Title

Collaborative Routing,Scheduling and Frequency Assignment for Wireless Ad Hoc Networks UsingSpectrum-Agile Radios

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Collaborative Routing, Scheduling and Frequency Assignment for Wireless Ad Hoc Networks Using Spectrum-Agile Radios

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Abstract— **We present the CROWN (Collaborative ROuting, scheduling and frequency assignment for Wireless ad hoc Networks) scheme. CROWN is a cross-layer optimization approach for spectrum-agile nodes to adjust their spectrum allocation and transmission scheduling according to the underlying traffic demands. Instead of choosing the optimal route based on predetermined transmission scheduling and frequency assignment results, CROWN incorporates the efficiency of the underlying frequency assignment and scheduling information into the routing metric calculation, so that the route with the maximal joint spatial and frequency reuse is selected. Simulation results show that CROWN efficiently exploits the frequency diversity and spatial reuse features of spectrum-agile radios.**

I. INTRODUCTION

Frequency assignment, routing and scheduling are dependent on each other in wireless networks, and the input of any component is partially decided by the outputs of the other two components. Hence, to fully leverage spatial and frequency diversities in ad hoc networks, frequency assignment, routing and scheduling must be solved as a joint, and this poses several challenges. Among the questions that must be answered we have: How should the available spectrum be allocated according to the traffic demands? What makes a transmission scheduling efficient in terms of both frequency diversity and spatial reuse? How should the MAC and network layers interact to exploit frequency diversity and spatial reuse at both layers?

We propose three mechanisms to address the above problems. We introduce a heuristic approach to dynamically adjust spectrum allocation according to the traffic demands and achieve fairness across different links. We propose a unified metric, which we call *transmission fraction*, to evaluate the efficiency of the joint spectrum allocation and link scheduling in terms of spatial and frequency reuse. We incorporate the efficiency of the underlying frequency assignment and scheduling information into the routing metric calculation so that the route with the maximal joint spatial and frequency reuse is selected. The rest of the paper is organized as follows. Section II describes the related work. Section III introduces the details of CROWN (Collaborative ROuting, scheduling and frequency assignment for Wireless ad hoc Networks). Section IV evaluates the performance of CROWN through simulations. Section V concludes the paper.

II. RELATED WORK

There has been considerable work on joint routing, scheduling and channel assignment, and due to space limitations we can only focus on a small sample of this work. The vast majority of the previous work consists of centralized approaches with some distributed heuristics [1] [2] [3] [4] [5] [6] [7] [8] [9].

Tam et al. [10] propose a joint multi-channel and multi-path control protocol (JMM). JMM coordinates channel usage among slots using a receiver-based channel assignment and schedules transmissions along dual paths. JMM uses a routing metric which explicitly accounts for the disjointness between paths and interference among links to select two maximally disjoint paths. Wu et al. [11] propose a channel cost metric (CCM) which reflects the interference cost and channel diversities. Based on CCM, a distributed joint frequency assignment and routing protocol is proposed.

There are several proposals addressing the joint routing selection and spectrum assignment issues in cognitive radio networks. DORP [12] employs on-demand routing that cooperates with a spectrum-assignment module. DOSS [13] proposes a collaborative approach in which a source node finds candidate routes through standard route discovery procedures. For each candidate route, DOSS finds all feasible frequency assignment combinations and estimates the end-to-end throughput performance. It selects the route and channel assignment that results in the best throughput, and schedules a conflict free channel usage for this route. The source node then

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broadcasts the decision to all the nodes on the route. However, all these proposals rely on the IEEE 802.11 MAC protocol, and do not exploit the spatial-reuse of the system.

Our survey of prior work reveals that the joint optimization of routing, scheduling and frequency assignment using spectrum-agile radios remains a problem yet to be solved.

III. DISTRIBUTED JOINT FREQUENCY ASSIGNMENT, ROUTING AND SCHEDULING

A. Problem Formulation and Assumptions

We assume that there are K radio interfaces at each node, and that all radios operate on unlicensed bands $[F_s, F_e]$. We focus on how to efficiently exploit the available spectrum resources, and do not address the primary user detection problem on licensed bands. We assume that each node is synchronized on slot boundaries and that nodes access the channel based on slotted time boundaries. Each time slot is numbered relative to a consensus starting point. The length of the time slot (t_s) is the minimal unit of the channel-access schedule over the time axis. A time frame is made up of L time slots ($T_f = Lt_s$). We assume the minimum interval by which the spectrum can be divided along the frequency axis is σ. The available spectrum is allocated in *frequency block* units. A frequency block $(f_0, \Delta f, t_0, \Delta t)$ is a portion of the spectrum $(f_0, f_0 + \Delta f)$ for the time interval $(t_0, t_0 + \Delta t)$.

We divide the joint routing, scheduling and frequency assignment problem into two sub-problems: First, we address the transmission scheduling and frequency assignment problem consisting of utilizing the available spectrum in the two-hop neighborhood of each link (i, j) to the largest extent. Second, given a transmission scheduling and frequency assignment of different links, we address the routing problem consisting of deciding which links to use and how to form the correct sequence/ordering of the transmission scheduling across the network.

In CROWN, there is a specific packet queue for broadcast packets. For unicast transmissions, given that neighbors of a node may be operating on different portions of the spectrum, we choose to schedule packets to each neighbor individually, unicast packet queues are maintained as per-neighbor FIFO queues. Each neighbor is identified with its unique MAC address.

We use a common control frequency block $[F_s, F_s + F_c, 0, T_c]$ in each time frame to exchange the topology information and traffic flow information. During time interval $[0, T_c]$ of each time frame, each node switches one of its radio interfaces to the control spectrum $[F_s, F_s + F_c]$. The control frequency block is further divided into mini-frequency blocks of equal size $[0, f_c, 0, t_c]$. Each mini-block is assigned with an unique id x. We define the *priority* of node i at frequency block x as:

$$prio_i = hash(i \oplus x) \quad (1)$$

Because each node has a unique hash code, Equation (1) guarantees that each node in the two-hop range will have a unique node priority in each mini-frequency block. The node with the highest priority is elected to obtain the corresponding frequency block, and it sends a Frequency Allocation Request (FAR) packet. The FAR packet from node i states its: (a) the minimal data rate requirement (r_{ij}) for each link (i, j) that has packets to send, (b) *neighbor information* consisting of its one-hop neighbor list and two-hop neighbor list, and (c) the existing transmission scheduling and frequency assignment result, which is indicated by *frequency allocation table* ($FAT(f, \Delta f, t) = \{(u, v), \dots\}$). It states the spectrum $[f, f + \Delta f]$ is occupied by link set $\{(u, v), \dots\}$ at time slot t.

The size of the mini-frequency block needs to be big enough to send an entire FAR packet (how to estimate the corresponding frequency block size given the traffic demands will be discussed in Section III-C). Based on the information collected in the previous time frame, nodes decides how the data frequency blocks are divided for the next time frame. The detailed approach is discussed in Sections III-C and III-D.

B. Transmission Scheduling

Given that frequency diversity is not beneficial for broadcast traffic, in CROWN, a broadcast source sends a request in the control frequency block, which reserves one data frequency block. Each receiving node in the communication range switches one of its radio interfaces to that data frequency block to receive the broadcast packet.

For unicast traffic, CROWN attempts to maximize the frequency/spatial reuse by assigning different links with different spectrums/time slots. A unified metric, the *transmission fraction*, is used to evaluate the efficiency of the joint frequency assignment and link scheduling for unicast transmissions. The *total transmission fraction* of link (i, j) (TTF_{ij}) is defined to be the overall spectrum resource that link (i, j) could utilize in its two-hop range, in one time frame and excluding the parts used for control information exchange, that is, frequency block $[F_s + F_c, F_e, T_c, T_f]$. The transmission fraction of link (i, j) (TF_{ij}) is defined as the the maximal proportion of frequency resources (i, j) could obtain through joint frequency assignment and link scheduling.

TF_{ij} is used as the link cost used to compute the *logical distance* (LD_p^{ij}) of path p if link (i, j). The route that has the minimum logical distance (which means that it can achieve the maximum end-to-end throughput) is selected. Once a path is selected, the transmission scheduling and frequency assignment that are incorporated in TF_{ij} are also established.

C. Data Rate Adjustment

To correctly divide the available frequency block $[F_s + F_c, F_e, T_c, T_f]$ along the time and frequency axes, the frequency block that each link (i, j) obtains must be guaranteed to satisfy its bandwidth requirements (r_{ij}). Given the available bandwidth $[f_s, f_e] \subseteq [F_s + F_c, F_e]$ and the minimal spectrum division interval σ, the set of all possible spectrum allocations for link (i, j) ($B_{ij} = \{[f_{s1}, f_{e1}], [f_{s2}, f_{e2}], \dots, [f_{sm}, f_{em}]\}$) is obtained, and then the corresponding data rate of each spectrum division is estimated using the following approach.

Let P_k^r denote the received signal power at node r for a signal transmitted by node k. The maximum physical-layer capacity is

$$C_{ij}^k = B_{ij}^k \times log_2[1 + \frac{P_i^r}{\sum_j P_j^r + \sigma_r^2}] \qquad (2)$$

where B_{ij}^k is the bandwidth of spectrum division $[f_{sk}, f_{ek}]$, σ_r^2 is the background or thermal noise power at the front end of the receiver r. Assuming that the sum of the interference power follows a lognormal distribution, we obtain the following approximate link capacity

$$E[C_{ij}^k] = B_{ij}^k \times log_2[1 + \frac{P_i^r}{E[\sum P_I] + \sigma_r^2}] \qquad (3)$$

where $E[\sum P_I]$ is the mean of the lognormal distribution.

We denote the maximal achievable data rate of link (i, j) (using spectrum $[F_s + F_c, F_e]$) by R_{max}. We define a data rate R_{ij}^k for link (i, j) to be *feasible* if it is greater than the minimal data rate requirement of link (i, j) (r_{ij}). We denote the feasible data rate set for link (i, j) by RS_{ij}:

$$RS_{ij} = \{R_{ij}^k \geq r_{ij}, k = 1, \ldots, K\} \qquad (4)$$

We propose a heuristic approach (Algorithm 1) to compare all possible data rate combinations of links in the two-hop range of (i, j). We use Jain's *fairness index (FI)* to choose the data rate combination that maximize the fairness across all links. Let N_{ij}^2 be the total number of links in the two-hop range of (i, j) that have traffic, then

$$FI = \frac{(\sum x_{ij})^2}{N_{ij}^2 \sum x_{ij}^2}, \quad with \quad x_{ij}^k = \frac{R_{ij}^k}{r_{ij}} \qquad (5)$$

Algorithm 1 Data rate adjustment algorithm

```
for each link $(u, v)$ in the two-hop range of $(i, j)$ do
    Estimate the feasible data rate set:
    $RS_{uv} = \{R_{uv}^k \geq r_{uv}, k = 1, \ldots, K\}$;
end for
for each link $(u, v)$ in the two-hop range of $(i, j)$ that have traffics do
    for each data rate $R_{uv}^k \in RS_{uv}$ do
        $x_{uv}^k = \frac{R_{uv}^k}{r_{uv}}$;
    end for
end for
$\{R_1, R_2, \ldots, R_{N_{ij}^2}\} = \arg\max_{k_1, \ldots, k_{N_{ij}^2}} \{\frac{(\sum_i x_{uv}^{k_i})^2}{N_{ij}^2 \sum_i (x_{uv}^{k_i})^2}\}$;
```

Through this approach, we obtain the data rate set for all links in the two-hop range of (i, j). We denote it by $R_{ij}^2 = \{R_1, R_2, \ldots, R_{N_{ij}^2}\}$, and the corresponding spectrum bandwidth is $B_{ij}^2 = \{B_1, B_2, \ldots, B_{N_{ij}^2}\}$.

D. Frequency Assignment

After the data rate of each link that has packets to send is obtained, given that the bandwidth required by link (u, v) is B_{uv}, and that the unit of transmission scheduling over time is t_s, then the data frequency block size for (u, v) is $[0, B_{uv}, 0, t_s]$. The problem of exploiting the frequency diversity and time-reuse in the two-hop range of link (i, j) to the largest extent is equal to placing as many different data frequency blocks as possible into the region of TTF_{ij}. We can map the joint frequency assignment and transmission scheduling problem into a 2D bin-packing problem. We adopt the first-fit decreasing strategy to solve this NP-hard problem. In our approach, the data frequency blocks are sorted in decreasing order of bandwidth requirements, then each link is inserted into the first time slot with sufficient remaining bandwidth, as Figure 1 shows. The output of the algorithm includes the amount of bandwidth that link (i, j) could obtain (BW_{ij}), and the average number that a link could be scheduled in one time frame (S_{ij}). Given that $TTF_{ij} = R_{max}(T_f - T_c)$, the transmission fraction of (i, j) is

$$TF_{ij} = \frac{S_{ij} BW_{ij}}{R_{max}(T_f - T_c)} \qquad (6)$$

E. Routing

The optimal routing policy for wireless ad hoc networks using spectrum-agile radios needs to jointly consider the throughput and the efficiency of spectrum utilization. To do so, we adapt a proactive distance-vector routing protocol. We use TF_{uv} to replace the link cost information used in the traditional routing distance calculation, and get the *logical distance* (LD_p^{uv}) of path p if link (u, v) is included. The route that has the minimum logical distance (i.e., it achieves the maximum end-to-end throughput) is selected. Once a path is selected, the transmission scheduling and frequency assignment incorporated in TF_{uv} are also established.

a) Logical distance calculation: The *logical distance (LD)* of path p is given by a path function f^p based on the transmission fraction of its consisting links. We define the f^p as:

$$f^p = min_{(u,v)}\{\frac{1}{TF_{uv}}\}, (u, v) \in p \qquad (7)$$

Let LD_j^i denote the logical distance from node i to destination j as known by node i. LD_{jk}^i denotes the logical distance LD_j^k from node k, which is a neighbor of node i, to destination j, as reported to node i by node k. FLD_j^i denotes the *feasible logical distance (FLD)* of node i for destination j, which is an estimate of the minimal logical distance maintained for destination j by node i.

Node i maintains a routing entry for each destination j, which includes FLD_j^i, LD_j^i and the successor set chosen for j (denoted by S_j^i) . Node i maintains a neighbor table that records the logical distance LD_{jk}^i reported by each node k in its neighbor set N^i for each destination j; and a link table that reflects the transmission fraction TF_{ik} for each adjacent link $(i, k), k \in N^i$. The multiple paths computed between node i and destination j are called the *logical shortest multipath*, denoted by LSM_j^i, and it is such that at least one of the paths in it has the minimal logical distance for j. In CROWN, each node maintains up to x LSMs for each destination.

We focus on the operation of node i's computation of LSMs for a destination j. Provided that each node maintains up to

PSEUDO-CODE OF SPECTRUM ALLOCATION ALGORITHM

Notations:
B_{uv}: bandwidth requirements for link (u,v);
R_{uv}: the corresponding data rate of B_{uv};
$RB(t) = [f_s, f_e]$: remaining bandwidth at time slot t;
$NR_i(t)$: number of available radios interfaces of node i at time slot t;
$FAT(f, \Delta f, t) = \{(u,v), \dots\}$: frequency allocation table, it indicates the spectrum $[f, f+\Delta f]$ is occupied by link set $\{(u,v), \dots\}$ at time slot t;
$I((m,n),(u,v))$: indicator function, $I((m,n),(u,v)) = 1$ if (m,v) or (u,n) is in the interference range of each other;
T_{uv}: the time that link (u,v) could transmit.
BW_{uv}: the amount of bandwidth link (u,v) could obtain;
S_{ij}: the average number a link could be scheduled in one time frame.

```
procedure INITIALIZATION( )
    $RB(t) \leftarrow [F_s + F_c, F_e]$;    ▷ for every time slot $t$
    $T_{uv} \leftarrow 0$;    ▷ for each link $(u,v)$
    $NR_i(t) \leftarrow K$;    ▷ for each node $i$ at every time slot $t$
    $FAT \leftarrow \emptyset$;
    /*exclude the existing broadcast transmissions*/
    for each broadcast transmission from node $u$ at frequency block $[f, \Delta f, t]$ do
        if $(NR_u(t) > 0)$ then
            $FAT(f, \Delta f, t) = u$;
            $NR_u(t) = NR_u(t) - 1$;
        end if
    end for
end procedure
```

```
procedure SPECTRUM_ALLOCATION( )
    SORT($B_{ij}^2 = \{B_1, B_2, \dots, B_{N_{ij}^2}\}$);
    /*Sort all links according to the decreasing order of required bandwidth ;*/
    for each link $(u,v) \in L_{ij}^2$ do
        for each time slot $t_s \in [T_c, T_f]$ do
            if $((NR_u(t) > 0) \wedge (NR_v(t) > 0))$ then
                /*There are available radio interfaces*/
                if $(FAT(f, \Delta f, t) \neq \emptyset)$ then
                    for each $(\Delta f \geq B_{uv})$ do
                        /*there are available bandwidths*/
                        if $(\forall (m,n) \in FAT(f, \Delta f, t),$
                            $I((m,n),(u,v)) == 0)$ then
                            /*$(u,v)$ does not interfere with any existing transmission schedules*/
                            $FAT(f, \Delta f, t) = FAT(f, \Delta f, t) \cup (u,v)$;
                            $NR_u(t) = NR_u(t) - 1$;
                            $NR_v(t) = NR_v(t) - 1$;
                            $T_{uv} = T_{uv} + t_s$;
                            return;
                        end if
                    end for
                end if
                if $((f_e - f_s) \geq B_{uv})$ then
                    /*there are available bandwidths*/
                    /*Assign links in different frequency spectrums*/
                    $f_s = f_s + B_{uv}$;
                    $FAT(f_s, B_{uv}, t) = (u,v)$;
                    $NR_u(t) = NR_u(t) - 1$;
                    $NR_v(t) = NR_v(t) - 1$;
                    $T_{uv} = T_{uv} + t_s$;
                end if
            end if
        end for
        $BW_{uv} = T_{uv} \times R_{uv}$;
    end for
    $S_{ij} = \frac{\sum_{(u,v)} T_{uv}}{t_s N_{ij}^2}$;
end procedure
```

Fig. 1. Spectrum allocation algorithm

x LSMs for destination j, node i may receive and record x values of LD_{jk}^i from each neighbor k; node i also reports to its neighbors the logical distances of the x LSMs from itself to destination j, of which the minimal value is also used as the feasible logical distance FLD_j^i of node i. When a node is powered up, FLD is set to ∞, and all the other entries are set to empty. For destination j we have $LD_j^j = 0$, $FLD_j^j = 0$, and $LD_{jj}^k = 0, \forall k \in N^j$. We also assume that node i knows the transmission fraction of each outgoing link $TF_{ik}, k \in N^i$.

When node i receives an input event at time t, node i behaves in one of three possible ways: (a) Node i remains idle and all distance estimates are left unchanged; (b) node i receives LD_j^k from neighbor k, updates the estimates LD_{jk}^i and leaves all other estimates unchanged; and (c) node i updates $S_j^i(t)$ and $FLD_j^i(t)$ for destination j based on the following equations:

$$S_j^i(t) = \{k | LD_{jk}^i(t) < FLD_j^i(t),\ k \in N^i\} \tag{8}$$

and updates its feasible logical distance by

$$FLD_j^i(t) = min\left(LD_{jk}^i(t), \frac{1}{TF_{ik}}\right) \tag{9}$$

for all LD_j^k reported by each neighbor k and over all neighbors in N^i. Then node i re-computes the logical distance of each LSM maintained for j (up to x LSMs), and sends neighbors updates if any change occurs; otherwise leaves all other estimates unchanged.

The aggregate of the routing entries for destination j maintained at each node forms a directed graph rooted at j, which is a subgraph of network G and is denoted by SG_j. This subgraph includes links $\{l_{i,k} | k \in S_j^i \text{ for } \forall i \in V\}$. If routing converges correctly, SG_j is a directed acyclic graph (DAG) in which each node can have multiple successors for node j.

Although multiple SG_j can exist for destination j in a given network, CROWN constructs SG_j in a way that the path with the shortest logical distance for destination j is always maintained (by Eq. (8) and (9)), and as such makes SG_j an optimal successor graph.

Loop-free routing is also attained by using Eqs. (8) and (9). The proof that this is the case is presented in [14].

b) Logical distance propagation and deduction: Logical distances are sent in the proactive routing updates messages. The propagation of routing updates messages consists of two phases. During the route discovery stage, routing updates propagate through the network for each destination in order to inform all nodes of possible routes to each destination, regardless of frequency assignments or transmission schedules. Neighbor update messages are transmitted as broadcast packets to accomplish this. After routes are established to destinations, the neighbor update messages that include the future transmission scheduling and frequency assignment information are transmitted as unicast packets to the specific neighbors. This way, multiple neighbor updates can be sent simultaneously over different parts of the spectrum.

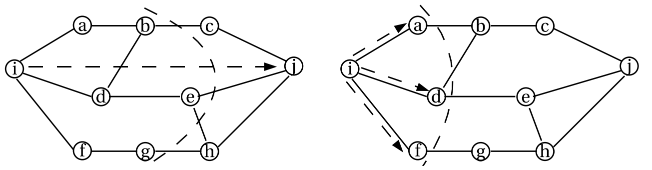
The distance vector reporting a path p for destination j by neighbor k is a tuple of $\{j, LD_j^k, TF_{ik}\}$, in which LD_j^k is the logical distance for p, and TF_{ik} is the transmission fraction for adjacent link (i,k). For each LSM p computed for destination j, besides the logical distance, the raw transmission fraction of adjacent link TF_{ik} must also be maintained, because TF_{ik} is used to verify whether p can be a feasible path when a request to forward traffic arrives.

Assume that the minimal logical distance reported by neighbor k for destination j at node i is $\widetilde{LD}_{jk}^i$, and that the current feasible logical distance for j at node i is FLD_j^i. Let $\circ$ denote the concatenation of two paths or links. According to Eq. (8), path $l_{i,k} \circ p$ is now considered as a candidate path for j if $\widetilde{LD}_{jk}^i < FLD_j^i$ $(i.e.,\ k \in S_j^i)$.

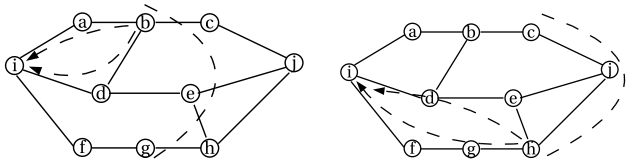
Path $l_{i,k} \circ p$ can be upgraded to a LSM if it has a smaller logical distance than the current feasible logical distance. In mobile scenarios, it may be the case that node i is unable to find a neighbor k that has reported a logical distance that is smaller than the feasible logical distance (FLD_j^i) maintained by node i at the time. CROWN uses diffusing computations to coordinate node i with all upstream nodes that use node i in their LSMs for destination j to update the corresponding logical distance and feasible logical distance (see [14]).

F. Example

Figure 2 illustrates how nodes run CROWN to deduce their LSMs for the destination j without knowing global network state. We assume that there is a traffic flow from i to j. Each node is labeled with (LD_j^i, FLD_j^i), i.e., its shortest logical distance and feasible logical distance for j; and each link is labeled with the associated transmission fraction.



(a) Data rate adjustment (b) Computation of $TF_{ia}, TF_{id}, TF_{if}$



(c) Compute LSMs at node b (d) Compute LSMs at node h

Fig. 2. Routing example

In Figure 2(a), based on its bandwidth requirement and the data rate of existing traffic flows in the two-hop range, node i first adjusts the data rate according to Algorithm 1. Then it calculates the transmission fraction for link $\{(i,a),(i,d),(i,f)\}$, and sends the corresponding results through neighbor updates. After receiving the broadcast requests from i on the control frequency, nodes $\{a,d,f\}$ switch one of their radio interfaces to the specified data spectrum to receive the neighbor update. Then nodes $\{a,d,f\}$ calculate the transmission fractions for links $\{(a,b),(d,b),(d,e),(f,g)\}$, and send the neighbor updates to their upstream nodes. In Figure 2(c), node b selects the optimal path to node i, and nodes $\{b,e,g\}$ calculate the transmission fraction for links $\{(b,c),(b,d),(e,j),(e,h),(g,h)\}$. In Figure 2(d), node h chooses between paths $(h \rightarrow e \rightarrow d \rightarrow i)$ and $(h \rightarrow g \rightarrow f \rightarrow i)$. This process continues until each node obtains the optimal path to the destination.

Note that a schedule is formed *in sequence* along the routing path from the destination to the source. Descendent nodes exclude the schedule of ascendent nodes, which is indicated in the FAR packets. With this approach, the schedule and frequency assignment along a specific route is compatible, while the schedules among different LSMs may be in conflict. This is why we only allow one LSM to be chosen each time. After the routes are established, the future neighbor update messages are sent through the existing transmission scheduling and channel assignment as unicast packets, e.g., when i updates the TF_{ia}, it will just send a neighbor update message to a. Other nodes that do not use a in their LSMs to i will not receive the TF_{ia}.

IV. PERFORMANCE EVALUATION

We implemented CROWN under Qualnet [15] and compare it with DORP [12]. We assume each node has four radio interfaces. The overall available spectrum is 86 MHz (the size of 2.4 ISM band). t_s is 50ms. A time frame is made up of 100 time slots ($L = 100$). The set of bandwidth interval (σ) includes 5, 10, 15 MHz. The bandwidth requirements of traffic flows are uniformly distributed in $1 \sim 10Mbps$. We assume that each 1 MHz spectrum delivers 1.2 Mbps data rate [16]. The packet length used is 1024 bytes. The duration of the simulation is 100 seconds. The simulations are repeated with ten different seeds to average the results for each scenario.

The performance gain of CROWN mainly comes from its joint optimization of frequency assignment and distributed link scheduling, as well as from choosing paths based on the efficiency of the underlying transmission scheduling and frequency assignment. We illustrate these performance improvements separately under different scenarios.

To illustrate the performance gain due to the joint frequency assignment and distributed link scheduling, we first investigate the performance of CROWN under a 6×6 regular grid with static routing of fixed flows. The transmission range of each node is T_R, each node is T_R away from each other. The interference range $I_R = \sqrt{2}T_R$. We set up five CBR flows, such that three of them have node-disjoint horizontal paths and two of them have node-disjoint vertical paths in the grid, with the vertical path crossing the second and second-to-last hops of the horizontal paths. The system throughput comparison is shown in Table I. The results indicate that CROWN improves the system performance significantly.

TABLE I

SYSTEM THROUGHPUT FOR GRID TOPOLOGY

DORP (5MHz)	DORP (10MHz)	DORP (15MHz)
15.38	13.96	11.27
CROWN (5MHz)	CROWN (10MHz)	CROWN (15MHz)
27.49	25.31	24.12

To illustrate performance improvement due to the joint optimization of MAC and routing, we generated 10 topologies with 60 nodes uniformly distributed across a 800 × 800 square meters area. We varied the number of traffic flows and the minimal bandwidth interval σ. As Figure 3 shows, system throughput decreases with increases of σ, which indicates a reduction of non-overlapping channels. There is a trade-off between the feasible data rates and the frequency reuse of the system.

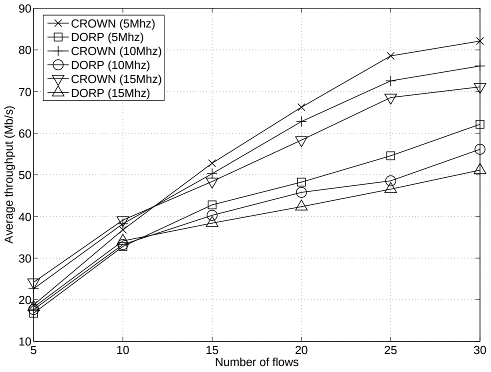


Fig. 3. Random throughput

From Table I and Figure 3, we observe that CROWN uses efficiently the available spectrum and outperforms DORP significantly.

V. CONCLUSION

We proposed a novel distributed link-layer scheduling and routing optimization approach for wireless ad hoc networks using spectrum-agile radios. Routing selection is made based on the efficiency of the underlying link-layer scheduling and frequency assignment schemes. Simulation results show that the proposed approach increases the system performance significantly by load balancing the traffic over different channels and different times.

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