Routing in Multi-Channel Wireless Ad-hoc Networks: OSPF-MCDS-MC

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Abstract* – The availability of low-cost network interface cards (NICs) has made the IEEE 802.11 medium access control (MAC) protocol the de facto MAC standard for wireless mobile ad-hoc networks. Although the IEEE 802.11 MAC protocol is designed to have stations share a single channel in a network, many of the IEEE 802.11 physical (PHY) layer standards define multiple channels and allow the simultaneous, non-interfering use of some of these channels. Therefore, simultaneous communications can occur through different channels, offering the opportunity to increase effective network capacity. We present an innovative routing protocol that utilizes multiple channels to improve performance in a mobile ad hoc network. The key feature of the protocol is that nodes can effectively use multiple channels for simultaneous useful transmissions, thus improving network capacity. The proposed scheme requires minor changes to existing proactive or table-driven routing protocols and no modifications to current the IEEE 802.11 MAC protocol. To mitigate the overhead of periodic updates in proactive routing protocols, the proposed scheme divides the network layer into control and data planes. To demonstrate the multi-channel routing scheme, we extend the OSPF-MCDS routing protocol to a multi-channel version, OSPF-MCDS-MC or, more simply, OMM. Simulation and experimental results indicate OMM successfully exploits multiple channels to increase network capacity. The protocol allows the network goodput to increase in proportion to the number of available channels, even as the number of nodes and network load increase, in both single-hop and multiple-hop networks. We also present a prototype implementation for experimental validation of the proposed multi-channel routing protocol scheme. The implementation includes the multi-channel routing protocol and a virtual interface module, which acts as a buffer for outgoing packets and performs channel-related functions, such as channel selection and switching, while ensuring portability.

Index Terms - **wireless ad hoc networks, mobile ad hoc networks, multi-channel routing, ad hoc routing protocols**

I. INTRODUCTION

Despite the fact that it is not optimal, the availability of low-cost, commodity network interface cards has made the IEEE 802.11 medium access control protocol [1] the de facto standard for wireless mobile ad-hoc networks (MANETs). The IEEE 802.11 MAC protocol is designed to share a single channel in a given network. Some of the IEEE 802.11 physical layer specifications define multiple channels and allow the simultaneous, non-interfering use of some of these channels, but the MAC layer uses only a single logical channel provided by the PHY. Since a single channel is used for a network, the MAC protocol is likely to face significant throughput degradation as the number of active nodes and the load increases. By using multiple channels, simultaneous communications can occur to increase effective network capacity [2]. The challenge, however, is to allow a single ad-hoc network to use the multiple channels provided by a PHY layer simultaneously in an efficient manner to increase effective capacity.

Several advantages are expected using multiple channels in wireless ad-hoc networks, such as increased throughput, reduced propagation delay, and the provision of additional services using multiple channels. In this proposal, a new routing protocol is proposed to use multiple channels, e.g., realized at different frequencies, in a wireless multiple-hop ad-hoc network by equipping nodes with multiple NICs. A complete multi-channel wireless ad-hoc network architecture requires topology discovery, traffic profiling, channel assignment, and routing [3].

The proposed proactive routing protocol, Open Shortest Path First-Minimal Connected Dominating Set with Multiple Channels (OSPF-MCDS-MC or OMM), an extension of OSPF-MCDS [4], provides not only a routing mechanism, but, also, a method to gather channel information to enable efficient channel assignment. One of the available channels is dedicated to control messages and the remaining one or more channels are used for data

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transfers. We consider in detail the case where each host is equipped with two transceivers, so that a host can listen on the control channel and one data channel concurrently. Hosts exchange routing messages, which include channel information, using the control channel. Simulation experiments are performed for both single-hop and multiple-hop networks to study performance and to verify the operation of the proposed protocol. Simulation results indicate that the proposed routing protocol provides the benefits of using multiple channels without modification to the current IEEE 802.11 MAC or PHY protocols. We show that routing overhead is not significant because hosts use the common control channel to advertise routing information.

In this paper, we extend these results by implementing and verifying the proposed protocol. The prototype implementation includes two major components, the multichannel routing protocol, OMM, and a Virtual Interface Module. OMM performs the generic routing functions including exchange of channel information and communication with the VIM for the interchange of channel information. The VIM is a logical network interface that does not provide any actual physical packet transmission. The VIM does perform channel-related functions, such as packet lookup, channel switching, and forwarding packets to physical interfaces, while maintaining portability and transparency. The idea of a virtual interface can be useful to implement special-purpose processing on data packets, while avoiding the complexity of changes to the kernel's network subsystem.

This paper is organized as follows. Section II reviews related work. Section III describes the OSPF-MCDS routing protocol and discusses issues related to effectively utilizing multiple channels. Section IV describes the proposed OMM protocol in detail. In Section V, we present and discuss simulation results. Section VI discusses the prototype implementation and insight gained from the implementation. Finally, Section VII draws conclusions and discusses potential future research.

II. RELATED WORK

There have been a number of investigations of multichannel schemes for ad-hoc networks in recent years. Multi-channel schemes can be broadly categorized according to their realization at the MAC (Layer 2) or network layer (Layer 3). Research on multi-channel MAC protocols is typically based on IEEE 802.11. Previously proposed multi-channel MAC protocols usually require modification to the IEEE 802.11 MAC and, therefore, cannot be deployed by using commodity hardware. In contrast, prior research focusing on network layer implementation typically makes use of standard IEEE 802.11 NICs. Key examples of these two approaches are described below.

A. MAC Approaches

Past multi-channel MAC schemes require changes to the IEEE 802.11 MAC and, thus, new hardware. For synchronization and communication between nodes, control messages need to be shared among nodes for channel reservation or negotiation. Neighboring nodes might use a common control channel or a common time period to exchange control information.

Dynamic Channel Assignment (DCA) proposed by Wu, et al. [5] assigns channels dynamically in an on-demand manner. The protocol assigns one channel for control messages and uses other channels for data. Each host has two transceivers so that it can listen on the control and data channels simultaneously. Nodes exchange Request-to-Send (RTS) and Clear-to-Send (CTS) frames on the control channel and the data channel is assigned using RTS and CTS messages. This protocol does not require tight synchronization. However, as the number of available data channels increases, the bottleneck in the control channel prevents full utilization of data channels.

Li, Haas, Sheng, and Chen [6] propose a modified IEEE 802.11 MAC protocol for multiple channels that includes a new channel-status indicator. One channel is designated as the common control channel and the other channels are data channels. Data packets and the associated acknowledgment packets are transmitted through the traffic channel. Nodes exchange RTS and CTS frames with channel information over the common control channel to make a channel reservation for transmission of data packets. After a successful exchange for channel negotiation, nodes change the working channel to the channel they negotiated. Nodes reside on the common access control channel, except when they transmit data on one of the traffic channels. Other nodes listening to the common control channel set their network allocation vector (NAV) and defer transmissions to the node that is transmitting or receiving.

Hung, Law, and Leon-Garcia [7] propose a new MAC protocol, Dynamic Private Channel (DPC), which uses multiple channels in an ad-hoc network to solve two problems, connectivity and load balancing, while maintaining good performance. These two problems can occur when the current IEEE 802.11 MAC protocol is used in multi-channel environments. DPC is connection oriented. Two mobile nodes (transmitter and receiver) negotiate the channel by exchanging RTS, Reply-to-RTS (RRTS), and CTS messages through a multicast Control Channel (CCH) before data exchange. Once a unicast Data Channel (DCH) is assigned to a transmitter-receiver pair, this channel is no longer shared. The communication ends either when they have no more data to exchange or when the reservation period expires. As acknowledged in [7], the blocking effect in DPC has a significant impact on performance. In addition, different blocking problems can occur if a node has multiple connections since a single transceiver is dedicated to a DCH.

Wiwatthanasaranrom and Phonphoem [8] propose a Multi-channel MAC (MMAC) protocol that utilizes multiple channels. Instead of a dedicated channel for channel negotiation, each node in the protocol negotiates channel assignments during IEEE 802.11's Ad-hoc Traffic Indication Messages (ATIM) window, which occurs at a fixed time after the beacon. The protocol requires only a single transceiver at each host and a separate common control channel. After successful channel negotiation during the ATIM window, nodes switch to the negotiated channel and exchange messages on the channel for the rest of the beacon interval. Each host periodically sends out beacons to synchronize time in a distributed manner as in IEEE 802.11. However, the time multiplexed control channel requires clock synchronization among all nodes in the network, which is difficult in a large multiple-hop ad-hoc network due to their dynamic nature.

B. *Network Layer Approaches*

Alicherry, Bhatia, and Li [9] mathematically formulate the joint channel assignment and routing problem, taking into account the interference constraints, the number of channels in the network, and the number of radios available at each mesh router in a mesh network. Their research targets infrastructure wireless mesh networks (IWMNs). In IWMNs, topology change is infrequent and the variability of aggregate traffic demand from each mesh router (client traffic aggregation point) is small. These characteristics allow periodic optimization of the network that may be done by system management software based on traffic demand estimation.

Raniwala, Gopalan, and Chiueh [3] propose a multichannel ad-hoc network architecture for wireless mesh networks. They develop centralized channel assignment, bandwidth allocation, and routing algorithms for multichannel wireless mesh networks. The proposed scheme assumes that a virtual link is formed between any two nodes that are within communication range of each other. However, a communication channel is required among nodes to build a virtual link. Additionally, their algorithm is based on heuristics and a worst performance bound on its performance is not known [9].

Gong and Midkiff [10] propose a family of distributed channel assignment protocols that combine routing with channel assignment using a single transceiver. They employ a cross-layer approach and present an example based on the Ad-hoc On-demand Distance Vector (AODV) routing protocol [11]. The scheme achieves significantly lower communication, computation, and storage complexity than existing channel assignment schemes, largely due to combining channel assignment with routing.

Kyasanur and Vaidya [12] study the problem of improving the capacity of multi-channel wireless networks by using a different interface for each channel. They provide a classification of interface assignment strategies and propose a new strategy that does not require modification of IEEE 802.11.

Compared to previous research, our scheme focuses on using a proactive routing protocol to assign a channel to each node and to deliver channel information in a fully distributed manner. Our protocol does not require synchronization among nodes. It assigns channels without using per-packet negotiation, which eliminates the overhead and delay before data transmission required for MAC-based channel negotiation. Our scheme provides a simple way to utilize multiple channels at the cost of dedicating one channel for control messages. Our scheme also allows the use of standard, unmodified IEEE 802.11 NICs.

III. BACKGROUND

This section briefly describes the OSPF-MCDS routing protocol and discusses channel assignment and the implications of the number of available interfaces.

A. *The OSPF-MCDS Routing Protocol*

OSPF-MCDS is a table-driven proactive MANET routing protocol that regularly exchanges topology information with other nodes [4]. It dynamically chooses nodes to form a minimal connected dominating set (MCDS) and only nodes in the MCDS re-broadcast the first-seen control messages sent by neighbors. Thus, the number of rebroadcasts is reduced. Link state information is propagated through the network via MCDS nodes so that all nodes in network keep identical and full topology information.

Dijkstra's algorithm [13] can be used to determine the shortest path to the destination. MCDS nodes are selected based on a heuristic algorithm and, as a set, cover all nodes in a network. Therefore, all nodes are guaranteed to receive propagated link state information via the MCDS nodes. The MCDS is used as the relay node set to replace the designated router concept used in the OSPF routing protocol [14, 15], which is widely used in traditional wired networks.

B. *Channel Assignment*

Channel assignment schemes can be categorized as Fixed Channel Allocation (FCA), Dynamic Channel Allocation (DCA), or Hybrid Channel Allocation (HCA) schemes, based on the flexibility of assigning channels to nodes [16]. In FCA schemes, a channel is assigned to each node according to some reuse pattern depending on the desired network size and the number of available channels at the time of network initialization. The FCA scheme is simple, but it does not adapt to changing traffic conditions and node mobility. DCA can overcome these deficiencies of FCA. In the DCA scheme, all channels are placed in a pool and assigned to new connections. At the cost of higher complexity, DCA provides flexibility to accommodate changing traffic conditions. However, DCA is less efficient than FCA under conditions of high node mobility due to the need to frequently change channel assignments. To overcome this drawback, HCA combines features of both FCA and DCA.

Channel assignment schemes can be implemented in a centralized or distributed fashion [3]. In a centralized scheme, a central controller assigns channels, while in a distributed scheme nodes select channels autonomously. In autonomously organized distributed schemes, each node chooses a channel based on its measurement criteria without the involvement of a central controller. The distributed scheme has lower complexity, but at the cost of lower efficiency. Both FCA and DCA can use a distributed assignment scheme based on local information [16].

A distributed channel assignment scheme can be categorized as being a Receiver-based Channel Assignment (RCA), Transmitter-based Channel Assignment (TCA), or Negotiation-based Channel Assignment (NCA) scheme [16]. In RCA schemes, each transmitting node must “tune” to the receiving channel assigned to the destination node. The RCA scheme must find a channel for each node to use to receive packets with the constraint that all logical neighbors of a given node have different receiving channels. In TCA schemes, all neighbors of a given node should have different transmit channels so that no two neighboring nodes can cause a primary conflict. Broadcast and passive acknowledgements are possible with TCA schemes. A receiver must be able to tune to any of its neighbor’s channels. In NCA schemes, a transmitter-receiver pair negotiates to acquire a channel such that no two adjacent pairs in the logical topology use the same channel. A large number of orthogonal channels are needed in a fully connected and heavily loaded network to avoid interference. However, this scheme can result in the utilization of a smaller number of channels than RCA and TCA schemes in a carefully controlled topology [17].

C. *Number of Transceivers*

Multi-channel approaches can be categorized based on the number of transceivers employed and whether nodes require a single transceiver or multiple transceivers. With a single transceiver, a node can access only one channel at a time. However, a single transceiver approach does not necessarily have to be a single channel approach since a transceiver is able to switch from one channel to another. Each node in a multi-channel environment with a single transceiver must perform functions such as negotiating channel allocations and sharing channel information among neighboring nodes. Prior research with a single transceiver relies on a designated period for control messages to which every node in the network should listen [6, 8, 18].

In contrast, nodes with multiple transceivers are able to access different channel simultaneously. Various schemes can be applied to coordinate multiple channels that can be accessed simultaneously using multiple transceivers. One channel can be dedicated to a control channel and the other channels can be used for data exchange [7, 19-24] or each channel can be accessed independently [25].

A more involved scheme is to assign transceivers based on the direction of messages. For instance, a particular channel can be assigned for reception and another channel for transmission. The disadvantage of dedicating a channel to each transmission direction is that the channel can be poorly utilized if message flows in the two directions are highly asymmetric, i.e., the data rate in one direction is far below the data rate in the other direction. However, in special cases such as data collection in a sensor network, dedicating a channel to reception of messages can increase network throughput [26].

IV. MULTI-CHANNEL ROUTING PROTOCOL

In this section, we propose a novel multi-channel routing protocol. We make the following assumptions. First, N data channels are available for use and all channels have the same capacity. None of the channels overlap, so packets transmitted on different channels do not interfere with each other. (Three such channels are available in IEEE 802.11b and 12 are available in IEEE 802.11a.) Nodes have prior knowledge of how many channels are available. Also, each node is equipped with two half-duplex transceivers. A single transceiver can either transmit or listen at a given time, but cannot do both simultaneously. A host equipped with multiple transceivers can listen to or transmit on a different channel simultaneously. We disregard the channel switching overhead since rapid channel switching will become feasible with the availability of better hardware [27]. We assume that no network is present other than the multichannel network, so nodes can use the common control and data channel without interference from other networks. Finally, all links are considered to be symmetric. Consideration of networks with asymmetric links is beyond the scope of this paper.

A. *Design Principles*

Our proposed multi-channel scheme can be combined with any typical proactive routing protocol. Only proactive routing protocols can provide each node with complete or almost complete topology information. This topology information is used for the initial channel assignment and for channel switching for data transmission. However, proactive routing protocols can be inefficient because of the need for periodic updates, regardless of the number of network topology changes and the traffic. To overcome this limitation, our scheme divides the network layer into a control plane and a data plane. Routing control messages use the control plane and user packets (packets from the upper layer) use the data plane. User broadcast and multicast packets are transmitted using the common control channel.

Each node is equipped with two transceivers so that it can listen on the control and data channel concurrently. The proposed routing protocol is compatible with the current IEEE 802.11 ad-hoc network mode of operation without modification to the MAC or PHY protocols. RTS, CTS, and acknowledgment (ACK) MAC control frames, are sent on the same channel as the associated data frame since the standard, unmodified IEEE 802.11 MAC protocol is assumed for all channels.

1) Channel Assignment: The principle for channel allocation is to combine channel assignment with routing. Piggybacking channel information in routing packets is motivated by the fact that each node using a proactive routing protocol maintains a consistent view of the network. In addition, passing channel information in routing control messages can greatly reduce the communication overhead of the channel assignment mechanism. For example, a proposed channel assignment algorithm has a communication complexity of O(d2), where d is the maximum number of one-hop neighbors for any node (maximum network degree) [28]. By carrying channel information through routing messages, the incremental complexity of computation at nodes can be reduced to O(1).

2) Delayed Hello Messages: When a node joins a multi-channel network, it needs to choose an initial data channel. In our scheme, this initial channel is selected based on the channels used by neighboring nodes. The least used channel is selected. Since data channel information is piggybacked with Hello messages, a newly joining node defers sending its own Hello message so that it can receive Hello messages from its neighbors to first build the channel information table for neighboring nodes. It then selects its initial data channel according to the channel information table. Since this process occurs only when a node joins the network, this delay should not impede routing functions, which is verified by simulation experiments and our implementation.

3) Advantages: We expect the following advantages by using the proposed multi-channel routing protocol in a wireless ad-hoc network.

First, no channel negotiation is required as in MAC-based multi-channel schemes [5, 6, 7]. Negotiation for a data channel when packets are available to transmit can lead to significant overhead in both latency and network traffic. When a sufficiently large number of nodes have data to transmit, channel negotiation over the control channel is a bottleneck and prevents data channels from being fully utilized [5, 7, 19]. In the proposed scheme, channel information is piggybacked in routing protocol packets. Therefore, channel information is available to neighboring nodes along with network topology information. Nodes are able to select the data channel of the destination node, or the next hop if the destination is more than one hop away, based on the channel information table without any channel negotiation. Consequently, we can reduce latency and congestion in the control channel.

Second, no channel scanning is required with the proposed scheme. With channel scanning, a node with a packet to transmit must first scan all channels to find the best channel and then select the channel with the lowest sensed power. This scheme provides a way to find the best channel at the sender, which reduces collisions at the receiver. However, the overhead of channel scanning can be high when network loads are heavy and the number of available channels is large [29]. In the proposed scheme, there is no overhead required to scan all available channels since nodes keep the channel information, which is updated as necessary with routing information. This can save time and processing resources.

Third, no synchronization is required. Each node in an ad-hoc IEEE 802.11 network periodically sends out beacons to synchronize time in a distributed manner. When transmitting a beacon, a node includes a timestamp based on its local timer. If a node receives a beacon from another node, it cancels its beacon and adjusts its timer according to the timestamp in the received beacon [1]. This is a relatively straightforward operation for a single-hop network. However, in a multiple-hop ad-hoc network, clock synchronization is a difficult task because of unpredictable communication delays and node mobility, especially when the network is large [8]. Our proposed routing protocol does not require such clock synchronization among nodes.

B. *The OSPF-MCDS-MC Protocol*

To demonstrate the multi-channel routing scheme, we extend the OSPF-MCDS routing protocol to a multichannel version, OSPF-MCDS-MC or OMM. The neighboring node table at each node lists all available neighboring nodes, the link state, channel index, etc. To maintain the consistency of routing tables in a dynamically varying topology, each node periodically transmits link state databases and transmits updates immediately when significant information is available, for example after a topology change or a channel switch.

When initially allocating channels, nodes consider neighbors up to two hops away to account for interference. In an RCA scheme, the data channel of the transmitting node is determined according to the receiving node's data channel. Therefore, a node intending to transmit packets should switch its data channel to the destination node's data channel or the next hop's data channel if the destination is more than one hop away (a node does not switch back, but stays on that channel after it switches). A node looks in the routing table to select a channel when it has a packet to transmit.

1) New Hello Message: Nodes in the OMM protocol periodically broadcast Hello messages to detect new neighbors. If a new Hello message is received (after the corresponding link is stable), the sender's Internet Protocol (IP) address is added to the receiver's next Hello message as the router ID for that new neighbor. If a node receives a Hello message containing its ID (its own IP address), a two-way connection is determined to be established. When the sender has the smaller node ID, the receiver sends a Link UP Link State Description message if there is no Link Database Description message to be sent soon. Otherwise, the new neighbor's IP address is included in the next Hello message. A new Hello message includes the list of newly detected neighbors and channel information. Fig. 1 shows the format of a Hello message with the channel index.

When a node joins a network, it receives Hello messages from neighboring nodes containing channel information. If an expected Hello message is missing in a period of Dead Interval time, the generator of that Hello message is considered to be lost. In other words, the link is considered to be down. In that case, the other node and its associated channel information are deleted from the routing table.

2) Channel Update (CU) Message: A node intending to transmit packets should switch its data channel to the destination node's data channel or the next hop's data channel if the destination is more than one hop away. A node looks in the routing table to select a channel when it has a packet to transmit. Based on the destination node, the node determines the next hop and its data channel from the routing table. If a route to a destination node is not available, packets to that destination are queued. If a node switches its data channel without sending a notification to its neighbors, then the neighboring nodes can have stale channel information in their routing table. This is the busy receiver problem. To avoid this problem, a node intending to change its channel broadcasts its routing information with the new channel index before it

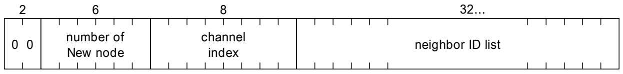


Figure 1. New OSPF-MCDS-MC Hello message.

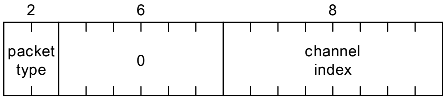


Figure 2. OSPF-MCDS-MC CU message.

switches to the new channel. Fig. 2 shows the format of the Channel Update packet in OMM.

V. SIMULATION AND RESULTS

A. *Simulation Experiments*

We performed simulation experiments using the ns2 simulator [30] with the CMU wireless extensions [31]. For our simulation, we introduce a new MobileNode object that can access multiple channels concurrently. The new MobileNode object supports multiple interfaces. However, the MobileNode object in our model uses just two interfaces since we assume two physical interfaces for each mobile node. The network stack in the new MobileNode model consists of a link layer (LL) and Address Resolution Protocol (ARP) module, an interface priority queue (IFQ), a MAC layer, and a network interface (NetIF) for each network protocol stack. These components are connected to the channel with same propagation model as in the original MobileNode object. Fig. 3 shows the schematic for the new MobileNode object.

We, also, introduce a new API along with the new MobileNode object. The new API provides the new MobileNode object with a channel switch function. The API receives the channel index as a parameter and provides a way to unlink old channels from the physical layer and link a new channel. The new API unlinks wireless channel from NetIF and links the new wireless channel to NetIF, as shown in Fig. 3.

The bit rate for each channel was 1 Mbps and the transmission rage of each node was approximately 250 m. Unless otherwise indicated, the other parameters were kept at the simulator's default values. Each source node generates and transmits constant bit rate (CBR) traffic. We ran each simulation for 200 seconds of simulated time. Each data point in the results is the average of 30 replications with independent random seeds, which we found led to reasonably tight 95% confidence intervals. Unless otherwise specified, the packet size was 512 bytes and the packet arrival rate from each node was 50 packets per second. To study the impact of these factors, we also performed simulations with varying parameter values.

Simulation experiments were performed for both single-hop and multiple-hop network scenarios with different numbers of nodes and different numbers of available channels. For the single-hop network simulations, all nodes were within the transmission range of all other nodes so every source node could reach its destination node in a single hop and, thus, there was no significant difference between stationary and mobile networks. For each scenario, half of the nodes were data sources and the other half were data destinations.

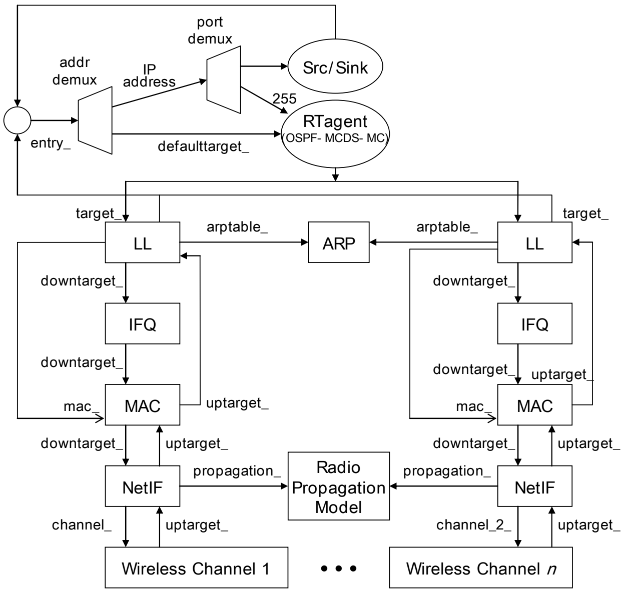


Figure 3. Schematic of the modified MobileNode object.

We considered both stationary and mobile ad-hoc networks for the multiple-hop network scenario. In the simulation of stationary nodes, nodes were randomly placed in a 670 m by 670 m square area and did not move. For mobile nodes, we used the random waypoint model with a 1000-second warm up period [32] and a maximum node speed of 5 m/s.

We use goodput as a performance metric. Goodput indicates the number of bits of useful (user data) information delivered over the medium per unit of time. Goodput excludes packet headers and signaling overhead and is useful for measuring performance as seen by higher layers. Goodput is calculated as the total number of information bits received at the destination divided by the simulation time.

B. *Simulation Results*

1) Results for Single-Hop Scenarios: We first compare the proposed OMM routing protocol with single-channel OSPF-MCDS in a single-hop network with 30 nodes. We measured the goodput of OMM while varying the packet arrival rate from 1 to 1000 packets/s at each node. The results in Fig. 4 show that the goodput of the network increases as the network load increases. While schemes using channel negotiation [5, 8] do not benefit from additional channels when the number of channels becomes large due to control channel saturation, our proposed scheme can utilize an increased number of channels efficiently.

Fig. 5 shows the impact of different numbers of channels and packet sizes on goodput. We varied the packet size from 100 to 1000 bytes. Generally, the goodput is higher when the packet size is larger mainly because there is relatively less control overhead. When the packet length reaches the RTS/CTS threshold, a larger amount of

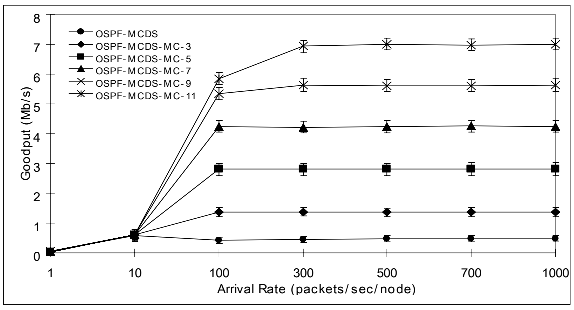


Figure 4. Goodput for varying packet arrival rate.

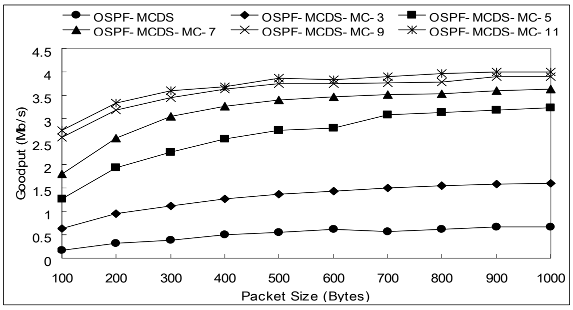


Figure 5. Goodput for varying packet size.

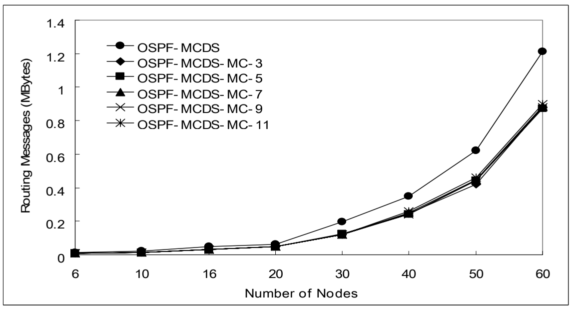


Figure 6. Routing messages for varying number of nodes.

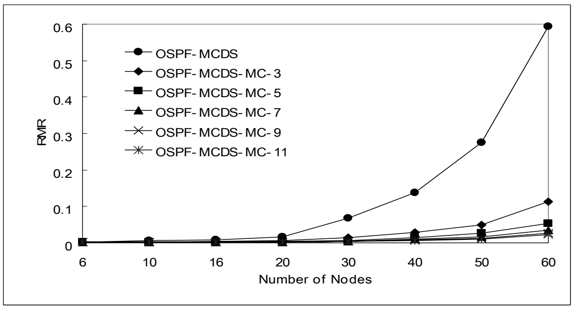


Figure 7. RMR for different numbers of channels for varying numbers of nodes.

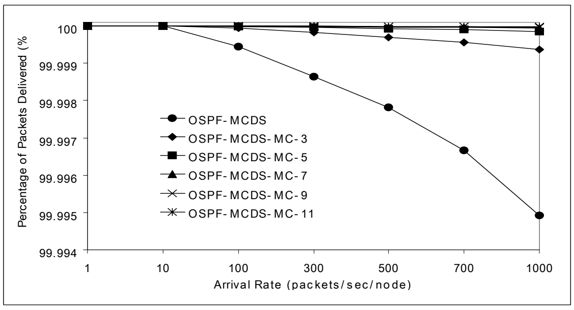


Figure 8. Percentage of packets delivered for varying packet arrival rate.

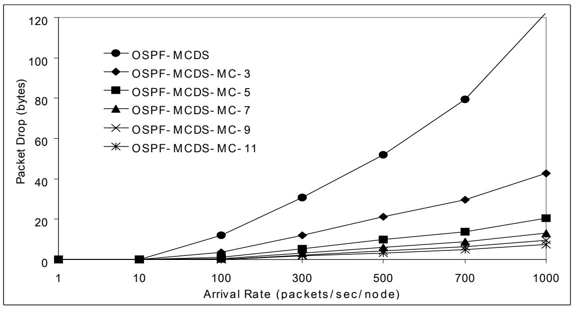


Figure 9. Packet drops for varying packet arrival rate.

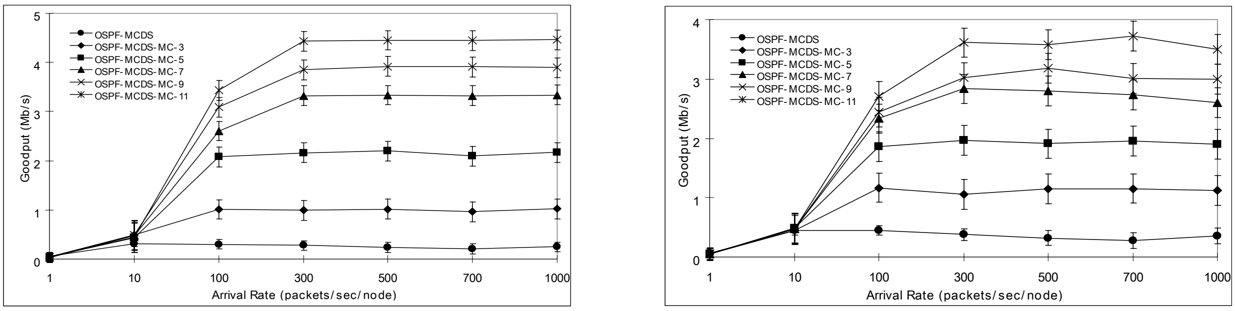
data is transmitted using RTS/CTS signaling and, thus, channel contention occurs less frequently.

When the packet size is small, the control channel can become a bottleneck if channel negotiation uses the control channel. However, since OMM does not require per-packet channel negotiation, the common control channel does not become a bottleneck. Therefore, the goodput of OMM does not decrease sharply as the packet size decreases.

To investigate the overhead of routing messages, we use the overall size of routing messages and the routing message ratio (RMR) as metrics. RMR is the ratio of the volume of routing messages to the total load on the network. As shown in Fig. 6 and Fig. 7, although OMM requires additional overhead to advertise channel information along with routing information, the number of routing packets in the network is close to the single channel case. However, in a single-channel network, the drop rate increases sharply as the network becomes congested and more routing messages are likely to be dropped since routing messages and control packets share a single channel. Therefore, after the network is saturated, the number of routing messages is likely to increase sharply. This is seen in Fig. 6 and Fig. 7 when the number of nodes increases and, in turn, the network load increases.

Fig. 8 shows the percentage of packets delivered successfully while varying the packet arrival rate from 1 to 1000 packets/s at each node. Packets include the control and user messages. As seen in the figure, as the number of packets increase in a network, i.e., as the network becomes congested, the percentage of packets delivered successfully drops dramatically in a single channel network due to the high drop rate as shown in Fig. 9. The communication can be distributed to the multiple channels in our scheme, so that the packet drop rate decreases as the number of channels available increases.

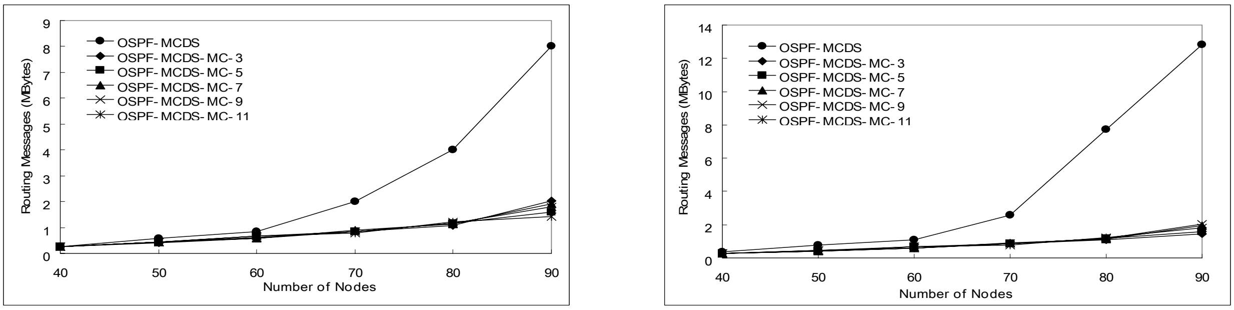
2) Multiple-Hop Scenarios: We compare the goodput and control overhead in multiple-hop scenarios. Fig. 10 shows the goodput of OMM for different packet arrival rates in stationary and mobile multiple-hop scenarios with 95% confidence intervals. As the network load increases, the goodput of OMM increases with the increased number of channels. Thus, the multi-channel routing scheme also increases network capacity in a multiple-hop scenario. However, due to the multiple-hop path and node mobility, the maximum goodput for OMM in both stationary and mobile configurations is lower than



(a) Stationary multiple-hop networks

(b) Mobile multiple-hop networks

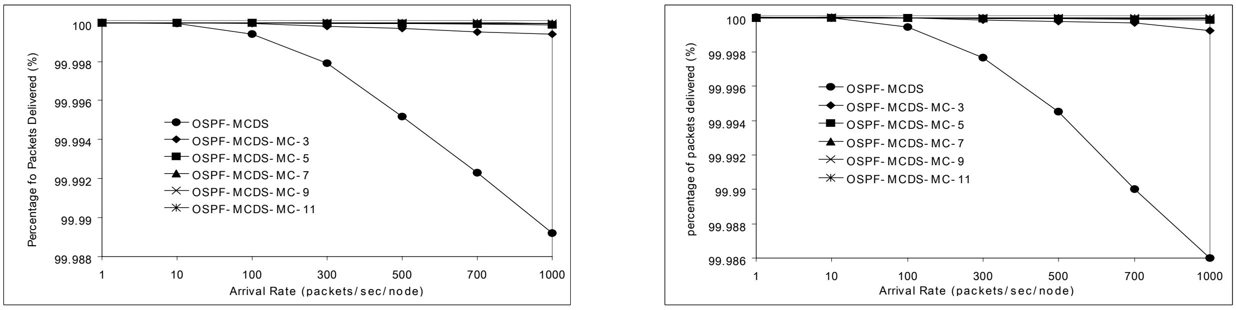
Figure 10. Goodput for varying packet arrival rates in multiple-hop networks.



(a) Stationary multiple-hop networks

(b) Mobile multiple-hop networks

Figure 11. Number of routing messages for different numbers of nodes in multiple-hop networks.



(a) Stationary multiple-hop networks

(b) Mobile multiple-hop networks

Figure 12. Percentage of packets delivered for varying arrival rates in multiple-hop networks.

that for single-hop scenarios. As may be inferred from Fig. 10, the smaller confidence intervals indicate that results for the stationary network scenario have greater certainty than results for the mobile network scenario.

We also compare the number of routing messages for different numbers of nodes in stationary and mobile multiple-hop scenarios. The number of nodes ranges from 40 to 90 and any randomly selected destination should be reachable from the corresponding random source node. Fig. 11 shows that the number of routing messages in a multiple-hop network is higher than in a single-hop network (in Fig. 6) due to the extra overhead of routing update messages caused by multiple-hop connections and node mobility. As seen in results for the single-hop network scenarios, the number of routing messages is likely to increase sharply after the network is saturated. However, since the multi-channel scheme increases the network saturation point, the number of routing messages does not increase sharply with OMM.

Fig. 12 compares the percentage of packets delivered successfully for different packet arrival rates in stationary and mobile multiple-hop networks. As a network becomes congested, the successful delivery rate drops dramatically in a single channel network due to the high drop rate. With our multi-channel scheme, transmissions can be distributed across multiple data channels and, therefore, multiple communications can occur simultaneously.

VI. PROTOTYPE IMPLEMENTATION

To validate the multi-channel routing scheme and the simulation results presented in the previous section, we implemented OMM in Linux and performed experimental validation. This section describes the implementation of the key modules, OMM and VIM. Architecturally, VIM is a loadable kernel driver and implements a virtual network adapter.

A. *OSPF-MCDS-MC Module*

OMM communicates with the VIM to populate the neighboring node table (NBR table) in the VIM. The neighboring nodes and channel information in the NBR table are referenced to choose the data channel according to the destination node or next-hop node of the packet to transmit.

The VIM is responsible for deciding to switch the data interface channel according to the NBR table, which is populated through communication with the OMM process. If VIM decides to switch the data channel, a CU message is broadcast to neighboring nodes before the VIM switches to the new data channel. On receiving a CU message from a neighboring node, a node updates channel information in the routing table. Since the VIM is a Loadable Kernel Module (LKM) and is not able to create and transmit packets, it sends the signal to the OMM process to have OMM broadcast the CU message.

B. *Virtual Interface Module*

The VIM is a logical network interface that does not provide any actual physical packet transmission. The idea of a virtual interface can be useful to implement special-purpose processing of data packets, while avoiding the complexity of changes to the kernel's network subsystem. It implements an interposition layer between Layer 2 (the link layer) and Layer 3 (the network layer). To higher-layer software, the virtual interface appears to be just another interface, albeit a virtual link.

This design has several significant advantages. First, higher-layer software runs unmodified over the multiple channels. No modifications to either network stack were required. It increases the portability and transparency of the current protocol structure. Second, while we have currently implemented only the OMM protocol, the design, in principle, can support any ad-hoc routing protocol, such as AODV [11].

The virtual interface acts as the buffering interface for outgoing packets and the end-point of communication with the OMM routing protocol. Outgoing packets initiate the channel-related functions (channel lookup, channel switch, etc.) in the VIM and are forwarded to the physical data interface to be transmitted.

The VIM determines the channel for the next-hop node, switches channels if needed, and forwards the packet to the data interface. Since the virtual channel is associated with the NIC for the data channel, the packets are not forwarded to NIC for the control channel. Multicast and broadcast packets do not traverse the VIM since they are transmitted through the control channel. Fig. 13 illustrates the data flow.

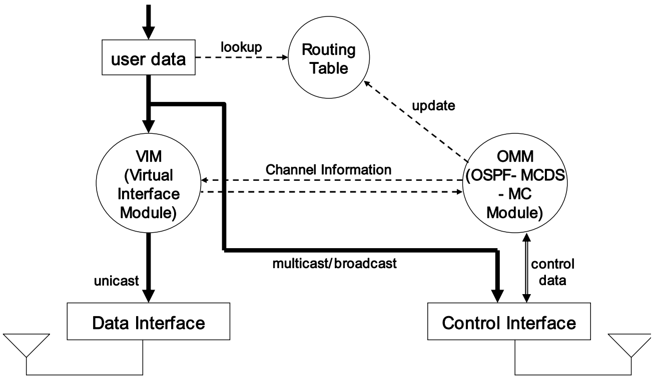


Figure 13. Design of data flow.

1) VIM Functions: The VIM looks up the destination of the packet to determine the data channel so that a node can switch the channel according to the destination or next-hop node. The VIM maintains the NBR table, which is updated through communication with OMM. The NBR table is a list with the IP address and channel information and can increase and decrease in size dynamically according to neighbor information from OMM. If events occur in OMM, such as discovery of a new neighbor node, channel update, or neighbor deletion, OMM updates the neighbor table in the VIM.

If the channel of a destination node is different from the current channel, the VIM switches the data channel to transmit a packet to the destination node and notifies OMM of the channel switch. This channel update notification triggers OMM to acquire the new channel index from the VIM and to broadcast a CU packet. After the channel index is determined, packets from the virtual interface module are forwarded to the physical interface to be transmitted.

C. *Implementation Issues*

1) Address Resolution: Address resolution refers to the process of finding an address of a computer in a network. The address is "resolved" using a protocol in which a process executing on the local computer sends a query to a process executing on remote hosts. If successful, a remote host responds to the query with a reply that provides the required address. The address resolution procedure completes when the local host receives a response from the remote host containing the required address [33].

The Address Resolution Protocol is a protocol used in IP version 4 to map IP network addresses to the hardware addresses used by a data link protocol. For IP version 6, ICMPv6 neighbor discovery replaces ARP for resolving network addresses to link-level addresses. Neighbor discovery also handles changes in link-layer addresses, inbound load balancing, anycast addresses, and proxy advertisements. Nodes requesting the link layer address of a target node multicast a neighbor solicitation message with the target address [33, 34].

An ARP miss occurs when a node cannot resolve the MAC address of a data interface if the ARP request cannot be delivered to the destination node (or next hop). The ARP miss can occur in the proposed implementation if a transmitting node's data channel is different from the receiving node's data channel in the multi-channel environment. Address resolution packets may not be heard by the destination node (or next hop) due to lack of channel synchronization.

To avoid the ARP miss problem in our implementation, address resolution messages are exchanged through the control channel, which is reasonable since the control channel is dedicated for broadcast or multicast packets. Our implementation synchronizes the caches for control and data interfaces. The ARP cache of the data interface is populated by the ARP cache of the control interface, which requires modifications to the ARP request mechanism since the ARP request should be transmitted through the control interface. Reception of address resolution messages refreshes the ARP cache of the control interface as well as data interface accordingly since each interface keeps separate ARP caches.

2) Number of Virtual Interfaces: The virtual interface scheme is adapted to leverage the portability and transparency of the current protocol structure in our implementation. Based on the number of virtual interfaces, we can categorize designs as being single or multiple virtual interface schemes.

With multiple virtual interfaces, the same number of virtual interfaces as the number of channels can be implemented. Since each NIC in a node looks at a channel, the number of virtual interfaces is the same as the number of physical interfaces, as illustrated in Fig. 14. In this multiple virtual interface scheme, each virtual channel handles packets for each available channel. The advantages include reducing overhead to look in the neighboring node table for channel information since the channel for the destination node (or next hop node) is already known. However, the interface item in the routing table must be updated according to any dynamic changes in a node's channel.

With a single virtual interface, as implemented in our design, the single virtual interface handles all packets. With a single virtual interface, all packets are forwarded to the virtual interface and the channel switch is performed by the virtual interface module according to the destination of the packet. Therefore, the virtual interface selects the channel, switches to the new channel, and forwards the packet to the physical interface. The single virtual interface scheme does not require frequent updates of the routing table as with the multiple virtual interface scheme. The drawback of the single virtual interface scheme includes the overhead to look up channel information in the neighboring node table for every packet.

VII. CONCLUSIONS

We presented a multi-channel routing scheme to efficiently utilize multiple channels in a MANET so that multiple simultaneous communications can increase effective network capacity. The proposed scheme requires relatively minor changes to an existing proactive routing protocol and no modifications to the current IEEE 802.11 MAC protocol. To avoid inefficiencies due to the transmission of periodic updates in proactive routing protocols, the proposed scheme divides the network layer into control and data planes. Updates and other routing control messages are sent using the control channel and user data is sent using one or more data channels. To demonstrate the multi-channel routing scheme, we extended the OSPF-MCDS routing protocol to a multichannel version, OSPF-MCDS-MC or OMM.

Simulation results show that OMM successfully exploits multiple channels to improve network capacity. Results imply that the packet drop rate decreases significantly when the number of channels increases since packets are distributed to more channels. Results also show that the control channel does not become a bottleneck in OMM since the proposed scheme does not require per-packet channel negotiation using the control channel. In addition, the number of routing packets in a network with OMM is close to the number for a single-channel system since routing packets are exchanged using the common control channel.

In addition to simulation results, we discussed a prototype implementation of OMM. We proposed a new Hello message format to include the channel index and the Channel Update message to avoid the busy receiver problem in a multi-channel network. For channel initialization, we introduce a scheme to delay transmission of the initial Hello message. We propose use of the logical network interface, VIM, to carry out the channel-related functions while maintaining portability and transparency. The VIM decides the data channel according to the destination or the next-hop node of a packet. The VIM, also, communicates with OMM to populate the neighbor table, forwards packets to the physical data interface, and switches its data channel as needed.

The ultimate goal is to achieve (at least) N times goodput compared to a single-channel system when N channels are available. Since the control channel does not become a bottleneck and the number of control (routing) messages does not increase significantly, our proposed scheme does come reasonably close to achieving this goal for a modest number of channels. Efficiency in channel utilization degrades as the number of channels increases due to traffic characteristics and since, in our study, we use a single transceiver per node for data.

While the results are encouraging, there are opportunities for improvement. In an RCA scheme, the data channel of the transmitting node is determined according to the receiving node's data channel. Therefore, a node intending to transmit packets should switch its data channel to the destination node's data channel or the next hop's data channel if the destination is more than one hop away. Thus, the data channels of nodes located in the path to a destination can converge and, as a result, the multiple channels cannot be fully utilized. We call this the channel convergence problem. Mitigating this problem is a topic for future research.

Utilization of multiple channels in ad-hoc networks provides the benefits of increasing network capacity and increasing efficiency by reducing the probability of collisions. Multi-channel schemes are becoming more attractive as the cost of transceivers decreases and the capacity requirements for potential ad-hoc and mesh network applications increase. However, channel assignment mechanisms may distribute channels unfairly to different nodes, thus leading to inefficient use of available capacity and creating system bottlenecks. For this issue, we are considering a new metric to explore channel distribution in multi-channel wireless ad-hoc networks. The approach lets each node measure the fairness of channel distribution among neighboring nodes. Most prior work on multi-channel schemes focuses on the channel assignment (CA) problem and multi-channel MAC protocols. Our channel distribution index (CDI) measures the fairness of channel distribution and indicates the dynamic channel distribution among neighboring nodes. The metric for multi-channel wireless ad-hoc networks can be used to evaluate the fairness of CA and MAC schemes and, in the future, to improve their efficiency. This research is currently being performed with integration into the prototype implementation of the multi-channel routing protocol [35].

Along with the channel distribution index, the channel utilization index is also a topic for future research. The channel utilization index (CUI) indicates the fairness of channel utilization from a network perspective. The purpose of this metric is to indicate the balance of channel utilization. Fair channel utilization implies that all channels are exploited equally, which leads to an increase in network capacity.

Cross-layer design is another promising research direction. For CUI estimation, channel usage information, such as such as interference and bandwidth, is needed from lower layer protocols to capture the status of the dynamic wireless environment. In addition, since a proactive routing protocol can provide complete or nearly complete topology information, it is possible to use this information to tune the parameters of lower and/or higher layer protocols.

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