

Distributed Topology Control in Multi-Channel Multi-Radio Mesh Networks

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Distributed Topology Control in Multi-Channel Multi-Radio Mesh Networks

Hua Zhu

ArgonST/San Diego Research Center
San Diego, CA 92121

Kejie Lu

University of Puerto Rico at Mayagüez
Mayagüez, Puerto Rico 00681

Ming Li

California State University, Fresno
Fresno, CA 93740

Abstract— In this paper, we propose a Distributed Topology Control (DTC) and the associated inter-layer interfacing architecture for efficient channel-interface resource allocation in multi-channel multi-radio (MCMR) mesh networks. The proposed solution is (i) routing agnostic but traffic adaptive; (ii) it fully achieves channel multiplexing over multiple interfaces; (iii) its well-defined over-the-air signaling mechanism can be incorporated with various distributed topology optimization algorithms; and (iv) it is fairly PHY/MAC-agnostic and can be integrated with various mesh access technologies.

Keywords—Multi-channel multi-radio; MCMR; Mesh network; Topology control

I. INTRODUCTION

Multi-channel multi-radio (MCMR) solution has attracted a lot of attention recently because it has the potential to solve the scalability problem of wireless mesh networks. Low cost radio design has made such solution economically feasible. However, it also places challenges in various new issues. Due to the space limit, we will not elaborate more on other related issues, such as multi-channel MAC design (not necessarily multi-radio) [1,2,3] and focus on one major challenge, which is how to dynamically allocate both radio interface and channel resource to achieve efficient spatial and spectrum reuse. Like many researchers, we termed this as a topology control problem in this paper.

We propose a distributed topology control (DTC) module in conjunction with a redesigned MCMR architecture (including MCMR inter-layer interface). The proposed DTC is unique because it achieves all of the following attributes:

- *Routing agnostic*: unlike joint routing and channel-interface adaptation approaches, it is (i) transparent to routing protocols so that it can be easily and seamlessly applied to existing applications without overhauling the system across protocol stack, and (ii) DTC adaptation has less impact on end-to-end route stability;
- *Traffic adaptive*: although it is routing agnostic, it is not traffic-agnostic, i.e., it fully supports dynamic channel-interface allocation based on generic traffic metric, and thereby it works well with both circuit-like traffic sessions (e.g., audio-visual flows) and general packet-based bursty data traffic.
- *Channel multiplexing*: it achieves unique channel multiplexing so that both traffic to different next-hop addresses

and the traffic on the exactly same route can be transmitted simultaneously. Many existing MCMR topology control approaches can only achieve the simultaneous transmissions for the former case, while they are required to work with multi-path routing protocols to fully achieve the channel multiplexing capability of MCMR nodes. This important feature further releases the often-limited link capacity constraint and enables more efficiency interface utilization;

- *MAC Decoupling*: although we choose 802.11 in this paper, DTC can be integrated with other multi-channel MACs that support dynamic channel switching.

It's worth noting that traffic adaptive does not have to be achieved by sacrificing routing agnostic, as many joint adaptation schemes are motivated to do. By distinguishing routing from traffic adaptation, we acquire both features.

The remainder of this paper is organized as follows. Section II discusses related works. Section III provides a general picture of MCMR network architecture and the inter-layer interfacing issue. Section IV proposes the distributed topology control (DTC) module. Section V presents simulation results, and Section VI concludes this paper.

II. RELATED WORKS

Existing work on MCMR topology control generally can be classified in various ways, e.g., whether it is centralized or distributed; what kind network architecture is in place; whether it is coupled with specific routing protocol; whether it is coupled with specific MAC; which metric is used for adaptation and what is the time scale for such adaptation, etc.

A joint routing and channel allocation problem was investigated by Alicherry et. al. in [4]. In this work, global knowledge on physical link connectivity graph and traffic flow topology are used in the formulation of joint optimization problem, and a linear programming solution was proposed. Another work, by Tang et. al. [5], on joint channel allocation is based on similar global knowledge. These works are centralized and require global knowledge a priori. Nevertheless, they are useful for theoretical analysis and can be used as performance benchmarks. One step further, Ramachandran et. al. [6] proposed a version of the centralized channel allocation algorithm at the central server that performs periodically information collection and adaptation. However, the scalability of such approach may be an issue. Given large number of nodes (e.g., hundreds of nodes), in conjunction with

even only a reasonable set of interfaces per node and limited number of channels in the network, the search space of possible resource allocation solutions is astronomical. Therefore, as a well-known NP-complete problem, even seeking for the heuristic near-optimal solution is extremely challenging in large scale networks.

Raniwala et. al. [7] designed a distributed channel allocation algorithm in the context of Hyacinth network architecture, where tree-based routing for wireless Internet access is used. Wu et. al. [8] proposed a joint channel allocation and routing solution in which the routing metric is the link between two partitioned optimization problems. Ko et. al. [9] proposed a distributed channel allocation algorithm for wireless mesh networks in similar structured network architecture with client and router nodes. However, the design approach in [9] is not coupled with any specific routing protocol. In fact, their design philosophy is to separate topology control from routing so that the topology control provides a fairly stabilized topology for routing protocols. To achieve such desirable transparency for routing, the metric adopted by the topology control in [9] has to be traffic-independent, i.e., mainly based on physical connectivity topology. Such transparency for routing, or *routing-agnostic*, is evidently a very attractive feature for practical reasons. In fact, this is also one of the important attributes of the topology control module proposed in this paper. However, by redesigning the inter-layer interface between routing and topology control, the proposed module is not *traffic-agnostic*. Instead, it leverages traffic metric (i.e., queue depth) independently in topology adaptation while still maintaining the routing-agnostic feature. Kyasanur and Vaidya [10] proposed an interesting idea with fixed channel allocation for reception at each node, which makes the channel-interface allocation simpler by reducing the freedom on allocating part of interface resource. Essentially, the solution in [10] relinquishes substantial degree of freedom in term of resource allocation because it not only employs fixed channel for one interface per node, also partitions interfaces into single-direction interfaces for transmission or reception only. The solution in [10] also introduces headache in handling broadcast. Duplicating broadcast on all channels with potential receivers or opportunistically selecting a subset of channels has been discussed as a patch to their channel-interface allocation solution.

III. MCMR SYSTEM ARCHITECTURE

The presence of MCMR radios and the capability of coordinated multi-interface topology control raise a unique issue on how to integrate routing protocol with lower layers. Many related works mentioned in Section II are coupled with routing protocols. The underlying motivation for this is actually to achieve traffic adaptation, which is evidently a desirable feature for channel-interface resource allocation. However, coupling topology control and routing together creates many unwanted side-effects, or conflict interests. For example, the more frequent lower layer channel-interface adaptation, the less stable routing topology may be. Such distributed and scalable algorithm for such joint adaptation or optimization is challenging when end-to-end routing is

involved. Fortunately, the concept of traffic adaptive can be nicely separated from routing by modification to the system architecture of MCMR nodes.

As shown in Figure 1a, in the traditional architecture, a route is directly bound with a physical interface. Therefore topology changes induced by channel switching on any interface inevitably affect the end-to-end routing process. Moreover, the one-to-one binding of route and interface implies that all traffic on a route can only leverage a single interface. Therefore, the MCMR potential capacity boost is critically limited in a very common case with large traffic demands on the same route. As a result, multi-path routing has to be used in conjunction with the traditional architecture, which incur obstacle for commercialization due to the lack of common practice on multi-path routing in the real world.

On the other hand, as shown in Figure 1b, in a modified MCMR architecture, routing is dealing with hyper interface, which dynamically delegates traffic to physical interfaces. Such subtle architectural modification is in fact critical because it well isolates the routing process from the MCMR topology control. In conjunction with the DTC described in the next section, such isolation prevents frequent end-to-end routing changes from frequent lower layer topology control. Furthermore, by doing this, the very important MCMR capacity improvements by channel multiplexing can be achieved without overhaul existing single path routing solution, which makes commercialization more practical. By leveraging low cost commercial off-the-shelf (COTS) radios, as well as such hyper-interface driver patch, MCMR nodes can be easily and quickly deployed and coexist with non-MCMR systems.

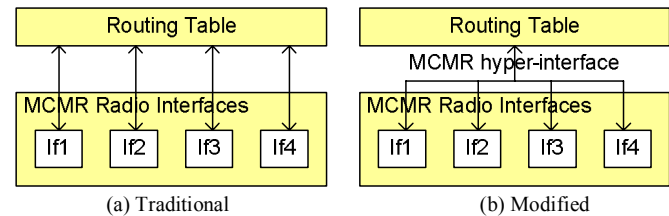


Figure 1. MCMR system architecture

IV. MCMR DISTRIBUTED TOPOLOGY CONTROL (DTC)

The MCMR inter-radio control may cover various aspects across the protocol stack, not necessarily limited to PHY layer and MAC sub-layer. In fact, the DTC module proposed in this paper mainly resides in 2.5 layer, i.e., cross layer design involving L3 metrics (network queue depth) and MAC/PHY operations. We use the term of “topology control” in the context of dynamic channel-interface allocation, instead of the traditional transmission power control. By dynamically assigning channels to MCMR radios, the link connectivity, topology, and capacity are changed. The objective of this module is to dynamically (i.e., on traffic demand) and allocate channel-interface resources in a distributed way to:

- Efficiently use radio interface resource of MCMR nodes;
- Efficiently use channel resource of the network;

- Significantly improve capacity and delay performance over that of single-radio and/or single-channel networks

A. Design Premises

In DTC algorithm design, we do not assume that all MCMR nodes have identical number of radio interfaces. However, we do assume that all the MCMR radios employ the same type of radio (PHY/MAC). We also assume that the number of orthogonal channels available is reasonable large compared with the average number of radio interfaces per node. What spectrum can be used for MCMR networks is out of the scope of this paper.

Since the proposed DTC module resides at 2.5 layer without tampering underlying MAC/PHY radio operations the MAC medium access, theoretically, the DTC module can be used with an arbitrary radio type with reasonable effort on customization. However, since we are more interested in investigate MCMR networks in the ad hoc or mesh networks, to minimize potential customization efforts on the radio, we pick 802.11 MAC-DCF and 802.11 PHY as the candidate in this paper. In fact, existing 802.11 MAC/PHY can be integrated with the DTC module without modification.

The DTC module can be implemented via either MAC broadcast, or MAC unicast if MAC promiscuous mode is supported and enabled. We adopt the latter since in 802.11, unicast is more reliable in 802.11.

B. General Concept

The DTC module can interact with any routing protocol transparently, through a hyper-interface delegating all MCMR radio interfaces that support the DTC module. It serves as (i) a controller that initiates and handles necessary message handshakes to reserve or release channels to or from radio interfaces; and (ii) a dispatcher between traffic loaded on the hyper-interface and corresponding radio interfaces.

At network layer, instead of assigning network address (e.g., IP) to each radio interface, all the MCMR radios sharing the same network address assigning to the hyper-interface. At MAC layer, there are two feasible MAC addressing options identical in all ways except minor difference with pros and cons. In option A, all the MCMR MACs use the same logical MAC address instead of their globally unique hardware addresses when generating the MAC frame header for transmission. In option B, hardware address is used for transmission, with a common logical MAC address shared by the DTC module. Option A requires less information in DTC over-the-air signaling messages because the source and destination addresses in the MAC header can be directly used in the DTC algorithm state machine. However, the COTS MAC driver may need to be modified to allow such address override, which is not feasible though. On the other hand, option B uses COTS MAC as it is, but requires addition information field on logical address on over-the-air signaling messages.

Based on the DTC algorithm, a default radio interface of each node is always actively operating on a logical common control channel, which is used by all DTC control messages

and data transmissions. Note that broadcast data will always be transmitted over this common channel. All remaining interfaces and channel resources are dynamically allocated according to traffic demand temporally, spatially, and “spectrally” so that they can be efficiently utilized wherever they are needed most. Note that the default control interface is always operating on the logical control channel regardless of the traffic dynamic. Therefore, the MCMR network can always maintain a fairly stable network topology for routing in spite of the traffic adaptive channel-interface allocation taking place on other MCMR interfaces.

In certain scenarios with the presence of strong local interferes, jammers, or primary spectrum users in the context of XG [13], a network-wise physical common channel may not be available. In these cases, the logical channel can consist of multiple regionally-common physical channels. Simple solutions are available in [12] for nodes to autonomously form a minimum set of regionally-common physical control channels, and to establish cross-channel communications across the boundary of these physical control channels. Essentially, nodes follow a predefined order in selecting which the physical control channel to operate on.

As for the traffic adaptive channel-interface allocation, when certain condition is met, the DTC module may initiate over-the-air message handshaking to reserve one or multiple channel-interface resources with one or more neighboring nodes. In current implementation, the condition triggering resource reservation is the traffic load (queue depth) on the hyper-interface. Channel-interface resource release is triggered by “keep alive” timer of the channel-interface resource. However, more variations on conditions to drive the DTC state machine can be further investigated. For example, in conjunction with using queue depth, additional measurement of radio idling time can also be used to better evaluate traffic load.

With light traffic load, other radio interfaces need not to be activated. Only when traffic increases, will additional channel-interface resource be allocated to accommodate such increasing need. More than one interface can be allocated to the same next-hop neighbor with high load. On the other hand, without enough traffic to sustain, allocated channel-interface resource will be released. Configurable thresholds on queue depth and “keep alive” timer can filter traffic fluctuations yet maintain prompt adaptation responsiveness.

C. Over-the-air Signaling and State Machine

There are five types of signaling messages, i.e., *RsvReq*, *RsvRsp*, *RsvCfm*, *RlsNtf*, and *RlsCfm*, respectively. In addition to the information conveyed by the MAC header (mainly the MAC SeqNo for handling duplicate receptions of unicast, MAC source and destination address), the message payloads include information described in Table 1.

TABLE I. DESCRIPTION OF SIGNALING MESSAGES

<i>RsvReq</i>	Reservation Request, including a channel map of available channel IDs at the requester [and logical MAC address of the requester if MAC addressing option B is employed]
<i>RsvRsp</i>	Reservation Response, including a channel map with selected channel [and the logical MAC address of the

	requestee if option B is employed]
<i>RsvCfm</i>	Reservation Confirmation, including a channel map with selected channel [and the logical MAC address of the requestee if option B is employed]
<i>RlsNtf</i>	Release Notification, include a channel map with released channel [and logical MAC address of the targeting neighbor if option B is employed]
<i>RlsCfm</i>	Release Confirmation, include a channel map with released channel [and the logical MAC address of the sender of <i>RlsNtf</i> if option B is employed]

The main message handshaking flows for channel-interface reservation and release are shown in Figure 2. Based on the message handshaking, each node maintains the channel usage of its own 1-hop neighborhood. The channel-interface allocation handshaking involves the collective decision making process of both requester and requestee, which covers 2-hop environment from each participant’s view. In the reservation handshaking, a channel reservation requires consents from both requester and requestee. Therefore, any new reservation is aware of the combinatorial neighborhood of the link to reserve. Depending on the decision policy adopted by the DTC module, such consensual reservation may bear different characteristics.

Based on the same over-the-air handshaking framework, various decision policies can be applied. For example, the decision policy we adopted in this paper is to reserve a channel between requester and requestee(s) *only if the channel is not currently used by the requester, the requestee(s), or any neighbor of them, and provided idle interfaces are available at both the requester and the requestee(s)*. Evidently, such policy is quite conservative in terms of resource allocation. Such conservative policy leads to dedicate collision-free link(s) upon reservation. However, more aggressive policy is also possible given MAC’s capability to resolve collisions in medium access, e.g., 802.11 DCF. For example, the requester and/or requestee may approve a reservation even if it is aware that a channel is being used by their neighbor(s), as long as the existing channel utilization is below certain threshold. In addition, QoS can be integrated into the decision policies so various traffic or services are treated differently in the resource allocation process. Of course, to achieve certain decision policy, corresponding information or measurements need to, and can be, conveyed via the same over-the-air signaling handshaking.

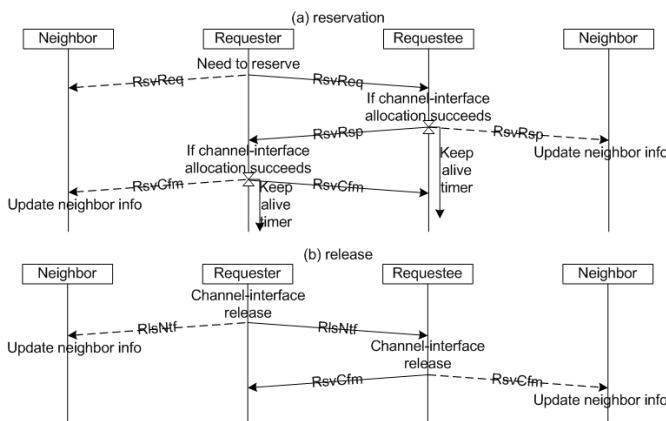


Figure 2. DTC signaling handshakes

In current design of the release handshaking, a requester releases the allocated resource solely based on a predefined duration. Although other design variations are possible, current design is selected due to the merit of simplicity and is considered sufficient as well.

The handshaking are simple and robust to message loss and local condition changes. For example, lost RsvRsp message at the Requester will eventually result in the timeout of the newly allocated channel-interface at the Requestee. Channel allocation conflicts due to message loss at neighboring nodes can be easily detected subsequently and resolved if necessary. Nevertheless, via 802.11 MAC, overlapping links allocated on the same channel only affect the load of the channel, but they do not break the links. In addition, since channel-interface resource is allocated on traffic demand, only the persistent conflict with substantial channel overloading requires re-allocation.

There are several possible enhancements on the framework implementation. For example, optional fields may be included in signaling messages, such as scheduled interface duration. Furthermore, multiple reservations or releases may be combination in single message. Note that even with unicast message implementation, piggybacking information for multiple neighbors is still feasible with appropriate information included in the message payload and MAC promiscuous mode enabled.

V. SIMULATION ANALYSIS

We evaluate the proposed DTC with hyper interface in QualNet [11] with default 802.11b PHY/MAC setting and fixed PHY data rate of 2Mbps. Each node has $M=4$ MCMR radio interface and the entire network has $C=10$ orthogonal channels. Note that 802.11b is currently provisioned with only 3 channels, while 802.11a with 13. However, since our purpose is to investigate the concept and performance of DTC, such realistic standard provision does not necessarily affect the validity of our results. We simulate the mesh network with high traffic load (of various patterns) to test its network capacity in fairly saturated condition. A static 4x4 grid is constructed, with traffic topology shown in Figure 3. Each of 17 Poisson traffic flows is of 333kbps and fixed packet length of 125Bytes. We pick this scenario because it covers diverse conditions seen by MCMR nodes, including both single and multiple ingress/egress serving traffic per node. It also involves different interference environments and can some perspective given certain

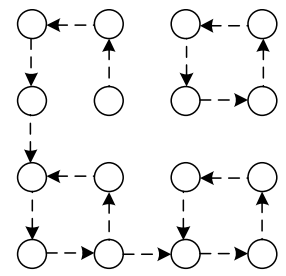


Figure 3. Traffic topology

Nevertheless, consistent performance has been observed for various traffic patterns. AODV routing is used in this scenario without any change.

The application throughput and end-to-end delay performance are shown in Figure 4a/b, respectively. Performance of a single-channel single-radio network $\{C=1, M=1\}$ and a $\{C=4, M=4\}$ network with fixed channel-interface

allocation (i.e., all nodes on the same four fixed channels) are also shown for comparison in Figure 4. We term them as “Simple $M=1$ ” and “Simple $M=4$ ”, respectively. In Figure 4, DTC 1-3 use the same algorithm with different configurations, i.e., the keep-alive timer value for releasing allocated channel-interface resource. DTC 1-3 use values of 10 sec, 3 sec and 1 sec, respectively. One can see that quicker adaptation yields better performance in this case. However, it may not be appropriate to adapt on an even faster packet-by-packet basis, which will incur unnecessary fluctuation and excessive control overhead. Figure 4 shows that DTC can improve all three performance metrics (i.e., throughput, delay and jitter) that jointly reflect the network capacity. Due to the space limit, results for more scenarios are omitted in this paper.

CONCLUSION

We investigate distributed topology control for efficient channel-interface resource utilization in MCMR networks. Simulation results show significant performance gains on network capacity by adopting the proposed DTC. In future work, we plan to further investigate other decision policies, as mentioned in Section IV, under the same over-the-air signaling handshaking framework.

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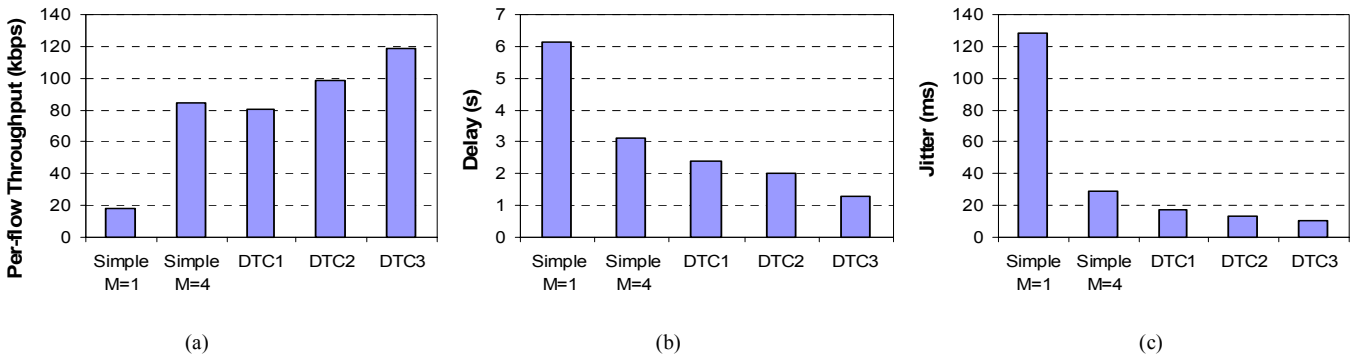


Figure 4. Topology control performance comparison