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A Channel Management Protocol for Multi-Channel, Single-Radio 802.11-based Wireless Mesh Networks

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***Abstract*—Wireless mesh networks (WMNs) have emerged as a key technology for next-generation broadband wireless access. While benefiting from larger coverage, WMNs also suffer from some scalability problems in terms of throughput, delay, and packet delivery ratio faced by all multi-hop wireless networks. Using multiple channels is a cost-effective solution to these problems. In this paper, we propose a channel management protocol for multi-channel, single-radio 802.11-based wireless mesh networks. In such an environment, two issues should be addressed: *channel assignment* and *channel switch scheduling*. Therefore, most existing multi-channel solutions involve a channel assignment scheme and a scheduling scheme to determine nodes' behaviors at different times. However, we observe that channel switching of some mesh points may not be necessary under this environment. In fact, even without channel switching, the benefit of using multiple channels (spatial reuse) can still be achieved. In this work, mesh points are divided into two sets. Those in the first set will be assigned channels and stay in the assigned channels to transmit/receive packets. On the other hand, those in the second set will switch to proper channels dynamically. With this design, a lot of channel switching overheads (switching delay, synchronization drift, etc.) can be mitigated. Extensive simulations are conducted to verify the efficiency of the proposed protocol.**

Keywords: channel management protocol, IEEE 802.11, IEEE 802.11s, wireless mesh network (WMN), wireless network.

I. Introduction

Wireless Mesh Networks (WMNs) provide a possibility to offer broadband wireless access for the areas where wired infrastructure is not available or not worthy to deploy [1]. Moreover, due to its self-configuring and self-healing capabilities, a WMN can be deployed and maintained easily. A WMN consists of a collection of mesh points, which cooperatively form a multi-hop backbone network. In this paper, we focus on IEEE 802.11-based WMNs where mesh points communicate with each other by IEEE 802.11 radio interfaces, and end users can connect to mesh points, which will forward traffics on behalf of them. Furthermore, some mesh points can serve as gateways to provide Internet access. An example of a WMN is shown in Fig. 1.

While benefiting from larger coverage, WMNs also suffer from some scalability concerns in terms of throughput, delay, and packet delivery ratio faced by other multi-hop wireless networks [2]. There are many approaches to addressing these concerns, such as using directional antennas, adopting transmission power control, assisting by location information, exploiting multiple channels, etc. Observing that most existing wireless interfaces provide multiple channels [3], [4], we look for cost-effective, multiple-channel solutions for WMNs. Multi-channel solutions have been studied intensively [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24]. Considering the number of radios per node, these protocols can be further categorized on *single-radio* and *multi-radio* schemes.

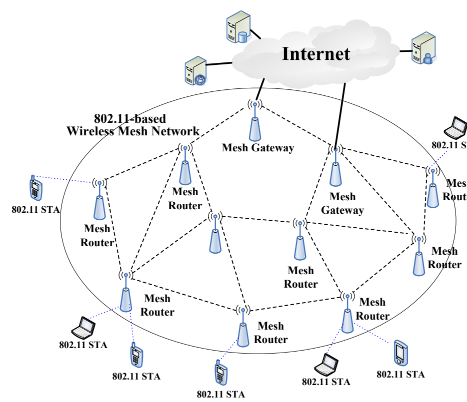

Fig. 1. An example of a WMN.

Taking practicality and cost effectiveness into consideration, this work proposes a multi-channel, single-radio solution for IEEE 802.11-based WMNs. Compared to previous multi-channel, single-radio solutions [10], [12], [16], our solution take both the routing and the network structure into consideration. Because each node has only one radio, it has to switch its operational channel periodically to ensure network connectivity when multiple channels are used. Usually, two issues should be addressed. One is *channel assignment* and the other is *channel switch scheduling*. In most literatures, these two issues are considered simultaneously; that is, each node needs two algorithms, a channel assignment algorithm and a channel switch scheduling algorithm, to determine its behavior.

In this paper, we propose a multi-channel, single-radio (MCSR) protocol for tree-based WMNs. We observe that even if some mesh points do not switch their operational channels, the network connectivity and the benefit of using multiple channels can still be achieved. This may significantly reduce a lot of channel-switching overheads. In our protocol, mesh points are divided into two sets. Mesh points in the first set will be assigned fixed channels to transmit/receive packets. On the other hand, mesh points in the second set will switch their operational channels dynamically according to their communication counterparts. We will develop three channel assignment algorithms to allocate channels to the mesh points in the first set. We will also develop a channel switching algorithm to help mesh points in the second set to determine their channel hopping schedule. A special feature of our protocol is that a mesh point needs to perform either channel assignment algorithm or the channel switching algorithm, but not both. In fact, our scheme does enforces the first set of mesh points to interleave with the second set of mesh points in the tree topology. This actually simplifies the design of our channel switching algorithms because whenever the second set of nodes want to transmit/receiver packets, they can switch to channels of the first set without considering their channel switching patterns. By this design, we believe that the side-effect of channel switch (such as channel switch delay, synchronization drift, etc.) can also be significantly mitigated.

The rest of this paper is organized as follows. We make an observation to motive our work in Sec. II. We present our proposed protocol in Sec. III. Performance studies are given in Sec. IV. Conclusions are drawn in Sec. V.

II. Observation

In [22], it has been shown that in a chain topology an ideal multi-channel MAC protocol could achieve an end-to-end throughput as high as $\frac{1}{2}$ of the effective MAC data rate in a single-radio, multi-channel WMN. Fig. 2 shows two possible channel switching schedules. In Fig. 2(a), each node switches between two channels. Continuous packets sent from A to F can form a perfect pipeline effect separated by two hops. Interestingly, the schedule in Fig. 2(b) has a similar effect, but only half of the nodes need to switch channels. The other half can stay in the assigned channels. With this design, a lot of channel switching overhead (such as switching delay, synchronization drift, etc.) can be mitigated.

Our design will also lead to the following benefits:

- *Improved Channel Reuse*: The very idea of channel reuse is to exploit the most compact spatial reuse pattern of each channel. However, if a node owns a fixed channel without using it (for examples, it may switch to another channel to communicate with other nodes), then that channel could be wasted. Our scheme can effectively avoid this problem because only some nodes have fixed channels. In fact, our scheme has the concept of compactness in mind when choosing those nodes with fixed channels.
- *Mitigated Collision*: Since our scheme enforces nodes with fixed channels to interleave with those without fixed channels, a lot of multi-channel hidden-terminal and missing-receiver problems can be avoided.
- *Simplified Channel Switching*: Since nodes without fixed channels will only communicate with those with fixed channels, the former can always find the latter (at the right channels) whenever they intend to. This will significantly simplify our design of channel switching.

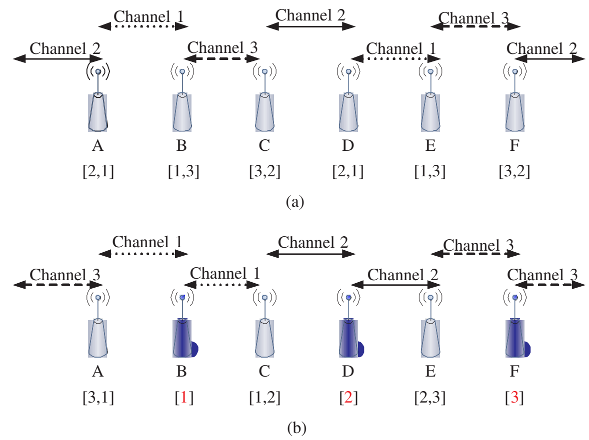

Fig. 2. Two ideal channel switching schedules in a chain WMN that can achieve the optimal pipeline effect.

III. The Proposed Channel Management Protocol

A. Network Model

We consider an 802.11-based WMN with one mesh point serving as the gateway. We assume that the WMN is mainly for providing Internet services, so most traffics will go through the gateway. There are multiple non-overlapping channels available. Each mesh point has one wireless radio, except that for performance reason the gateway has multiple radios equal to the number of available channels.

For such a multi-channel, single-radio WMN, we need a channel management protocol to help a mesh point to determine its channel and a channel scheduling protocol to determine its channel-hopping pattern. The main idea of our work is to divide mesh points into two sets V and V'. Each mesh point in V will be assigned a *fixed* channel, while each in V' will not have a fixed channel but will switch to a proper *operational* channel channel at proper time.

To determine V and V', we will construct a tree T rooted at the gateway (any such algorithm, such as HWMP[25], can be used here). Let the root be at level 0. Then, mesh points in the odd levels of T will be assigned to V, and those in the even levels of T will be assigned to V'. An example is shown in Fig. 3.

Our scheme works in a TDMA-over-CSMA manner. Time is divided into equal-length superframes. Each superframe consists of k slots. The first slot is used not only for supporting

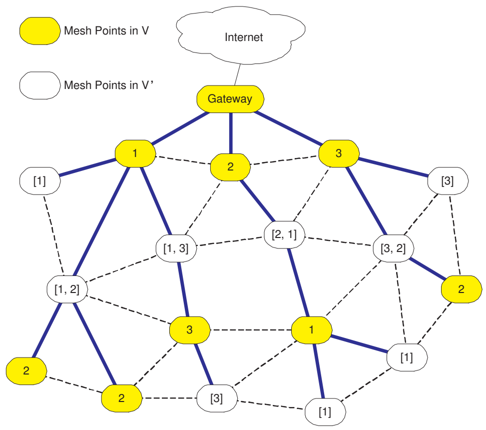

Fig. 3. An example of our proposed network architecture. Solid lines are tree edges and the dotted lines mean neighboring relations. The numbers labeled on the mesh points in V denote their fixed channels and the numbers labeled on the mesh points in V' are their switchable operational channels.

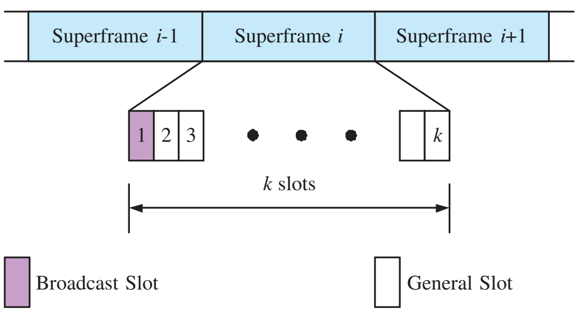

Fig. 4. The superframe structure of our protocol.

broadcast but also for sending out the channel switching schedules for nodes in V'. So mesh points must switch to the same default channel. For the other $k-1$ slots, node in V will switch to their fixed channels (refer to Sec. III-B) and nodes in V' will switch to different slots according to schedules (refer to Sec. III-C). Fig. 4 shows the superframe structure. Inside each slot, node will contend the medium using a typical CSMA protocol (such as IEEE 802.11). We assume that each slot is large enough to accommodate several packet transmissions.

B. Channel Assignment Algorithms for V

During general slots, each mesh point x in V will own a fixed channel for transmissions. We propose three strategies for x to choose its fixed channel.

- ***Interference-Based Strategy*** : The operation will be triggered from the gateway. When a mesh point x is triggered and gets all of its 2-hop neighbors' permission, x will choose the least used channel used by its 2-hop neighbors as its fixed channel to minimize potential interference. However, x should also avoid using the same channel as its grandparent to prevent collisions at x's parent. Then, x will trigger its 2-hop neighbors in T to choose their fixed channels. Fig. 5(a) shows a partial network with $y \in V'$. Assuming four available channels, Fig. 5(b) shows the assignment result.
- ***Delay-Based Strategy***: The above strategy intends to minimize interference, but it may lead to long delay for y because y has to switch among four operational channels. To relieve this problem, this strategy tries to enforce all children of $y \in V'$ to choose the same fixed channel (refer to Fig. 5(c) for an example). Therefore, y only needs to switch between two channels. The operation is also triggered from the gateway. When a node $x \in V$ is triggered, it will try to get all of its 2-hop neighbors' permission to choose a channel. The channel-selecting rules are as follows:
    1) If x is a child of the gateway or none of its siblings has owned a channel, it will choose the least used channel among its 2-hop neighbors except the one used by its grandparent as its fixed channel.
    2) Otherwise, x chooses the same channel used by any of its siblings as its fixed channel.
- ***Hybrid Strategy***: It can be seen that although the delay-based strategy can decrease delay, the corresponding interference among y's childrenmight be raised. In fact, latency and interference are conflicting factors. To balance these concerns we propose a hybrid strategy (refer to the example in Fig. 5(d)). The triggering operation is the same. When any $x \in V$ gets permission from all its 2-hop neighbors, the following rules are checked.
    1) If x is a child of the gateway or none of its siblings has owned a channel, it will choose the least used channel among its 2-hop neighbors except the one used by its grandparent as its fixed channel.
    2) Otherwise, if one of x's one-hop siblings has owned a fixed channel, it will choose that channel as its fixed channel.
    3) Otherwise, only x's two-hop siblings have owned fixed channels. Then x will choose the least used channel (which is different from its two-hop siblings) among its two-hop siblings as its fixed channel.

It remains to state how a node gets permission from its 2-hop neighbors to choose channel. Let $x.ID$ and $x.LVL$ be the ID and level of x, respectively. For two mesh points x and y, we say $x < y$ if $(x.LVL < y.LVL) \vee (x.LVL = y.LVL \wedge x.ID < y.ID)$. A node is triggered when it receives a CHL_GRANT message. When an odd-level node x receives the CHL_GRANT, it will send a CHL_REQ to its one-hop and two-hop neighbors. When a mesh point y receivers a CHL_REQ from x, it will send a CHL_GRANT to x if $y.LVL$ is even. If y does not own a channel yet and $y > x$, y will send a CHL_GRANT to x. Otherwise, y will keep on waiting for others' CHL_GRANTs. Once x receives all CHL_GRANTs from all its one-hop and two-hop neighbors, it can select its fixed channel based on the earlier strategies. After that, x will send a CHL_GRANT to all its one-hop and two-hop neighbors.

Note that when packet loss is possible, a node can proactively ask for CHL_GRANTs from its neighbors.

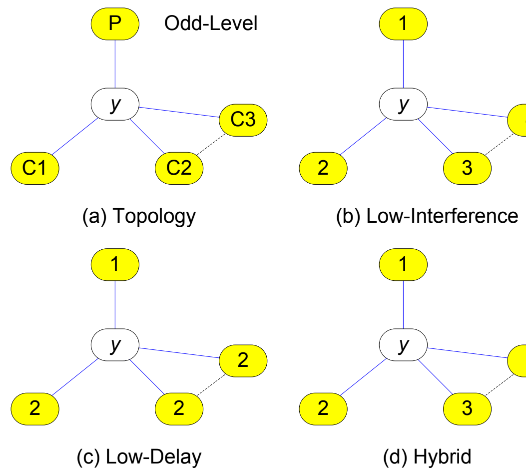

Fig. 5. Examples of different channel assignment strategies. (a) Network topology. (b) Interference-based strategy. (b) Delay-based strategy. (c) Hybrid Strategy.

C. Channel Switching Schemes for V'

Next, we present how a mesh point $y \in V'$ switches its operational channel in the $k-1$ general slots of a superframe. It is clear that if y is a leaf node, it is sufficient to always set its operational channel to its parent's fixed channel. So we only consider a non-leaf y below. We propose a scheme that allows y to switch its operational channel dynamically based on traffic conditions.

In this scheme, traffic conditions will be exploited. In the first slot of each superframe, each node $y \in V'$ will announce its channel switching schedule. Let $PC(y)$ be the set of y's parent and children. We define two terms. For each $z \in PC(y)$, let $f(y,z,i)$ be the traffic load between y and z estimated by y in superframe i (this can be measured by, say, the number of packets transmitted between them and the backlog at y destinated to z). Further, we define $F(y,z,i)$ as the weighted traffic load between y and z estimated by y until the i-th superframe. such that

- For each $z \in PC(y)$, define $F(y,z,i)$ as the weighted traffic flow between y and z estimated by y until the i-th superframe. More specifically, the recursive definition of $F(y,z,i)$ is as follows:

$$F(y,z,i) = \begin{cases} \alpha \times f(y,z,i-1) + & \\ (1-\alpha) \times F(y,z,i-1) & ,i > 2 \\ f(y,z,1) & ,i = 2 \\ 1 & ,i = 1 \end{cases} \quad (1)$$

  where $0 \leq \alpha \leq 1$.

Based on $F(y,z,i)$, y calculates its slot allocation as follows. First, it will reserve one slot for each member in $PC(y)$. Here we assume that $(k-1) \geq |PC(y)|$. Then, the remaining slots will be allocated evenly to members in $PC(y)$. More precisely, the number of slots allocated to $z \in PC(y)$ will be

$$\left\lfloor ((k-1) - |PC(y)|) \times \frac{F(y,z,i)}{\sum_{\ell \in PC(y)} F(y,\ell,i)} \right\rfloor + 1. \quad (2)$$

Note that since a floor function is used, some slots will actually be free. We can distribute these slots to $PC(y)$ based on some round-robin scheme. Also, locations of these slots can be permuted with others' slots to ensure fairness.

TABLE I
THE DEFAULT VALUES OF PARAMETERS USED IN THE SIMULATION.

Underlining MAC	IEEE 802.11b with RTS/CTS
Simulation Area	100 units x 100 units
Transmission range	25 units $\sim$ 45 units
Link capacity	2 Mbps
Flow data rate	300 kbps (for each flow)
Channel Switch Delay	12 ms
Slot size	400 ms
Data frame size	512 bytes
Number of available channels	3
Number of slots in one frame	11
Simulation Time	200 s
The buffer size	200 packets (per node)

IV. PERFORMANCE EVALUATION

We have developed an in-house simulator to verify the performance of our channel management protocol by executing comprehensive simulations. We compare our protocol with the single-channel scheme. We also modify JMM[22] so that we can compare our protocol with it. In the simulation, 25 mesh points are deployed as a 5×5 grid network. We assume that each node equips only one radio except for the gateway equipping 3 radios and 3 non-overlapping channels are available. Two types flows are simulated: up-link flow and down-link flow. In up-link flow, traffic flows from the mesh points to the gateway. In down-link flow, traffic flows from the gateway to the mesh points. 80% down-link and 20% up-link flows are used in our experiments. The impact of channel switching is an important issue. Thus, channel switch delay and time synchronization error are simulated. Besides, each result is achieved by averaging 20 runs. The default values of parameters are shown in Table I.

Fig. 6 shows the simulation results. We can see that the single channel scheme has the worst performance because it does not benefit from multiple available channels. Our protocol outperforms the MJMM no matter which channel assignment strategy is used. The major reason is that our protocol reduces the channel switch overhead. We allow that several packets can be transmitted in a slot. Thus, when packets arrives at mesh points in V, mesh points in V can forward these packets immediately in the same slot. Thus, mesh points do not need to store many packets in their buffers. This can relieve the buffer overflow problem. This can be verified by Fig. 7. We can see that our protocol has the best performance in terms of the packet drop rate. (The packet drop rate is defined as the ratio of the number of packets dropped to the number of packet generated.) We can further observe that if there exists

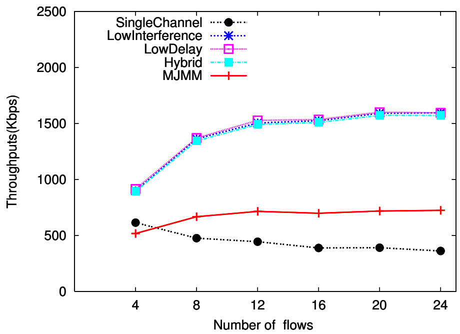

Fig. 6. Comparison of throughput performance under a 5×5 grid network.

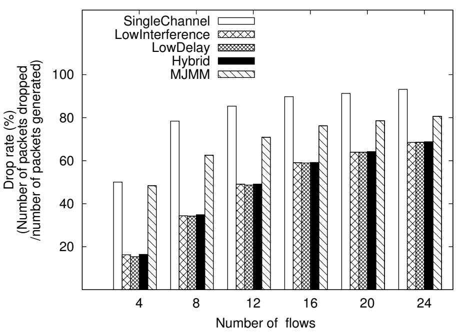

Fig. 7. Comparison of packet drop rates under a 5×5 grid network.

one quality of service (QoS) demand of 50% packet drop rate, our protocol can support up to 12 traffic flows transmission. Both MJMM and the single channel scheme can support about 4 traffic flows. Finally, we can see that the channel assignment strategies do not impact on performance deeply.

V. Conclusions

In this paper, we propose a channel management protocol to mitigate channel switching overhead and increase network throughput. Our protocol is a distributed and hierarchical approach to deploy a multi-channel environment in tree-based wireless mesh networks. Simulation results also demonstrate the efficiency of the proposed protocol.

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References

[1] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Computer Networks*, vol. 47, no. 4, pp. 445–487, March 2005.
[2] M. Gerla, R. Bagrodia, L. Zhang, K. Tang, and L. Wang, "TCP over Wireless Multihop Protocols: Simulation and Experiments," in *Proceedings of the IEEE International Conference on Communications (ICC)*, June 1999.
[3] IEEE 802.11 Working Group, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications," 1997.
[4] IEEE 802.11a Working Group, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications - Amendment 1: High-speed Physical Layer in the 5 GHz band," 1999.
[5] M. X. Gong and S. F. Midkiff, "Distributed Channel Assignment Protocols: A Cross-Layer Approach," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, March 2005.
[6] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *Proceedings of the ACM International Conference on Mobile Computing and Networking(MobiCom)*, September 2004.
[7] A. Raniwala and T. cker Chiueh, "Architecture and Algorithms for an IEEE 802.11-Based Multi-Channel Wireless Mesh Network," in *Conference on Computer Communications (INFOCOM)*, March 2005.
[8] P. Kyasanur and N. H. Vaidya, "Routing and interface assignment in multi-channel multi-interface wireless networks," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, March 2005.
[9] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng, and J.-P. Sheu, "A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks," in *International Symposium on Parallel Architectures, Algorithms, and Networks (I-SPAN)*, December 2000, pp. 232–237.
[10] J. So and N. H. Vaidya, "Multi-channel MAC for Ad Hoc Networks: Handling Multi-channel Hidden Terminals Using a Single Transceiver," in *Proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, May 2004, pp. 222–233.
[11] A. Adya, P. Bahl, J. Padhye, A. Wolman, and L. Zhou, "A Multi-Radio Unification Protocol for IEEE 802.11 Wireless Networks," in *International Conference on Broadband Networks (BROADNETS)*, October 2004, pp. 344–354.
[12] P. Bahl, R. Chandra, and J. Dunagan, "SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Ad-hoc Wireless Networks," in *Proceedings of the ACM International Conference on Mobile Computing and Networking(MobiCom)*, September 2004.
[13] A. Nasipuri, J. Zhuang, and S. Das, "A Multichannel CSMA MAC Protocol for Multihop Wireless Networks," in *Proc. of IEEE Wireless Communications and Networking Conference (WCNC)*, September 1999.
[14] N. Jain, S. Das., and A. Nasipuri, "A Multichannel CSMA MAC Protocol with Receiver-Based Channel Selection for Multihop Wireless Networks," in *IEEE International Conference on Computer Communications and Networks (IC3N)*, October 2001.
[15] A. Nasipuri and S. R. Das, "Multichannel CSMA with Signal Power-Based Channel Selection for Multihop Wireless Networks," in *IEEE Vehicular Technology Conference (VTC)*, September 2000.
[16] A. Tzamaloukas and J. Garcia-Luna-Aceves, "A Receiver-Initiated Collision-Avoidance Protocol for Multi-Channel Networks," in *Proceedings of IEEE INFOCOM*, 2001.
[17] J. S. Pathmasuntharam, A. Das, and A. K. Gupta, "Primary channel assignment based MAC (PCAM) - a multi-channel MAC protocol for multi-hop wireless networks," in *Wireless Communications and Networking Conference (WCNC)*, March 2004.
[18] S.-C. Lo and C.-W. Tseng, "A Novel Multi-Channel MAC Protocol for Wireless Ad Hoc Networks," in *Vehicular Technology Conference, 2007. VTC2007-Spring.*, April 2007, pp. 46–50.
[19] J. Chen and Y.-D. Chen, "AMNP: Ad Hoc Multichannel Negotiation Protocol for Multihop Mobile Wireless Networks," in *Proceedings of the IEEE Interneational Conference on Communications (ICC)*, June 2004.
[20] Q. Xue and A. Ganz, "Temporal Topologies in Multi-channel Multihop Wireless Access Networks," in *International Conference on Broadband Networks (BROADNETS)*, October 2005.
[21] R. Vedantham, S. Kakumanu, S. Lakshmanan, and R. Sivakumar, "Component Based Channel Assignment in Single Radio, Multi-channel Ad Hoc Networks," in *ACM International Conference on Mobile Computing and Networking (MOBICOM)*, May 2006, pp. 378–389.
[22] W.-H. Tam and Y.-C. Tseng, "Joint Multi-Channel Link Layer and Multi-Path Routing Design for Wireless Mesh Networks," in *Conference on Computer Communications (INFOCOM)*, May 2007.
[23] F.-Y. Leu, I. You, and Y.-T. Huang, "A coordinated multiple channel assignment scheme and ap deployment for channel reuse in metropolitan scale wireless networks," *Journal of Network and Computer Applications*, vol. 34, no. 2, pp. 632–643, March 2011.
[24] S. Jiang and Y. Xue, "Providing survivability against jamming attack for multi-radio multi-channel wireless mesh networks," *Journal of Network and Computer Applications*, vol. 34, no. 2, pp. 443–454, March 2011.
[25] IEEE, "Draft amendment: ESS mesh networking," *IEEE P802.11s/D1.07*, September 2007.