transmit power control and channel allocation for mitigating the interference among neighboring nodes. In the PCC algorithm, the construction of interference graph plays an important role in identifying the number of orthogonal channels that are required to avoid interference among neighboring nodes. If the number of required channel is smaller than the available channels, the transmit power needs to be adjusted. In addition, we provide the medium access protocol for data exchanges among nodes in multi-channel environment.

The rest of this paper is organized as follows. In Section II, we introduce a graph-based representation for wireless networks. Next, we describe our proposed power control with a channel allocation algorithm and multi-channel coordination protocol in Section III and Section IV, respectively. We then present the simulation results in Section VI. In Section VII, we provide a summary of related work in the literature. We conclude the paper in Section VIII.

II. PRELIMINARY

A. Network Graph

A wireless network can be represented by a graph G=(V, E), where V is the set of vertices, and E is the set of edges between any pairs of vertices. We consider the connectivity and interference graphs as a method of representing communication and interference links between any pair of nodes, respectively. For successful packet reception, the SNR at receiver j, which is expressed as a function of the transmission power $P(i)$ of sender i, should be greater than or equal to a communication threshold γ_c as follows:

$$\frac{P(i)}{N_0(D(i,j))^\eta} \geq \gamma_c, \tag{1}$$

where N_0 is the thermal noise power spectral density, $D(i,j)$ is the distance between nodes i and j, and η is the path loss exponent. By (1), the transmission range $d_c(i)$ of node i is given by

$$D(i,j) \leq \left(\frac{P(i)}{N_0\gamma_c}\right)^{\frac{1}{\eta}} =: d_c(i). \tag{2}$$

From this relationship, we can build an *undirected connectivity graph* where any two nodes are connected with an edge only if they are in the transmission range of each other.

For successful transmission against the interference, the interference range $d_I(j)$ [27] is given by

$$d_I(j) = \sqrt[\eta]{\gamma_c} \cdot \max_{i \in \mathcal{N}(j)} D(i,j), \tag{3}$$

where $\mathcal{N}(j)$ is a set of the neighboring nodes that may transmit to node j. For example, when γ_c is 10, and η is 4 under the two-ray ground pathloss model, the interference range of node j is $d_I(j) = 1.78 \cdot D(i,j)$. If a node k is within the interference range of node j, i.e. $D(k,j) < d_I(j)$, node j is affected by the interference from node k. On the basis of this relationship, we can build an *undirected interference graph* where the interference link is connected if either of any two nodes interferes with one another. The interference graph may have a large number of edges than a connectivity graph because an interference range is typically larger than a transmission range at a node.

B. Vertex Coloring

Vertex coloring has been widely used for channel assignment algorithms [19]–[25] to assign different channels to vertices that have interference relationships with each other. If two vertices interfere with each other, the vertices are connected by a unique edge, called a *conflict edge*. In contrast, the constituent edges are said to be *conflict-free* if two vertices do not cause interference with each other. Vertex coloring can remove the interference of a conflict edge by assigning different colors to corresponding vertices.

Greedy coloring [28] is a method used to assign a number of channels to a vertex as a vertex coloring. When the vertices in a graph are sorted in a certain ordering, each vertex is sequentially assigned its first available color among its adjacent nodes. This coloring does not guarantee the minimum number of colors, and the number of colors depends on the vertex ordering. For any graph, the greedy coloring needs at most a number of colors equal to the maximum degree plus one for assigning colors to the graph.

III. Joint Transmit Power and Channel Allocation Control

In multi-channel wireless networks, the throughput performance can be maximized when the nodes use the highest transmission rate without interfering neighboring nodes. In this section, we consider the joint transmit power and channel allocation control to fully exploit the multi-channel availability. The joint coordination enables each node to use high transmission power as long as different orthogonal channels can be assigned to its adjacent nodes.

A high transmission power of a wireless node increases the probability of successful data transmissions and allows a transmitter to use a higher transmission rate by increasing the SNR level at its intended receiver. However, the significant interference due to the high transmission power may cause packet reception failures at its neighboring nodes and thus result in a significant network-wide throughput degradation. To avoid the interference among neighboring nodes, multi-channel availability can be exploited by enabling adjacent interfering nodes to have different non-overlapping and orthogonal channels.

However, the number of orthogonal channels is typically not sufficient to be allocated to all interfering nodes, which are 3 and 12 in IEEE 802.11b/g and IEEE 802.11a, respectively. If the number of orthogonal channels is smaller than the number of interfering nodes, each interfering node cannot have a different orthogonal channel; thus, the nodes using the same channel may interfere with each other. In this case, the nodes have to decrease their transmission power to reduce the interference to neighboring nodes.

We propose a joint transmit power and channel allocation control (PCC) for multi-channel wireless networks. The basic idea is that each node increases its transmission power as long as different orthogonal channels can be assigned to its interfering nodes, in order to maintain a high data transmission rate. The proposed algorithm consists of three sub-algorithms. First, each node independently performs the power adjustment to find the highest transmit power for a given number of orthogonal channels under Algorithm 1. In Algorithm 1, the computation of the number of orthogonal channels for topologies under the power control is performed by

Algorithm 1 Proposed power control for wireless networks with a limited number of channels at node i

```
if topology changes then
    P_LMST(i) ← transmit power obtained by LMST
    while P(i) < P_max do
        Build an interference graph G(V(i), E(i)).
        Compute the number of required channels C_est(i) by Algorithm 2.
        if C_est(i) < C then
            P(i) ← P(i) + ε
        else if C_est(i) > C then
            P(i) ← P(i) − ε
        else if C_est(i) = C then
            break
        end if
    end while
    P(i) ← max(P(i), P_LMST(i))
    Update G(V(i), E(i)) and C_est(i).
    Broadcast C_est(i) and interference edges.
end if
```

Algorithm 2. Then, the node collaborates with its neighboring nodes to finalize the channel assignment for the topology obtained by the power adjustment in Algorithm 3.

These algorithms use the interference graph of nodes. The interference graph for node i is denoted by $G(V(i), E(i))$, which consists of a set of its neighboring vertices $V(i)$ and edges $E(i)$. To build the interference graph, node i gathers the interference graph information of other nodes by overhearing the control packets from its neighboring nodes. The control packet contains the number of required channels and the interference edges. If $G(V(i), E(i))$ is inconsistent with the overheard information, it is regarded as the network topology changes, and node i should re-build its interference graph.

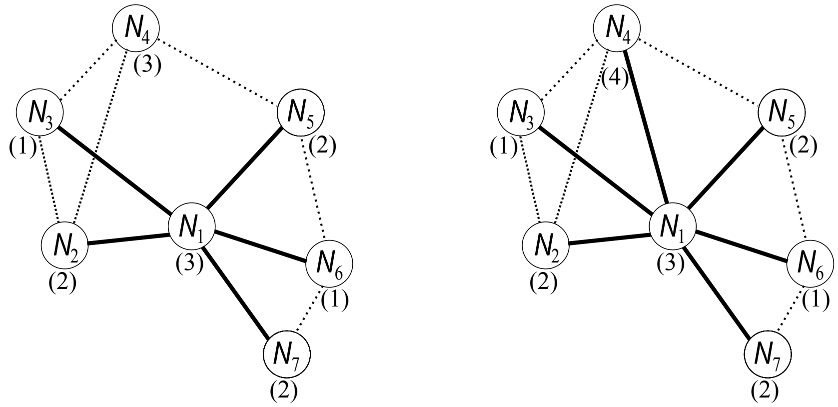
Algorithm 1 describes the proposed power control for wireless networks with a limited number of channels. We employ the local minimum spanning tree (LMST) topology control [29] to obtain the minimum transmission power that preserves the network connectivity. If there is a

Algorithm 2 Local estimation of the number of required channels $C_{est}(i)$ at node i

// $I(i)$: a set of nodes sharing an interference edge with node i.
for each interfering node $j \in I(i)$ in $G(V(i), E(i))$ **do**
    $clique\_list \leftarrow (i, j)$
    for each interfering node $k \in I(i)$ in $G(V(i), E(i))$ **do**
        if k has interferences to all l in $clique\_list$ **then**
            Append k to $clique\_list$.
        end if
    end for
    $s(j) \leftarrow$ number of vertices in $clique\_list$
end for
$C_{est}(i) \leftarrow \max_{j \in I(i)} s(j)$

topology change, node i first computes a minimum transmit power $P_{LMST}(i)$ by LMST, which is appropriate for maintaining network connectivity. Then, it constructs an interference graph to identify the interference relationship between itself and its neighboring nodes. Based on the interference graph, it computes *the number of required channels* $C_{est}(i)$ by Algorithm 2. If $C_{est}(i)$ is smaller than the number of available channels C of the wireless network, the node increases its transmission power to use a higher transmission rate. Note that the interference will not affect its neighboring nodes because the orthogonal channels can be assigned to each neighboring node. On the other hand, if $C_{est}(i)$ exceeds C, the node may interfere with its neighboring nodes because it cannot help using the same channel, and thus it has to decrease its transmission power to reduce the interference. The transmit power is continuously adjusted until $C_{est}(i)$ equals C. Then, the power is set to a value that is at least equal to $P_{LMST}(i)$ for preserving network connectivity on line 14, and the interference graph and the number of required channels are updated with the power. Finally, the node broadcasts $C_{est}(i)$ and the interference edges so that its neighboring nodes re-build their interference graph in order to reflect the latest topology information.

Algorithm 2 computes the number of required channels $C_{est}(i)$ for node i on the interference graph, which is the size of the maximum clique that includes node i. Figure 1 illustrates how the algorithm finds $C_{est}(i)$. In Fig. 1(a), an interference graph is built by node N_1, which has



(a) $C_{est}(N_1)$=3, C=4 (b) $C_{est}(N_1)$=4, C=4

Fig. 1. Interference graph at a node N_1. The lines between any two nodes represent that they interfere with each other. The interference related to N_1 is drawn as a solid line. The number in parentheses indicates the channel number.

five interfering nodes. Let $I(i)$ denote a set of nodes sharing an interference edge with node i. Each node $j \in I_i$ extends $clique\_list$ by appending its interfering node $k \in I_i$ if a clique can be constructed with node k and nodes in $clique\_list$. Four different maximal cliques can be constructed: (N_1, N_2, N_3) by N_2 and N_3, (N_1, N_5) by N_5, (N_1, N_5, N_6) and (N_1, N_6, N_7) by N_6, and finally (N_1, N_6, N_7) by N_7. It should be noted that N_4 cannot be included in any cliques because $N_4 \notin I_i$. Because the number of nodes that form the maximum clique is three, $C_{est}(N_1)$ = 3. Now that $C_{est}(N_1)$ is smaller than the number of channels C, which is four in this network, the network can still maintain the interference-free coloring. In Fig. 1(b), node N_1 increases its transmission power and has six interfering nodes. Nodes N_1, N_2, N_3, and N_4 become a clique and interfere with each other because of the new interference link between nodes N_1 and N_4, so that $C_{est}(N_1)$ = 4. Now that $C_{est}(N_1)$ is equal to C, node N_1 stops performing its power control.

In Algorithm 3, each node performs the vertex coloring based channel assignment to assign available orthogonal channels to its interfering nodes. On line 4, each node waits for the channel assignment completion of nodes with larger C_{est}. Based on the channel assignment, if multiple channels are available at a node, it randomly selects one of the channels and broadcasts the channel assignment information.

A difficulty in the channel assignment is that the topology may need more than C channels, even though C_{est} for every node is smaller than or equal to C. Note that each node adjusts its

Algorithm 3 Vertex coloring based channel assignment at node i

// Ω: set of available channels in a wireless network
// $\Omega(i)$: set of available channels at node i
// $\omega(i)$: assigned channel at node i
Wait for the completion of channel assignment at all $j \in I(i)$ where $C_{est}(j) > C_{est}(i)$.
Receive the channel assignment $\omega(j)$ from $j \in I(i)$.
$\Omega \leftarrow \{1, \ldots, C\}$
$\Omega(i) \leftarrow \Omega - \{\omega(j)\}$, for $j \in I(i)$
if $\Omega(i) \neq \emptyset$ **then**
    $\omega(i) \leftarrow$ randomly selected channel $c \in \Omega(i)$
    Assign $\omega(i)$ to itself and broadcast $\omega(i)$.
else
    $P(i) \leftarrow P(i) - \epsilon$
    Update $G(V(i), E(i))$ and $C_{est}(i)$.
end if

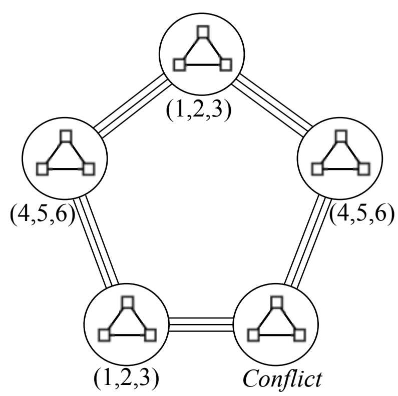


Fig. 2. The case when the channel assignment with C=6 is in conflict. Each node in the 3-cliques forms a 6-clique with three nodes in one side of the adjacent angular points. The number in parentheses indicates the channel number.

transmission power based on its local interference graph $G(V(i), E(i))$ without the knowledge of the whole network topology. As an example, Figure 2 illustrates a case of channel assignment conflict when C = 6. The network topology is a five-sided polygon, and three nodes at each angular point form a clique, where the nodes are directly connected with each other. Each node in a clique is also connected to all six nodes belonging to its two adjacent angular points, so that $C_{est}(i)$ = 6 for every node i. However, as shown in Fig. 2, the number of colors needed for vertex coloring of all nodes is C_{real} = 9. This implies that there is a channel assignment conflict. To resolve this problem, if there is no available channel at a node, the node has to decrease its transmission power until the channel is available, as shown on line 12 in Algorithm 3. Indeed, the number of colors required for vertex coloring lies between the maximum of C_{est} and (Δ+1), i.e., $\max_{i \in V} C_{est}(i) \leq C_{real} \leq \Delta + 1$, where Δ is the maximum node degree of the network.

The time complexity for the joint transmit power and channel allocation control depends on that for the computation of $P(i)$ and $C_{est}(i)$ of node i. To determine $C_{est}(i)$, node i iterates through all the interfering nodes twice to solve the maximum clique problem in Algorithm 2. Thus, the time complexity for determining $C_{est}(i)$ is $\mathcal{O}(n^2)$, where n is the number of nodes in the network. While node i determines $C_{est}(i)$, it adjusts its transmit power $P(i)$. In addition, if there is a channel conflict in performing the channel assignment, $P(i)$ needs to be decreased. The computational cost required for the convergence of $P(i)$ grows linearly while $P(i)$ is adjusted, which depends on the interference relationship in the network topology.

IV. Multi-Channel Coordination Protocol

In this section, we consider a simple multi-channel coordination (MCC) protocol that can coordinate data transmissions between nodes on different channels, which are determined by the PCC algorithm. Each node has a *primary channel* and knows the primary channel of its neighboring nodes. The data transmission is performed on the primary channel of the receivers. Note that the interference graph is constructed such that both the sender and receiver do not interfere with their neighbors on the same channel when they use the assigned transmit power. When a sender has a data packet to an intended receiver, it independently performs channel switchings to the primary channel of the intended receiver and exchanges a data packet. After the sender receives the acknowledgement packet from the receiver, it switches back to its primary channel. It should be noted that a node performs two channel switchings alternating its own primary channel and that of the receivers for each data transmission.

Figure 3 presents the basic operation of the MCC protocol between the sender and receiver, each of which resides on a different channel according to the PCC algorithm. The MCC protocol is based on a DATA/ACK frame sequence adopted by an IEEE 802.11 distributed coordination function (DCF), where the carrier sense multiple access with collision avoidance (CSMA/CA) and the binary exponential back-off (BEB) algorithms are used.

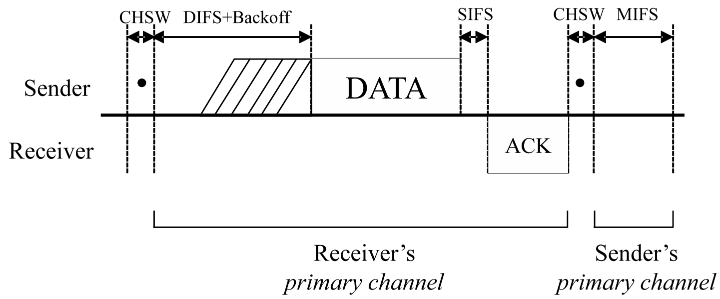


Fig. 3. Basic operation of the proposed protocol. The channel switching is denoted by •.

For the channel rendezvous, each node needs to identify channel information in advance about which channels its neighboring nodes are using. Each node maintains a channel table consisting of channel usage information that contains a set of channel numbers that have been assigned for its neighboring nodes. From the channel information, a sender performs its channel switching to the primary channel of its intended receiver. As in the IEEE 802.11 DCF, a sender exchanges one DATA/ACK packet with its receiver after performing the BEB algorithm. When it is sensed that a channel has been idle for a specific time interval, called the distributed inter-frame space (DIFS), the sender selects a random back-off timer, which is uniformly distributed in [0, CW -1], where CW is the size of the contention window. CW is initially set to its minimum value CW$_{min}$ and is doubled after a transmission collision. The back-off timer is decreased by one if the channel is sensed to have been idle for one physical time slot, and the timer is suspended if the channel is sensed to be busy. The node transmits its frame when the back-off timer reaches zero. Note that the number of retransmissions is limited by two, i.e., if the data transmission fails twice, it immediately returns back to its primary channel for the following reasons:

- If the intended receiver switched to another channel for data transmission with another node, it does not currently reside on its primary channel.
- One of the neighboring nodes may want to perform data communications on the primary channel of sender.

When the data frame is successfully received at the receiver, it sends back the acknowledgment (ACK) frame to the sender. After the data transmission is performed on the primary channel of the receiver, the sender immediately switches to its own primary channel. Then, it listens to its own channel for a certain time interval, called the multi-channel inter-frame space (MIFS), without switching to another channel for the next data transmission. We set $MIFS = 2 \cdot DIFS + T_{ACK}$, where T_{ACK} is the length of the ACK packet transmission at the lowest basic rate. During this MIFS period, if some nodes attempt to transmit a data packet, it can exchange the data packet with them. After the MIFS expires, it may perform the channel switching for a data transmission. This mechanism also helps reduce the transmission failures due to the channel information inconsistency, which may happen when the network is congested.

In multi-hop scenarios, a sender may fail to transmit a data packet to its intended receiver if the receiver is transmitting to its next-hop node on the primary channel of the next-hop node. In this case, the sender returns back to its primary channel when it fails to transmit twice, and has to remain on its primary channel during the MIFS period. We will show that MCC works well in multi-hop scenarios in Section VI.

V. Discussion

A. Multi-channel hidden terminal problem

The multi-channel hidden terminal problem [15] occurs when a node attempts to use a channel that is currently occupied by other nodes, which unintendedly causes interference to other nodes. To tackle this problem, PCC allows a node to gather interference information from other neighboring nodes by overhearing control packets and to perform the vertex coloring based channel assignment in order to avoid interference among neighboring nodes. Because each node is assigned one of the orthogonal channels by the channel assignment, the number of nodes sharing a same channel is significantly reduced. Therefore, the proposed algorithm helps reduce the possibility of interferences caused by the multi-channel hidden terminal problem.

B. Exposed terminal problem

The proposed PCC constructs an interference graph based on the SINR relationship among nodes. Each node can transmit on a different channel without significant interference to other nodes. Under a CSMA/CA channel access mechanism, a sender defers its transmission if it senses that the channel is busy. In this case, even if the SINR at a receiver is sufficiently high for successful transmission under PCC, the sender may unnecessarily defer its transmission. This is called the exposed terminal problem. PCC does not explicitly consider the throughput degradation owing to the exposed terminal problem, but it can help mitigate the exposed terminal problem because each sender has fewer neighboring nodes within its carrier sensing range on its channel under PCC. Further research on the exposed terminal problem remains as our future work.

C. PCC with other multi-channel protocols

The traditional multi-channel protocols [10], [15] usually consist of two parts: channel negotiation and data transmission. Specifically, a pair of nodes selects a channel for data transmission by exchanging control packets, i.e. RTS/CTS negotiation, and performs the data transmission on the selected channel. The pair of nodes should always perform the channel negotiation before their data transmissions. On the other hand, the proposed PCC makes nodes perform data transmission on the channel of the receiver without channel negotiation once the channel assignment is done.

It is also possible to adopt PCC in other multi-channel protocols. In the PCC, the power control of each node is performed in order to mitigate the interference and to maintain a high transmission rate between nodes. If the channel assignment under PCC is excluded, other multi-channel protocols can be alternatively exploited with PCC for the channel selection and the data transmissions between nodes. Another extension is that if there are multi-channel coordination protocols that enable data transmissions between nodes residing on different channels, the PCC can be directly applied to such multi-channel protocols.

D. Applications in real environments

The proposed PCC and MCC algorithms are based on the interference graph that describes the relationship between the interferences among neighboring nodes. In Section II, it is assumed that the connectivity and interference among nodes are determined by the distances among nodes. However, it is not the case in real wireless environment, and the characteristics are affected by various factors such as a signal attenuation, a channel fading, and obstacles. To achieve a robustness of the proposed algorithms, it is very important to obtain an accurate connectivity and interference relationship among nodes. While the connectivity relationship can be readily obtained by a hello-message broadcasting, it is more difficulty to estimate the set of potential interfering neighboring nodes by a measurement-based approach. Therefore, the interference relationship needs to be indirectly inferred using the distances to neighboring nodes within a connectivity range, and the interference model in (3).

The proposed PCC and MCC algorithms can be applied in various wireless networks such as a static mesh network and a mobile ad hoc network. For example, in a wireless mesh network, the nodes are deployed at specific areas, and form a wireless mesh network, where they exchange their local information without relying on any infrastructure. Once the proposed PCC and MCC are adopted, the nodes can exchange the measured information on the pre-assigned channel, of which the neighboring nodes can be found by channel scanning. Since all nodes use the coordinated channels, the effect of interferences between nodes can be significantly reduced, and high-rate transmissions can be performed with the interference among nodes mitigated.

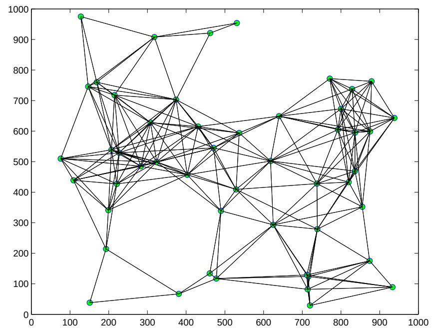
If the proposed algorithm is applied to an ad hoc network with high mobility, the connectivity between nodes could be more intermittent due to the mobility of nodes and the change of wireless channel condition. In such the case, the algorithms need to more frequently broadcast hello-messages to update the connectivity status as long as the network topology changes. Whenever the topology change are detected, each node should transmit the latest topology information again to its neighboring nodes so that the information can be updated in its interference graph.

In addition, if control packets are lost, the topology control may not be properly configured because it highly depends on the information from neighboring nodes. However, whenever the topology changes, each node transmits the latest topology information again so that the information can be updated in its interference graph.

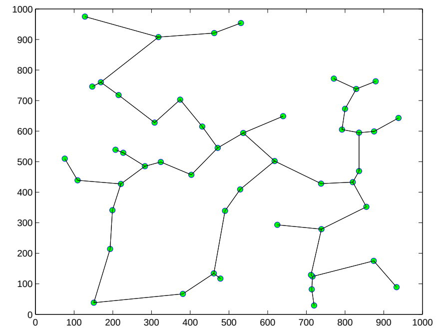
VI. Performance Evaluation

We have conducted ns-2 simulations to evaluate the performance of the proposed algorithm and compare it with that of other multi-channel protocols. For topology control, we consider two methods, i.e., the common transmission power method (COMM), which uses a fixed transmit power of 24.5 dBm for the maximum transmission range of 250 m and LMST, in which each node uses its minimum transmission power that can preserve the global network connectivity. For multi-channel coordination, we employ the most representative multi-channel MAC protocols, MMAC [15] and AMCP [10], and combine them with the topology control methods of COMM and LMST in a pairwise manner. Furthermore, we investigate the performance of the MAC protocol using [30], called MCMR (Multi-Channel Multi-Radio), when each node has two interfaces, The first interface is fixed on its primary channel and the second one is switchable on that of its intended receiver as described in [31]. Under MCMR, the IEEE 802.11 DCF protocol is employed for data communications on each interface.

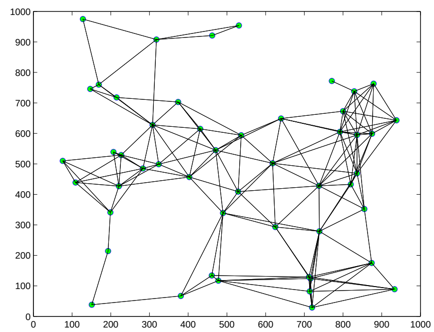
Here, we consider the network topology where the nodes are randomly distributed in a 1000 m $\times$ 1000 m topology, where the number of orthogonal channels is 12, as defined in IEEE 802.11a.



(a) COMM



(b) LMST

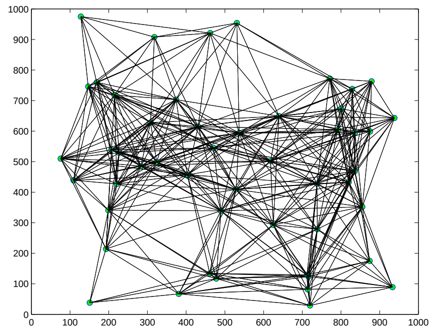


(c) Proposed PCC

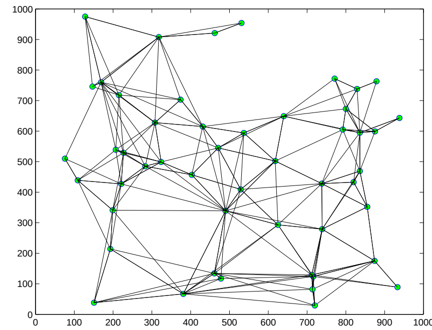
Fig. 4. Connectivity graph for 50 nodes under the three algorithms.

The nodes have an initial transmission range of 250 m and an interference range of 375 m. The maximum transmission power P_{max} is 30.5 dBm for the maximum transmission range of 350 m. We assume that source nodes are always backlogged with the packet size of 1000 bytes, and they are configured to transmit constant bit rate (CBR) traffic. We used a static routing, called *NOAH* [32], to exclude the coupled effects of routing algorithms on throughput performance of multiple-hop network scenarios. In this routing protocol, each node maintains its routing table including a next-hop node-ID and a destination node-ID. It determines where to send the packet according to the destination field of a frame. In addition, the RTS/CTS mechanism is disabled. In all the methods, the nodes transmit data packets with the most appropriate transmission rate [33] supported in IEEE 802.11a in terms of the SNR level at their intended receiver. The simulation time was 50 s, and each data point was obtained by averaging the values of five runs.

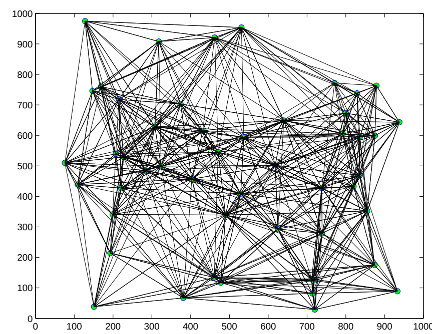
Figure 4 depicts the connectivity graph under the three algorithms for 50 nodes in the network. In all topologies, we observed that the network connectivity remains preserved under the three



(a) COMM



(b) LMST



(c) Proposed PCC

Fig. 5. Interference graph for 50 nodes under the three algorithms.

algorithms. In Fig. 4(a), each node is able to communicate with other nodes within the common transmission range of 250 m. In Fig. 4(b), each node is minimally connected to its neighboring nodes because LMST is designed such that each node uses its minimum transmission power to communicate with its adjacent node while preserving the network connectivity. In the proposed algorithm, each node initially has the minimum transmission power obtained by LMST and independently and gradually increases the power as long as different orthogonal channels can be assigned to its adjacent nodes. Thus, the degree of the nodes is higher than that in LMST, as shown in Fig. 4(c).

Figure 5 shows the interference graph corresponding to Fig. 4. Because the interference range is larger than the transmission range, the number of interference edges notably increases. In Fig. 5(a), most nodes can be affected by strong interference from the adjacent nodes, and thus the level of spatial reuse is severely deteriorated. In Fig. 5(b), the interference to adjacent nodes is mitigated because each node uses the minimum transmission power. As a result, the nodes are

TABLE I

SIMULATION RESULTS WITH RESPECT TO MAXIMUM, MINIMUM, AND AVERAGE DEGREES FOR CORRESPONDING ALGORITHMS IN FIGS. 4 AND 5.

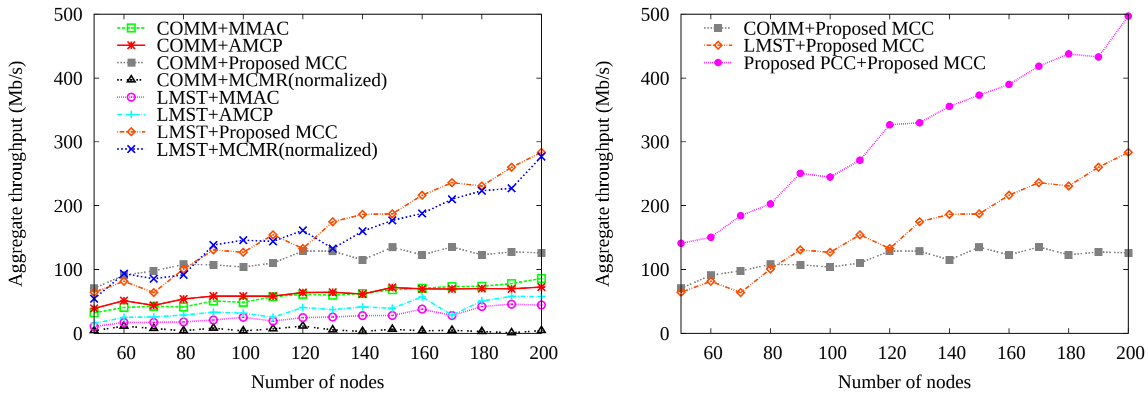
Figure	Algorithm	Maximum degree	Minimum degree	Average degree
Fig. 4	COMM	17	3	10.16
	LMST	3	1	2
	Proposed PCC	12	1	6.52
Fig. 5	COMM	28	5	17.52
	LMST	17	2	7.16
	Proposed PCC	37	13	20.44

able to perform concurrent transmissions, which promotes the level of spatial reuse. In particular, as shown in Fig. 5(c), the proposed algorithm produces the largest number of interference edges, because of the high transmission power at each node. However, the effect of interference can be significantly minimized because non-overlapping multiple channels are assigned to interfering nodes, even though each node transmits with a high transmission rate.

Table I provides the maximum, minimum, and average degrees for the corresponding network topologies illustrated in Figs. 4 and 5. The topology generated by the common transmission power shows the largest maximum and average degrees, which implies that there is severe interference, and thereby the number of concurrent transmissions is limited by the interference. Conversely, LMST shows the smallest degrees for all degree metrics because of the use of a minimum transmission power at each node. Thus, concurrent transmissions are highly activated while the effect of interference is not severe. Indeed, the proposed algorithm shows a larger number of degrees in comparison with those of LMST because each node increases its transmission power. However, the effects of severer interference due to higher transmission power can be alleviated by letting neighboring nodes use different orthogonal channels.

We now compare the throughput performance of MMAC, AMCP, and the proposed MCC in the topologies generated by COMM, LMST, and the proposed PCC. we consider a single-hop and a multi-hop scenarios as follows:

- Single-hop scenario: randomly selected two adjacent nodes form a sender-receiver pair. Since nodes are randomly distributed in the network, the number of sender-receiver pairs are typically less than half of the number of total nodes, and the same number of pairs are



(a) MAC protocols under COMM and LMST

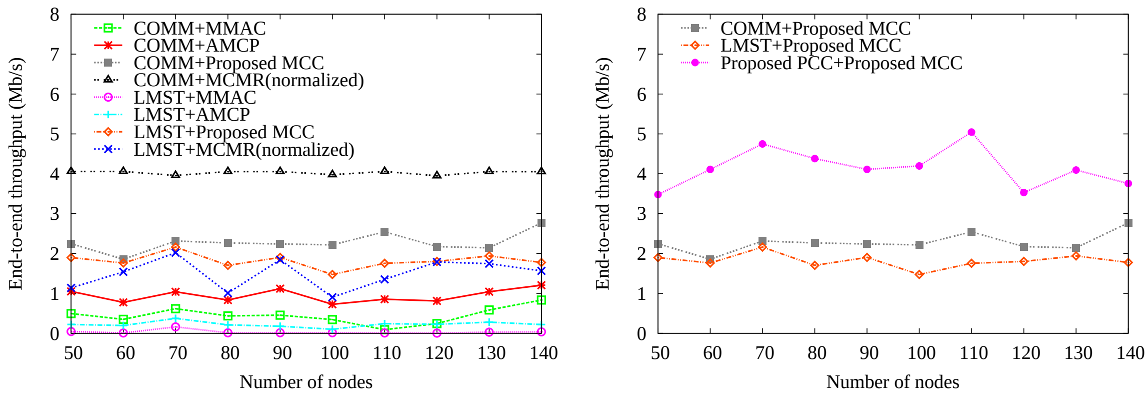
(b) Topology control under MCC

Fig. 6. Throughput performance with respect to the number of nodes in a single-hop scenario.

used for each method.

- Multi-hop scenario: packets are routed from a source to a destination node through a single routing path. The leftmost node is selected as a source node and the rightmost node is selected as a destination node. Thus, packets generated from the source node are relayed by a number of intermediate nodes along a static routing path and finally arrive at the destination node. Because each node has a different transmission range depending on its transmission power, the routing path and the hop-count under COMM, LMST, and the proposed PCC are also different according to the transmission range of the relay nodes.

Figure 6 shows the throughput performance with respect to the number of nodes in a single-hop scenario. Note that the throughput per interface is plotted under COMM and LMST with MCMR. As the number of nodes increases, more transmission links between sender-receiver pairs are established, thereby causing higher interference on multi-channels. In the multi-channel protocols such as MMAC and AMCP, for one packet transmission, a sender-receiver pair selects a channel through the channel negotiation and it exchanges a data packet on the selected channel. The performance of MMAC and AMCP highly depends on which channel is selected among all the available channels for each transmission; if the transmission occurs on a channel with a significant inference, it may result in a poor performance. However, as shown in Fig. 6, MCC achieves the highest throughput performance in comparison with MMAC and AMCP because multiple pairs use the channels determined by PCC, which interfere less with each other. Under the proposed PCC, the interference rarely affects nearby nodes because different



(a) MAC protocols under COMM and LMST

(b) Topology control under MCC

Fig. 7. Throughput performance with respect to the number of nodes in a multi-hop scenario.

non-overlapping channels are assigned to potentially interfering nodes. Thus, MCC with PCC enables the nodes to transmit packets without interfering with other neighboring nodes, achieving the highest throughput performance. When each node uses two interfaces, LMST with MCMR shows a significant increase of throughput performance, whereas COMM with MCMR achieves very low throughput. Because nodes under COMM have a higher transmission power that that under LMST, the interference from two different channels can severely affect neighboring nodes. Note that if we consider the throughput performance per one interface, the performance of the proposed PCC with MCC could be higher than that of LMST under MCMR.

Figure 7 shows the throughput performance with respect to the number of nodes in a multi-hop scenario. In LMST, the number of hops in the routing path is the largest because each node has its minimum transmission power to communicate with its neighbor node. On the contrary, in the proposed PCC, the number of hops is significantly reduced because each node uses a sufficiently high transmission power. As shown in Fig. 7(b), when each node has a single interface, the proposed PCC with MCC significantly outperforms the other schemes in the entire range of the number of nodes. When each node uses two interfaces under MCMR, the throughput performance is much higher than the other schemes in Fig. 7(a) because relay nodes can simultaneously transmit data packets while receiving packets from its previous node. Even though MCMR using two interfaces significantly increases the throughput performance, the throughput performance per one interface is similar with that of the proposed PCC+MCC. In Fig. 7(b), the proposed PCC achieves the highest throughput performance with the proposed

MCC.

VII. Related Work

A. Power Control

Power control has been extensively studied in ad hoc wireless networks. Ramanathan *et al.* proposed the CONNECT and BICONN-AUGMENT algorithms [3], which aimed to adjust the transmission power in multihop wireless networks. Narayanaswamy *et al.* proposed COMPOW [4], which allows nodes to use a common minimum transmission power that is sufficient to guarantee network connectivity. For a topology with homogeneously dispersed nodes, Kawadia *et al.* proposed CLUSTERPOW and tunnelled CLUSTERPOW [5], which increase the network capacity by using power control, clustering, and routing techniques. The authors also presented MINPOW [5], which can minimize power consumption, providing power optimal routing.

Wang *et al.* [6] proposed RTS/CTS-based MAC protocols, where each link attempts to minimize its transmission power to maximize the spatial utilization in the network. Muqattash and Krunz proposed POWMAC [7], which is a single-channel power control MAC protocol with a single transceiver to exchange the interference information. POWMAC can achieve significant throughput enhancement over the IEEE 802.11 protocol. Kim *et al.* devised PRC [8] that is based on the level of spatial reuse determined by the relationship between the transmission power and the carrier sense threshold. PRC allows each transmitter to use the highest data rate while minimizing the effect of interference to other neighboring nodes. Mwamila *et al.* proposed a centralized power control algorithm [9], in which all nodes increase the common transmission power until the maximum node degree of a network interference graph Δ reaches $(C-1)$, i.e., $(\Delta+1) \leq C$, because the greedy coloring can color at most Δ+1 colors in any graph. The problem is that if one node has a large degree comparable to C, all nodes stop their transmission power adjustment.

B. Coloring-based Channel Allocation

Brélaz *et al.* proposed DSATUR [19] for channel allocation, where adjacent nodes are assigned with different colors by using the saturation degree. This algorithm was used to assign channels to access points on the basis of an interference graph in wireless LANs [20]–[22]. In wireless LANs, each AP chooses the channel with the smallest number of associated clients, which is considered as the least congested channel, called LCCS [23]. To overcome the limitation of interference recognition in LCCS, Mishra *et al.* presented Hminmax and Hsum [24] to mitigate the effect of interference between APs by considering the weights of each edge. Mishra *et al.* [25] also formulated the centralized channel management as *conflict set coloring*, which considered the communication range and interference relationship of clients in wireless LANs. In [34], [35], greedy heuristic algorithms were proposed to minimize the total interference with partially overlapping channels on the basis of weighted graphs. Wang *et al.* [36] proposed a distributed greedy algorithm for solving a resource allocation problem when primary and secondary users coexisted in wireless networks.

C. Multi-Channel MAC Protocol

So *et al.* proposed MMAC [15], which adopted the IEEE 802.11 power saving mechanism in order to synchronize the clocks between neighboring nodes. In MMAC, two fixed-duration sessions are defined: one for negotiation and the other for data transmission. During a negotiation session, nodes exchange control packets to enable the sender-receiver pairs to communicate with each other on the reserved channel during the following data transmission session. Shi *et al.* proposed AMCP [10] as a method of alleviating starvation problems. In AMCP, each sender-receiver pair chooses a data channel according to its own internal channel table. When an agreement is made, both the nodes switch to the data channel and transfer one DATA/ACK packet, after which they immediately return to the control channel. Luo *et al.* devised CAM-MAC [11], in which the channel and node information was exchanged cooperatively. In CAM-MAC, the basic operation is similar to that of AMCP, except that when the requested channel or receiver is temporarily unavailable, the neighboring nodes can notify the sender of this fact.

On the other hand, McMAC [12] is considerably different in that it can perform a parallel rendezvous on different channels. In McMAC, a node performs periodic channel switching according to its pseudo-random hopping sequence. If there are any pending messages in the queue, a sender temporarily deviates from its default sequence and then transmits them to a receiver on another channel. In SSCH [13], nodes periodically tune into another channel according to a randomized hopping sequence. If a sender wants to transmit a packet to a receiver, it first attempts to rendezvous with its corresponding recipient and then changes its hopping schedule so that its schedule can overlap with that of the receiver. Patel *et al.* [14] divided a network into several sub-networks and then allocated different channel hopping sequences to each network. In this scheme, the transmission sequence is scheduled such that each sub-network can rendezvous with another sub-network on every channel hop.

VIII. Conclusion

In this paper, we have considered how to improve network throughput performance by allowing a node to use the highest transmission rate without interfering with its neighboring nodes. We proposed the PCC algorithm to maximize the network throughput performance by fully exploiting the multi-channel availability. The proposed algorithm enables each node to use high transmission power as long as different orthogonal channels can be assigned to its adjacent nodes. Once the network topology is constructed, the MCC protocol can efficiently coordinate data transmissions among nodes that reside on different orthogonal channels. Through extensive simulations, we then showed that the proposed algorithm achieves high network throughput performance.

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