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Route and Spectrum Selection in Dynamic Spectrum Networks

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***Abstract*— Efficient spectrum allocation in dynamic spectrum systems is a challenging problem, particularly for multi-hops transmissions. The inter-dependence between route selection and spectrum management makes it important to examine interaction between the two and the corresponding performance and complexity tradeoffs. In this paper, we explore two design methodologies: a decoupled design where these tasks are carried out independently by different protocol layers, and a collaborative design that integrates them into a single task. Experimental results show that the collaborative design, if well-provisioned, offers significant performance improvement compared to the decoupled design.**

I. Introduction

Wireless radio spectrum is a precious finite resource. Given that the current spectrum licensing policy facing near-future threat of spectrum scarcity and the increasing crowd in unlicensed spectrum band, efficient spectrum management is necessary and critical to future development of system and networking[2], [9]. While maximizing utilization is the primary goal, a good management scheme also needs to minimize interference and provide a degree of fairness across users. Our previous work on decentralized spectrum allocation focuses on dynamic spectrum selection which is in general the responsibility of Medium Access Control(MAC) layer [3], [14]. Using a single-hop traffic model, we show that user collaboration leads to results that closely approximate the optimal centralized allocation.

For general dynamic spectrum networks, modifications are required at higher layers to respond to dynamically changing spectrum availability and interference pattern. In this paper, we focus on the behavior of multi-hop transmissions where destination user is out of the transmission range of source user, and packets are routed to the destination by users in between. Unlike in single-hop transmissions, the choice of packet route heavily impacts the traffic load on each transmission link and the amount of spectrum required. Observing a strong inter-dependence between route selection and spectrum management, we examine the interaction between the two and the corresponding performance and complexity tradeoffs. In particular, we focus on two design methodologies: 1) a decoupled design where the two tasks are carried out independently by MAC and network layer, and 2) a collaborative design which integrates them into a single task at the network layer - network layer selects route and schedules conflict-free channel usage on the route.

This paper makes three contributions. First, we propose two types of interaction between route selection and spectrum management. Second, we develop detailed implementations that tradeoff performance with communication overhead and computational complexity. Finally, we use extensive simulations to quantify the impact of different approaches on network access.

II. Background and Related Work

In this section, we briefly introduce the background of dynamic spectrum systems and existing work on spectrum management. In dynamic spectrum networks, channels are the fundamental units of spectrum usage, and the operational spectrum is partitioned into non-overlapping channels. Each user performs spectrum sensing to track it spectrum opportunities, *i.e.* the set of channels it can transmit on without interfering with primary users (a set of "legacy" users with the highest priority in spectrum access, see [2], [14]). Users also experience *spectrum heterogeneity*, *i.e.* their spectrum availability fluctuates over time and location[14].

Spectrum management coordinates users' channel usage to prevent conflicts, while promoting utilization and fairness. Existing work in this context took a collaborative approach, where secondary users negotiated spectrum with neighbors in order to maximize system utility, as defined by optimization objectives such as fairness and utilization [3], [10], [14]. The work in [10], [14] reduces the problem to a variant of graph coloring problem and proposes a labelling scheme to prioritize users in channel assignment. In [3], users negotiate spectrum assignment within local self-organized groups. Spectrum management is also responsible for coordinating channel usage at each pair of transmitter and receiver to ensure successful data reception [13].

Existing work on spectrum management mainly focuses on single-hop transmissions. For large scale networks such as sensor or ad hoc networks, devices's transmission range is constrained by their transmission power. When destination user is out of the transmission range of source user, packets are routed to the destination by users in between - *i.e.* through multi-hop transmissions. To utilize spectrum efficiently in multi-hop transmissions, we need to jointly consider route selection and spectrum management. That problem is addressed in this paper.

III. SYSTEM MODEL

A. Assumptions

We first describe our assumptions. We assume that each user keeps track a list of channels available for transmission. Each user is equipped with a single half-duplex radio and hence can only transmit or receive from one channel at a time. This assumption is consistent with the current implementations of IEEE 802.11 end-devices. While having multi-radio interfaces expands communication capability, it may heavily stress energy resources of constrained networks such as sensor and ad hoc devices. This type of network in general consists of many low-cost low-power devices equipped with a single radio. We further assume that each radio is frequency-agile: it can fast switch across channels. Considering that channel switch consumes extra power, we restrict the frequency of switch by using a frame based transmission format and limiting the number of switch in each frame.

We assume each user transmits using a predefined combination of operating parameters (power, modulation, etc.) Power control can also be jointly considered in spectrum management and route selection. We disable this feature since it introduces extra complexity in characterizing interference condition and performing system optimization. This leads to pseudo-static interference environment. We also assume that each channel has similar average throughput.

B. Network Architecture

In our work, each secondary device has the following components. First a *spectrum manager* monitors spectrum usage in the neighborhood and identifies available spectrum. For single-hop transmissions, the *spectrum manager* can choose an appropriate channel to use. Any environment change such as user movement or traffic variation might trigger a spectrum adjustment. Each device also has a *frequency agile radio* module which reconfigures RF to switch to the newly selected channel, and uses the appropriate protocol and modulation on each channel. For multi-hop transmissions, modifications are required at higher layers to respond to dynamically changing spectrum availability. In particular, we introduce a *spectrum aware routing protocol* that adapts route selection to spectrum fluctuations. The design of this *spectrum aware routing protocol* depends on the interaction between route selection and spectrum management.

While the general route selection problem has been well studied for wireless networks, particularly for multi-channel multi-hop ad hoc networks, it is possible to apply some existing solutions to the new problem. However, existing work on general route selection does not consider the availability of multiple spectrum opportunities and fluctuations in such opportunities [7]. Existing work on route selection with multi-channels assumes that each device is equipped with multiple radio interfaces and hence can transmit and receive on different channels concurrently [8], [1], [11]. The work in [12] assumes single-radio devices but restricts the selection to one channel on each route. This restrictive assumption tradeoffs performance with design complexity. Overall, to deploy dynamic spectrum systems with single radio devices, new solutions are necessary to exploit spectrum diversity. For multi-hop transmissions, it is important to examine the interaction between route selection and spectrum management.

IV. ROUTE SELECTION AND SPECTRUM MANAGEMENT

The interaction between route selection and spectrum management specifies tradeoff between performance and signaling complexity, as well as functionality carried out by network and MAC layers. The design is complicated by the requirement of handling spectrum fluctuations and other network dynamics. In this section, we present two design methodologies.

A. Decoupled Route Selection and Spectrum Management

We start from a simple approach where route selection and spectrum management on each device are carried out independently by network layer and MAC layer, respectively. An example implementation of this approach would be

Route selection- The source node invokes path discovery to collect information of the nodes and selects the path using a performance metric. For example, the well-known shortest-hop routing selects the path with the least number of hops.

Spectrum management - The nodes on the selected path invoke MAC coordination protocol, such as HDMAC [13] to schedule packet transmissions. In particular, each node pair coordinates time and spectrum/channel for each transmission.

The decoupled design offers a simple, modular solution to the problem of managing spectrum for multi-hop transmissions. One can integrate different routing schemes with MAC spectrum management schemes. It also enables quick adaptation to network dynamics, which is essential for dynamic spectrum systems where users experience location-dependent and time-varying channel availabilities. Spectrum fluctuations can be quickly "absorbed" by spectrum management, and thus become transparent to route selection. On the other hand, the decoupled design faces several performance tradeoffs. First, optimization in spectrum management focuses on single-hop traffics, and thus does not address end-to-end performance. Second, it is difficult to predict link quality since links switch between channels frequently. This could potentially reduce the reliability of route selection.

Fig 1 illustrates the structure of the decoupled design. There is minimum interaction between route selection and spectrum management. To perform route selection, each source node relies on link connectivity information [1] to construct route. The source node can refine route selection by collecting information on traffic loading and link delay, and integrating it into route selection metric [4]. However, the decision is independent of how single-hop transmissions are performed, in particular, the channel used.

The task of scheduling channel for single-hop transmissions, namely spectrum management, is carried out by MAC layer. The broadcast nature of radio transmissions makes links in

[1]Note that in dynamic spectrum networks, two nodes can connect if they are within transmission distance and have at least one available channel in common.

close proximity interfere with each other if using the same channel. In dynamic spectrum systems, each user observes multiple available channels. By assigning interfering links with different channels, one can exploit spectrum diversity to reduce interference and improve performance. The design of spectrum management is further complicated by the single-radio configuration. In particular, transmitter and receiver need to coordinate with each other to synchronize their channel usage. A coordination protocol is essential to enable frequent handshaking without exhausting communication resources. Section V presents the detailed implementation.

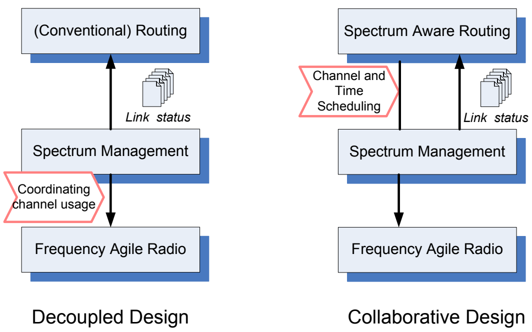

Fig. 1. System Design.

B. *Collaborative Route and Spectrum Selection*

The decoupled design distributes tasks onto MAC and network layers. While simple and modular, it can not address end-to-end optimization which is essential for multi-hop transmissions. To address end-to-end optimization, collaboration between route selection and spectrum management is necessary. Next, we propose a collaborative design.

In this design, some tasks of spectrum management are integrated into route selection. In particular, each source node makes decision on both route and channel selection - the decision include not only the selected packet route, but also the channel to be used by each link on the route, and a time schedule of the channel usage (see Fig 1). The objective of time-scheduling the channel usage is to approach a conflict free channel usage. This scheduling allows for explicit and guaranteed throughput provisioning and control over packet delay. Compared to random access and coordinated channel access [13], such direct influence provides quality of service guarantees in an ad hoc network, especially for real-time applications. The tight control and performance enforcement allows accurate prediction of link performance, and improves accuracy and reliability of route selection. However, the trade-off is additional complexity and communication overhead. In addition, route selection is sensitive to spectrum fluctuations - any spectrum change triggers a new route and channel assignment process.

An example implementation of this approach would be

Route and channel selection - Each source node uses shortest-hop based DSR routing to find candidate paths. It also schedules a time and channel usage for each hop. The information is broadcast to all the users on the path. A detailed algorithm on combined route and channel selection will be included in Section V.

Spectrum management - The nodes along the path follow the time and channel schedule to communicate with each other. There is no additional coordination except those required for time synchronization among users.

V. Implementations

We have described general methodologies of the decoupled and collaborative design. In this section, we present a detailed implementation of both approaches.

A. *Decoupled Design*

The decoupled design can be implemented through integrating existing algorithms on routing and spectrum management. These algorithms are executed by individual nodes assuming no central management. For route discovery and selection, we use DSR [7] with the shortest hop metric. One interaction between network and MAC layers is that MAC layer needs to provide a broadcast mode for route discovery messages.

For spectrum management, we use the MAC coordination protocol in [12], [13] to select channel and schedule transmissions. Time is divided into super-frames, each consisting of a beacon broadcast (BEACON), a coordination window (CHWIN) and a data transmission period (DATA). The single radio interface limits the device to accessing one channel at a time. Hence, the protocol uses a dedicated control window CHWIN to disseminate coordination information. During CHWIN, users switch to the common control channel (*e.g.* channel 0) to solicit transmissions and negotiate the channel for data transmissions. The coordination messages are sent during CHWIN following the CSMA/CA protocol. Each user records the number of successful negotiations on each channel by eavesdropping on coordination messages, and selects the channel with the minimum number of requests or the least traffic load. Detailed protocol design can be found from [13].

At the beginning of DATA, users switch to the selected data channel to send/receive data packets. Note that operations related to transmissions during DATA reflect the normal operation in a single channel system. Users can request and confirm packet transmissions using RTS/CTS control. Compared to a single-channel system, this system has the advantage of distributing data traffic (including RTS/CTS traffic) into multiple data channels. It should be noted that coordination is performed on the fly and not provisioned in advance.

B. *Collaborative route and channel selection*

The collaboration between MAC and network layer is achieved through a hierarchical route and channel selection process. A source node finds candidate routes through standard route discovery procedures, and collects information on link connectivity and quality. For each candidate route, the algorithm finds all feasible channel assignment combinations and estimates the end-to-end throughput performance for each combination (*Algorithm B*). It selects the route and channel assignment that results in the best throughput, and schedules a conflict free channel usage for this route (*Algorithm A*). The source node then broadcasts the decision to all the nodes on the route. In order to predict link quality, users in close proximity should exchange their channel assignment and time schedule.

For large scale networks, it is beneficial to employ a decentralized architecture where each source node makes decision independently or through collaboration. While this is our ultimate goal, in this paper we restrict ourselves to a centralized architecture when deriving the route and channel decision. That is, both *Algorithm A* and *B* are executed by a central "gene" who has the knowledge of global network topology and large computing power. The purpose of using centralized algorithms is to obtain a upper-bound on system performance that a collaborative design can achieve. This result, when compared to that of the decoupled design, offers insights for selecting design methodologies. We are currently researching on a distributed implementation of the collaborative design. Next we will describe these algorithms in detail.

We start by modelling the network using a conflict graph G. In particular, each single-hop link maps to a vertex in the graph. An edge exists between two vertices if the corresponding links can not be active concurrently. Since each user is equipped with a half-duplex radio, two links sharing a common node conflict with each other, and will have an edge in between. In addition, links in close proximity will interfere with each other if they are assigned with the same channel. These links are connected with edges.

When routes are selected and channel usage on each route is planned, a conflict-free time and channel scheduling is required for users to communicate data packets. Using conflict graph, we reduce this problem into a variant of maximum independent set problem. The scheduling is generated by a recursive process that finds the weighted maximum independent set of the graph.

Algorithm A: conflict-free scheduling

1) n=1
2) Each vertex is assigned with a weight that is equal to its degree (the number of edges it is associated with).
3) Find the weighted maximum independent set of the conflict graph [5], namely $IS(n)$.
4) Delete the vertices of $IS(n)$ and the associated edges from the conflict graph
5) If the conflict graph is empty, stop; otherwise set $n = n+1$, go to (2).

Given the independent set, we can schedule transmissions by dividing time into fix-length frames. During frame i, all the links in $IS(i)$ can transmit since they will not interfere with each other. Hence, the number of time frames required to carry packets from sources to destinations is equal to the number of independent sets, *i.e.* n from *Algorithm A*. n is also referred to as the chromatic number of the conflict graph. It is easy to show that the aggregated system throughput is inversely proportional to n. This throughput estimation can be integrated into *Algorithm B* to select the best route and channel combination for given network flows.

Algorithm B: route and channel selection

1) Find all possible candidate routes for existing flows.
2) Find all possible channel assignments for each route.
3) For each route/channel combination, execute *Algorithm A* to derive n.
4) Find the route/channel selection that minimizes n, and the corresponding conflict-free scheduling (obtained by *Algorithm A*).

Finding n and the maximum independent set requires a set of complex computations. Given that the scale of possible route and channel combinations increases exponentially with the number of nodes, this approach is not computationally feasible. It has been shown that a graph's maximum clique number provides a low-complexity approximation to the chromatic number. Hence, we propose an *Algorithm C* to replace step (3) of *Algorithm B*.

Algorithm C - estimating the maximum clique number

1) For each vertex u, delete all the vertices that are not connected with it.
2) Construct a vertex set, VE. Set $VE = \{u\}$.
3) Continue to add the remaining vertices to VE, starting from the vertex with the largest degree. Repeat this step until all the vertices in VE become fully-connected.
4) $C(u) = |VE|$.

The maximum clique number is derived as $\max_{u \in G} C(u)$.

VI. Experimental Results

We conduct experimental simulations to quantify the performance of route selection and spectrum management. We compare the aggregated network throughput of the decoupled design to that of the collaborative design assuming off-line time and channel scheduling. We also vary the number of available channels per device to examine the benefits of spectrum diversity.

We assume a mobile ad hoc network by placing users on an area, and use a binary interference metric - two users conflict if they are within distance of 550, two users can communicate if they are within distance of 250. This corresponds to the protocol interference model [6], [10], which provides an approximation to the effects of interference in real wireless systems without delving into complex detection and decoding algorithms.

We extend NS-2 simulations with CMU wireless extensions to implement the MAC coordination protocol that allows user to negotiate channel usage [13]. We only simulate CBR traffic to evaluate system performance without impacts from transport protocols, and assume that each source user is backlogged. Each frame is 100ms and each CHWIN is of 15ms. For the collaborative design, the CHWIN is set to 0ms. Each user can only adjust its channel usage (*i.e.* switch from one to another) at the beginning of each frame. There is a 5ms switch delay during which no transmission or reception are performed. Each single-hop link can transmit at 11Mbps.

We start from a few sample topologies in Fig. 2. Table I summarizes the aggregated system throughput using different design. For easy notation, we refer to the decoupled design

TABLE I
PERFORMANCE OF DECOUPLED AND COLLABORATIVE DESIGN
(AGGREGATED SYSTEM THROUGHPUT(MBPS))

Topo	DC (1CH)	JNT (1CH)	DC (2CH)	JNT (2CH)	DC (3CH)	JNT (3CH)
I	0.75	0.93	0.68	1.77	0.82	2.52
II	0.79	0.95	1.13	1.77	1.17	2.52
III	0.74	0.95	1.08	1.76	1.39	1.76
IV	0.72	0.95	1.35	1.80	1.81	2.71

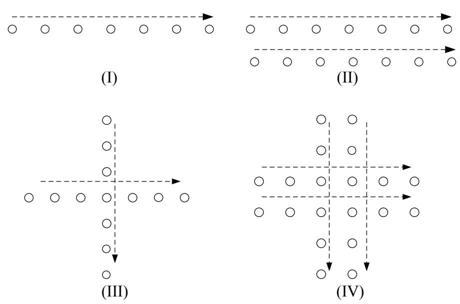

Fig. 2. Fixed topologies

as "DC" and the collaborative design as "JNT". We examine the performance assuming 1, 2 and 3 channels are available at each device, referred to as "1CH", "2CH" and "3CH", respectively. Results confirm that increasing the number of available channels, *i.e.* spectrum diversity, leads to significant performance improvement. With 2 channels, the decoupled design achieves 45% gain compared to the same design using 1 channel, and 15% gain compared to the collaborative design using 1 channel. With 3 channels, the gain improves to 145% and 86%, respectively.

We observe that there is still a noticeable amount of difference between the decoupled design and the collaborative design. Since the results of collaborative design are obtained assuming a centralized planning with global knowledge, the corresponding distributed implementation might lead to performance degradation. We are currently investigating distributed implementations of the collaborative design.

We also examine the performance of the collaborative design in a random network where 50 nodes are randomly deployed in an area. For each simulation, we randomly choose 10 pairs and route CBR traffics between each. Figure 3 illustrates the aggregated system throughput under different node deployments. We observe that the collaboration design leads to linear throughput growth with the number of available channels. This further illustrates the importance of collaboration between network and MAC layers.

VII. CONCLUSION

In this paper, we consider the problem of managing spectrum for multi-hop wireless transmissions. We focus on the interaction between spectrum management and route selection which are in general decoupled and independently executed by MAC and network layers, respectively. We propose a collaborative design, where route selection also includes channels to be used on each hop and the time schedule of the channel usage. Experimental results show that the collaborative design, if well-provisioned, provides significant improvement in end-to-end performance.

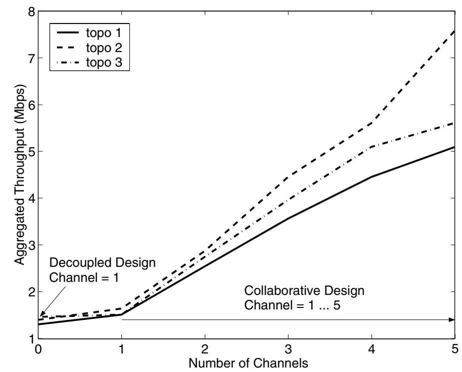

Fig. 3. Aggregated Throughput under Random Topologies.

REFERENCES

[1] ADYA, A., BAHL, P., PADHYE, J., WOLMAN, A., , AND ZHOU, L. A multi-radio unification protocol for ieee802.11 wireless networks. In *IEEE international conference on broadband networks (Broadnets)* (2004).

[2] BERGER, R. J. Open spectrum: a path to ubiquitous connectivity. *ACM Queue 1*, 3 (May 2003).

[3] CAO, L., AND ZHENG, H. Distributed spectrum allocation via local bargaining. In *IEEE SECON* (Santa Clara, CA, Sept. 2005).

[4] DRAVES, R., PADHYE, J., AND ZILL, B. A high-throughput path metric for multi-hop wireless routing. In *Proc. ACM SIGCOMM* (Aug. 2004).

[5] HALLDÓRSSON, M. M. Approximations of independent sets in graphs. In *proceedings of APPROX '98: Proceedings of the International Workshop on Approximation Algorithms for Combinatorial Optimization, LNCS 1444* (1998), Springer-Verlag, pp. 1–13.

[6] JAIN, K., PADHYE, J., V.N.PADMANABHA, AND QIU, L. Impact of interference on multi-hop wireless network performance. In *Proc. ACM Mobicom* (2003).

[7] JOHNSON, D. B., AND MALZE, D. A. *Mobile Computing*. Kluwer Academic Publishers, 1996, ch. Dynamic Source Routing in Ad-Hoc Wireless Networks.

[8] KYASANUR, P., AND VAIDYA, N. H. Routing in multi-channel multi-interface ad hoc wireless networks. Tech. rep., UIUC, Dec. 2004.

[9] MCHENRY, M. Spectrum white space measurements. *New America Foundation Broadband Forum* (June 2003).

[10] PENG, C., ZHENG, H., AND ZHAO, B. Y. Utilassignmentd fairness in spectrum assignemnt for opportunistic spectrum access. *Mobile Networks and Applications (MONET)* (2006). to appear.

[11] RANIWALA, A., GOPALAN, K., AND CKER CHIUEH, T. Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks, 2004.

[12] SO, J., AND VAIDYA, N. A routing protocol for utilizing multiple channels in multi-hop wireless networks with a single transceiver. Tech. rep., UIUC, Oct. 2004.

[13] ZHAO, J., ZHENG, H., AND YANG, G. Distributed coordination in dynamic spectrum allocation networks. Accepted by Dyspan, Baltimore, Nov. 2005.

[14] ZHENG, H., AND PENG, C. Collaboration and fairness in opportunistic spectrum access. In *Proc. 40th annual IEEE International Conference on Communications* (June 2005).