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A Distributed Cross-layer Routing Protocol with Channel Assignment in Multi-Channel MANET

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Abstract— An innovative cross-layer routing approach, **MCORCA (Multi-Channel On-demand Routing with Coordinate Awareness), is presented that utilizes multiple channels to improve the performance of wireless ad-hoc networks. The proposed cross-layer scheme adapts the strategy of channel assignment and the mechanism of dealing with conflicts. Channels are divided into a control channel and data channels; the control channel is used for scheduling, and data channels are used for data transmissions. MCORCA is an extension of an on-demand routing protocol for single channel wireless networks, called ORCA (On-demand Routing with Coordinates Awareness). Simulation results indicate that MCORCA yields a significant capacity improvement as well as lower end-to-end delays by using multiple channels.**

I. INTRODUCTION

Many routing protocols have been developed for mobile Ad-hoc wireless networks (MANET) over the years based on proactive and on-demand signaling [1], and many proposals have been made to improve the performance of routing protocols in various ways (e.g., using multiple paths [2] or reducing loops [3]). Interestingly, the medium access control (MAC) protocol assumed in most MANET routing protocols is the IEEE 802.11 distributed coordination function [4]. Given that IEEE 802.11 DCF is based on carrier sense multiple access with collision avoidance (CSMA/CA), its performance degrades with multiple access interference (MAI) [5], and it is well known that MAI has a negative impact on the capacity of wireless networks [6], [7]
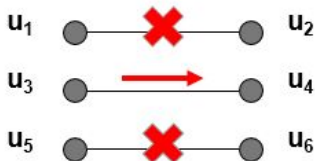

Fig. 1.   Single Channel

Figure 1 illustrates the limits on concurrent channel utilization imposed by a single-channel, contention-based MAC protocol. Three pairs of senders and receivers attempt transmit data; however, only one pair (u_3, u_4) can successfully deliver data due to interference over the shared single channel. As shown in Figure 2, a multi-channel MAC protocol can allow the three communicating pairs of nodes to transmit data concurrently, which increases the overall packet delivery rates and reduces average delays in the MANET.
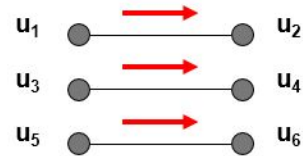

Fig. 2.   Multiple Channels

The previous example motivates the need to exploit the concurrency attained by the availability of multiple channels at the MAC layer. In this paper we introduce a cross-layer approach aimed at taking advantage of the IEEE 802.11 DCF with multiple channels, without any major changes to the physical and MAC layers. We call this approach MCORCA (Multi-Channel On-demand Routing with Coordinate Awareness), which combines a channel-assignment strategy at the MAC layer with ORCA (On-demand Routing with Coordinate Awareness) [8].

In MCORCA, the available channels are organized into one control channel and multiple data channels. Channel assignment is carried out over the control channel, and the process is initiated by the sender side.The goal of channel assignment is to schedule the data channel where a sender and intended receivers should switch to exchange data. Receivers respond to senders either accepting or rejecting a binary bit token over the control channel. Once a data channel is assigned, data transmission takes place, but conflicts may arise when different sender-receiver pairs are assigned the same data channel during the same time, or multiple senders are assigned to one common receiver.

Section II provides a summary of prior related work. Section III describes the routing mechanism of MCORCA and specifies its channel assignment policy. Section IV presents the results of simulation experiments used to evaluate the performance of MCORCA by comparing it with ORCA.

II. Related Work

Although IEEE 802.11 DCF provides multiple non-overlapping channels, most routing protocols for MANET have been proposed assuming the use of a single channel, and nodes equipped with a single radio, such that a given node can listen and transmit over a single channel at a time.

ORCA (On-demand Routing with Coordinates Awareness) [8] is designed to operate in a MANET in which a single channel is used. Nodes use geographical coordinates to attain efficient route signaling and full coverage of all nodes when route requests must be sent in the MANET. Each node selects at most six forwarders for its route requests by computing the shortest distances from all neighbors to four polars $\{P_E, P_S, P_W, P_N\}$, and then adding secondary forwarders if neighbors exist that have distances to the selected relay nodes that are greater than the transmission radius r. The selection of relays by a node in ORCA is illustrated in Figure 3. Nodes a, b, c, and d are selected as primary forwarders, and nodes e and f are selected as secondary forwarders. The route requests from node u state the set of these six relays.

The disadvantage of assuming a single channel in ORCA and most prior MANET routing protocols is that network capacity is limited by the negative effects of MAI.
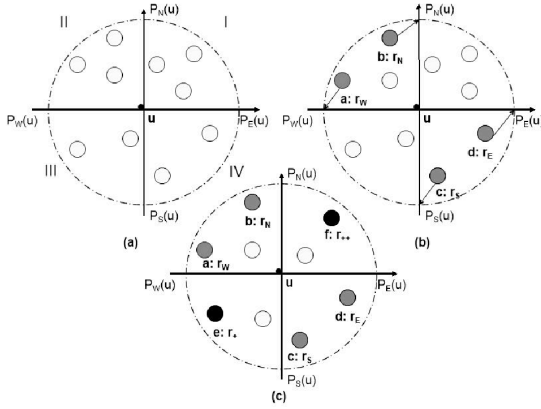

Fig. 3. Selection of relay nodes in $ORCA$

The IEEE 802.11 standard divides the available frequency into orthogonal (non-overlapping) channels and provides multiple channels. IEEE 802.11a supports 13 orthogonal channels in the 5 GHz spectrum and 802.11b has 11 channels in the 2.4 GHz spectrum, three of which are orthogonal. For simplicity, we assume that packet transmissions on these orthogonal channels do not have co-channel interfere.

A number of approaches have been proposed for wireless networks operating over multiple channels with nodes having a single transceiver. For instance, Bahl et al. [9] proposed a link-layer protocol called Slotted Seeded Channel Hopping (SSCH), which increases the capacity of an IEEE 802.11 network by utilizing frequency diversity. Each node using SSCH switches across channels in such a manner that nodes desiring to communicate overlap, while disjoint communications mostly do not overlap, and hence do not interfere with each other. So and Vaidya [10] proposed a routing protocol for utilizing multiple channels in multi-hop wireless networks with a single transceiver to improve network capacity and throughput without using additional hardware or changing the MAC protocol. They also proposed a routing protocol [11] for networks with multiple channels and nodes operating with a single network interface that finds routes and assigns channels to balance load among channels while maintaining connectivity. The protocol discovers multiple routes to multiple access points, possibly operating on different channels. Based on traffic load information, each node selects the best route to an access point, and synchronizes its channel with the access point.

Prior work has also been reported for the case in which a wireless network operates in multiple orthogonal channels and nodes use multiple network interface cards.

Kyasanur et al. [12], [13] proposed a link-layer protocol and a new on-demand routing metric to use multiple channels by using multiple interfaces, and the number of interfaces per host is typically smaller than the number of channels. This design showed an improvement on network capacity by utilizing all the available channels.

Raniwala et al. [14] proposed a set of centralized channel assignment, bandwidth allocation, and routing algorithms for multi-channel wireless mesh networks . The approach serves as the backbone for relaying end-user traffic from wireless access points to the wired network by exploiting multiple channels to achieve higher capacity and support backbone traffic.

III. MCORCA Protocol Design

A. Assumptions

The following assumptions are made in the description of MCORCA, and Table I summarizes the nomenclature we use.

Each node is equipped with a single wireless card, which contains only a single half-duplex transceiver. Hence, a given node can transmit or receive over a single channel at a time, and cannot do both simultaneously. Each network interface card (NIC) has C multiple available channels. The available channels are assumed to be orthogonal and non-overlapping. Each node still implements the standard of IEEE 802.11 DCF at the MAC layer. However, the time slotting approach used in SSCH is assumed [9]. Each node has a unique identifier, and nodes are capable to know the scheduling policy a priori.

B. Routing Mechanism

In most MANET routing protocols, each node transmits a HELLO message to all its neighbors periodically. In on-demand routing protocols, when a source s has data to send to an intended destination for which it does not have a valid route, it proceeds with a route discovery process. Node s broadcasts a route request (RREQ) to establish a valid route by flooding the RREQ throughout the network in order to find the destination or a node with a valid route to the destination.

A RREQ in ORCA specifies the list of relays for the RREQ. Any node receiving the RREQ may send a route reply (RREP)

TABLE I

MCORCA Notation

u	a node
N	Total number of nodes in the network
C	Total number of available channels
CID	The assigned channel ID
t_0	The start time slot of switching to data channel
t_{RREQ}	The duration of a route request RREQ
t_{RREP}	The duration of a route reply RREP
t_{data}	The duration of data
$\mathcal{N}(u)$	Set of one-hop neighbors of u

if it has a valid route to the destination. However, only the nodes listed in the relay list of the RREQ can propagate the RREQ. At most six relay nodes forward a RREQ transmitted by a node. A route reply (RREP) is unicast back to the source of the RREQ from the destination or any node with an active route to the destination that receives the RREQ. When a node is asked to forward a data packet for which it has lost its valid route, then a route error (RERR) is sent towards the source of the packet.

C. Channel Assignment Policy

Figure 4 illustrates how channel access takes place in MCORCA. Given a set of C available channels, they are organized into a control channel C_0, which is used for channel assignment and the transmission of Hello messages, and $C - 1$ data channels used to transmit routing packets and data packets. The assignment of channels is sender-initiated as the scheduling policy is implemented by senders when they have packets to transmit. Hello messages are sent over the control channel. Before a RREQ, RREP or data packet is sent, the sender schedules a data channel with the intended receivers. The transmission proceeds after the scheduling step has been successful.
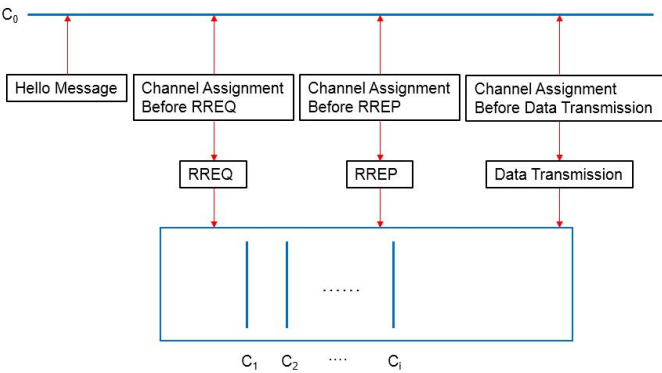

Fig. 4. Flowgram of MCORCA

1) RREQ: Before node u broadcasts a RREQ to its set of neighbors $\mathcal{N}(u)$, it is required to assign the set $\mathcal{N}(u)$ to a specific data channel for the purpose of transmitting it

RREQ. A data channel is used for the transmission of RREQs because the size of a routing packet is larger than the size of a scheduling packet, which is composed of $\{CID, \mathcal{N}(u), t_0, t_{RREQ}\}$.

The assigned channel ID is computed as follows:

$$CID = (Rand([1, N]) \oplus Rand([1, C])) \, mod \, C$$

The function of $Rand([1, N])$ represents for the random number generated between 1 and N, given the probability of generating each number randomly is equal. Once the random numbers for node ID and channel ID are generated, use concatenation to obtain another number. This way can much better avoid the concatenated chain number to be same as the last one because the last digit of channel ID would be different each time. Then using modulo operation gives the remainder of the euclidean division by the total number of channels. The result is the schedule channel ID for the receivers to switch.

Sender u broadcasts the scheduling packet to $\mathcal{N}(u)$. Each receiver is required to acknowledge a binary digit token to the sender upon receiving the scheduling packet. The token is either 1 or 0, where 1 represents accepting the assignment and 0 represents for rejecting due to all kinds of reasons.

As long as the sender receives the feedback token from at least one receiver, it initiates switching to data channel C_i as scheduled. All committed receivers must switch to the assigned data channel C_i for receiving RREQ. In ORCA, at most six nodes implement the task of relaying RREQ, thus at most six embedded in RREQ packet will repeat the same process of channel reservation to their neighbors, until destinations receive RREQ or timeout is expired.

2) RREP: Once destinations or the intermediate nodes knowing destinations receive RREQ, RREP will be unicasted in the backward direction toward source and accumulate the path from source to destination. All nodes switch back to channel C_0 to be ready for next assignment. The nodes unicasting RREP are required to do channel assignment and broadcast the schedule packet to the node delivering RREQ. The packet is composed of $\{CID, \mathcal{N}(u), t_0, t_{RREP}\}$. After the acknowledge token "1" is committed, they switch to data channel C_i for execution of delivering RREP. Therefore, repeat the same process until source receives RREP eventually.

3) Data Transmission: When an active route is established between sources and destinations, data transmission is initiated by the source. Following the same process of channel reservation policy outlined above on channel C_0, node u assigns the next data channel to its receiver for data transmission. The scheduling packet is composed of $\{CID, \mathcal{N}(u), t_0, t_{data}\}$. Once the acknowledgment token "1" is committed, they switch to the data channel C_i for transmitting data packets. After the transmission is complete, they switch back to channel C_0 ready for the next assignment.

D. Scheduling Conflicts

If a receiver senses multiple assignment from more than one sender, the receiver drops the latter and picks the earlier

scheduling. Once the receiver completes the assigned switching task, switch back to control channel C_0 immediately and send a request to the sender which was rejected before. As the sender receives the request over channel C_0, it re-sends the scheduling packet to the receiver and re-initiates second round of switching.

If two senders assign the same channel concurrently to their receivers, then they could conflict with each other. To solve this issue, they are required to carry out an exponential back-off and re-assign the scheduling.

IV. Performance Evaluation

We used simulation experiments based on Qualnet [15] to compare MCORCA with ORCA. In the simulations, the terrain size is set to be an area of 800x800 m^2 and 1200x1200 m^2 for total 50 nodes placed randomly in an area. Each node is equipped with only one half-duplex transceiver. At the physical layer, we use the IEEE 802.11 protocol operating with a data transmission rate of 2M bit/s. At the MAC layer, we use the IEEE 802.11 DCF protocol for ORCA while MCORCA is used with multiple channels using the approach advocated

Fig. 5. Average throughput in the scenario of 800m x 800m

Fig. 6. Average delay in the scenario of 800m x 800m

in [9] with the channel assignment we have summarized. At the transport layer, we use the UDP protocol. Six UDP flows are generated in the network. Each UDP flow has an offered load ranging from 100 kbps to 1000 kbps. The channel switch delay is set to be 80 μs [9]. There are 6 or 12 different data channels available. In all simulations, the radio range of a node is set to 250 m and the interference range is set to 550 m, which is approximately twice the radio range. The nodes move with the speed randomly chosen between 1m/s and 5m/s according to the random waypoint (RWP) mobility model. The simulation time is set to be 500 seconds. We primarily measure throughput and average delay under a traffic load of maximum rate UDP flows. In particular, we use Constant Bit Rate (CBR) flows of 512 byte packets sent every 50 μs. This data rate is more than the sustainable throughput of IEEE 802.11a operating at 54 Mbps.

Simulation results show that MCORCA always performs better than ORCA in both scenario networks, given an equal number of channels. The performance gap between the two increases as the number of available channels decreases. As shown in Figures 5 and 7, we observe that average throughput in MCORCA combined with multiple channels can have 2 times and 4 times higher than ORCA with the IEEE 802.11 MAC. Figure 6 shows that the end-to-end delay increases for all schemes when the data rate increases. However, multi-channel one MCORCA utilizing 12 data channels have much lower delay than ORCA with the original 802.11 MAC scheme. In the second scenario, the performance gaps between different schemes are not as large as those as shown in Figure 8. The interference and collisions generated by neighboring nodes is lower compared to those in a dense network because in a sparse network, each node has fewer neighbors and the distance between neighbors is greater. Therefore, the performance gain of multi-channel MAC schemes is not as significant in a sparse network.

The simulation results indicate that utilizing more available channels improves network capacity in MANET. The performance advantage of MCORCA over the IEEE 802.11 MAC scheme is not in proportion to the number of channels utilized. For instance, for MCORCA with 12 available channels, the throughput gain can be up to 4 times, not 12 times, compared to the throughput achieved by the IEEE 802.11 MAC.

V. Conclusions

We presented an innovative cross-layer routing approach, MCORCA, for single NIC multiple channel wireless networks, assuming a single transceiver at each node. The goal of the design is to improve network capacity and shorten end-to-end delay by taking the advantages of simultaneous data transmission in multiple channels. MCORCA exploits a distributed channel assignment methodology based on an existing on-demand routing protocol ORCA designed for the single NIC single channel MANET. Channels are thus divided into two parts, a control channel and multiple data channels, which are used for different tasks.
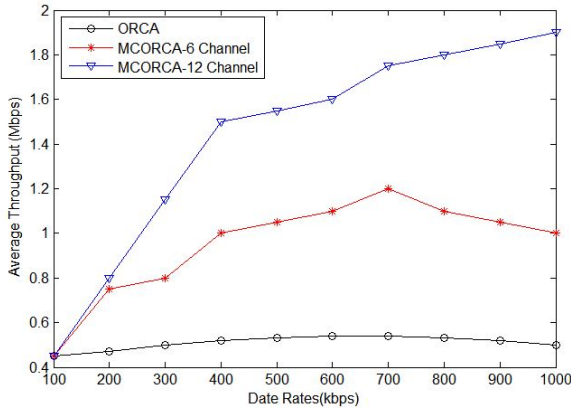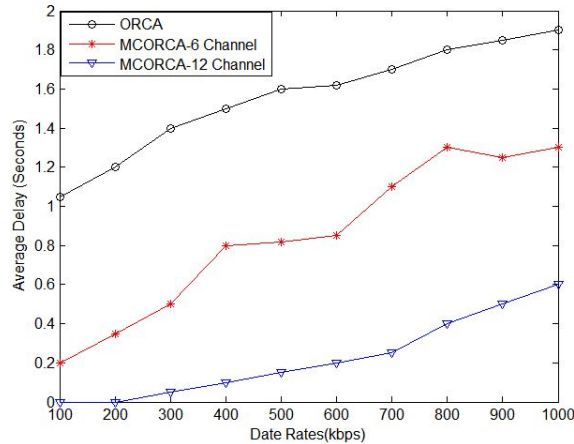
In control channel, Hello messages are periodically conveyed and channel reservation are assigned. All other channels are used for the transmission of routing packets and data packets. Once each node completes the task of either routing discovery process or data transmission, MCORCA requires switching back to the control channel for a next assignment. Simulation results show that MCORCA improves network throughput substantially over ORCA by efficiently allocating channels.

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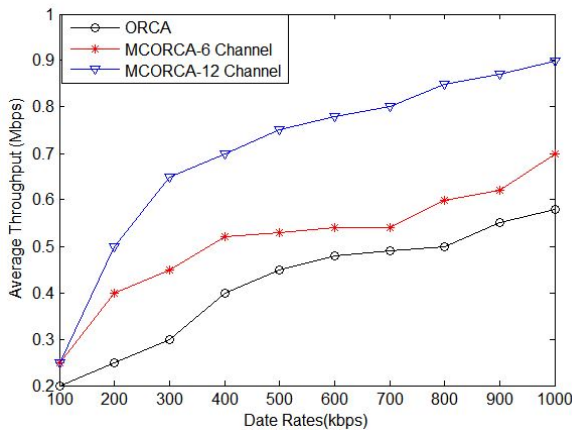[15] *Qualnet Simulator*, Scalable Network Technologies, Inc.
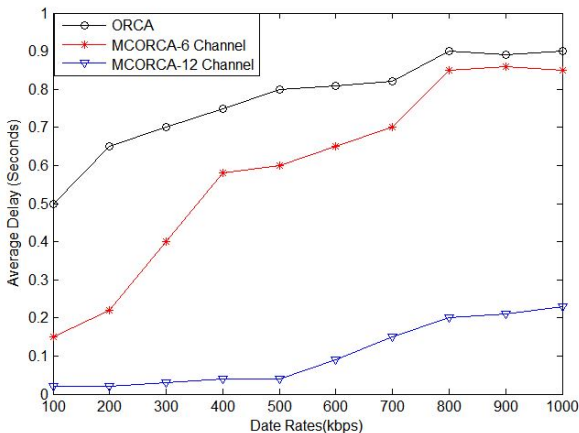
Fig. 7. Average throughput in the scenario of 1200m x 1200m

Fig. 8. Average delay in the scenario of 1200m x 1200m