Software-defined Joint Routing and Waveform Selection for Cognitive Ad Hoc Networks

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***Abstract*—The problem of throughput maximization in a cognitive radio network with decentralized control (i.e., a cognitive radio ad hoc network) is considered in this paper. First, decentralized and localized algorithms for throughput maximization through joint cognitive routing and interference-avoiding waveform selection are proposed, based on a nonlinear optimization framework. The proposed algorithms adapt to time-varying traffic demands, interference profile, and network topology to locally maximize the achievable data rate while avoiding harmful interference to co-located primary or secondary users. Second, a prototype implementation of the proposed decentralized control algorithms is presented. The prototype is based on a software-defined-radio USRP2 platform that distributively senses and adapts its transmission based on results from real-time nonlinear optimization. Experiments on the software-defined-radio platform demonstrate the superior adaptivity of the proposed algorithm with respect to state-of-the-art non-cognitive approaches.**

***Index Terms*—Cognitive radio ad hoc networks, dynamic spectrum access, power allocation, software defined radio.**

I. Introduction

Cognitive [1] radio networks [2] are emerging as a promising technology to improve the utilization efficiency of the existing radio spectrum. A key challenge in the design of cognitive radio networks is dynamic spectrum allocation, which enables wireless devices to opportunistically access portions of the spectrum as they become available. Consequently, techniques for dynamic spectrum allocation have received significant attention in the last few years, e.g., [4], [5], [9], [10], [14]. However, mainstream cognitive radio research has so far been focused on infrastructure-based networks, while the underlying root challenge of devising decentralized spectrum management mechanisms for infrastructure-less cognitive radio ad hoc networks is still substantially unaddressed. Additionally, throughput maximization is one of the main challenges in cognitive radio ad hoc networks with multi-hop communication requirements, where spectrum occupancy is location-dependent and time-varying.

With this respect, we propose decentralized and localized algorithms for throughput maximization through joint cognitive routing and interference-avoiding waveform selection based on a nonlinear optimization framework. The proposed algorithms adapt to time-varying traffic demands, interference profile, and network topology to locally maximize the achievable data rate while avoiding harmful interference to co-located primary or secondary users.

In [6], we developed a framework based on nonlinear optimization for joint routing and dynamic spectrum allocation for cognitive ad hoc networks with decentralized control. In this paper, we first specialize the framework in [6] to the case of joint routing, channel, power and transmission rate selection based on an adaptive modulation scheme. Then, we describe a prototype implementation of the decentralized control algorithm on a software defined radio platform based on GNU radio [1] and USRP2 (universal software radio peripheral version 2). Experiments on the software-defined-radio platform demonstrate the superior adaptivity of the proposed algorithm with respect to state-of-the-art non-cognitive approaches.

The remainder of this paper is organized as follows. In Section II, we introduce the system model. In Section III, we formulate the problem. In Section IV we propose decentralized algorithms to perform joint cognitive routing and interference-avoiding waveform selection. The software-defined-radio platform is described in Section V-A. Section V evaluates the performance of the algorithm on the software-defined-radio platform. Finally, Section VI concludes the paper.

II. System Model

We consider a cognitive radio network consisting of M primary users and N secondary users. Primary users hold licenses for specific spectrum bands, and can only occupy their assigned portion of the spectrum. Secondary users do not have any licensed spectrum and opportunistically send their data by utilizing idle portions of the primary spectrum.

Let the multi-hop wireless network be modeled by a directed *connectivity* graph $\mathcal{G}(\mathcal{V},\,\mathcal{E})$, where $\mathcal{V}=\{v_1,...,v_{N+M}\}$ is a finite set of nodes, with $|\mathcal{V}|=N+M$, and $(i,j)\in\mathcal{E}$ represent a unidirectional wireless link from node v_i to node v_j (referred to also as node i and node j, respectively, for simplicity). Nodes from the subset $\mathcal{PU}=\{v_1,...,v_M\}$ are designated as primary users, and nodes from subset $\mathcal{SU}=\{v_{M+1},...,v_{M+N}\}$ are designated as secondary users.

A. Channel Model

The available spectrum is assumed to be organized in two separate channels. A *common control channel* (CCC) is used by all secondary users for spectrum access negotiation, and

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is assumed to be time slotted. A *data channel* (DC) is used for data communication. The data channel consists of a set of discrete minibands $\{f_{min}, f_{min+1}, \cdots, f_{max-1}, f_{max}\}$, each of bandwidth w. Each backlogged secondary user contends for spectrum access on the control channel f_{cc}, where $f_{cc} \notin [f_{min}, f_{max}]$. All secondary users exchange local information on the common control channel.

B. Traffic Demands

Traffic flows are, in general, carried over multi-hop routes. Let the traffic demands consist of a set $\mathcal{S} = 1, 2, \cdots, S$, where $S = |\mathcal{S}|$, of unicast sessions. Each session $s \in \mathcal{S}$ is characterized by a fixed source-destination node pair. We indicate the arrival rate of session s at node i as $\lambda_i^s(t)$, and with $\mathbf{\Lambda}$ the vector of arrival rates.

C. Queueing

Each node maintains a separate queue for each session s for which it is either a source or an intermediate relay. At time slot t, define $Q_i^s(t)$ as the number of queued packets of session s waiting for transmission at secondary user i, and $\mathbf{Q}$ for the network. Define $r_{ij}^s(t)$ as the transmission rate on link (i, j) for session s during time slot t, and $\mathbf{R}$ as the vector of rates. For $\forall i \in \mathcal{SU}$, the queue is updated as follows:

$$Q_i^s(t+1) = \left[Q_i^s(t) + \sum_{k \in \mathcal{SU}, k \neq i} r_{ki}^s(t) - \sum_{l \in \mathcal{SU}, l \neq i} r_{il}^s(t) + \lambda_i^s(t) \right]^+ . \quad (1)$$

III. Problem Formulation

In this section, we first derive the interference conditions under which multiple cognitive radio nodes can transmit simultaneously on the shared wireless medium. Specifically, all network transmitters need to satisfy receiver BER requirements (reliability constraint), and avoid harmful interference to co-located primary or secondary users (sharing constraint). Then, we discuss link capacity maximization under the derived constraints. Finally, we formulate the throughput maximization problem.

A. Reliability Constraint

Let $\mathrm{SINR}^{th}(BER^*)$ represent the minimum SINR that guarantees a target bit error rate BER^*, and $P_i(f)$ represent the transmit power of transmitter i on miniband f. The first constraint for link (i, j) can be expressed by

$$\frac{P_i(f) L_{ij} |h_{ij}|^2}{NI_j(f)} \geq \mathrm{SINR}^{th}(BER^*), \quad (2)$$

where L_{ij} is path loss power attenuation, h_{ij} is the channel coefficient of link (i, j), and $NI_j(f)$ is the noise plus interference at receiver j on miniband f. The numerator represents the received power at receiver j.

Define $P_i^{min}(f)$ as the value of $P_i(f)$ for which (2) holds with equality. Thus, $P_i^{min}(f)$ is the minimum required transmit power of link (i, j) on miniband f. The constraint in (2) states that the SINR at receiver j needs to be above a certain threshold to allow receiver j to successfully decode the signal given its current noise and interference. For clarity, we use $P_{ij}^{min}(f)$ to denote the minimum required transmit power of transmitter i for receiver j.

B. Sharing Constraint

Let $P_i^{max}(f)$ denote the maximum allowed transmit power of transmitter i, $i \in \mathcal{V}$. If there is ongoing reception of primary user on miniband f, i.e., $A(f) = 1$, no transmission of i is allowed,

$$A(f) \cdot P_i^{max}(f) = 0, \quad \forall i \in \mathcal{V}, \forall f \in [f_{min}, f_{max}]. \quad (3)$$

In the following we will discuss $P_i^{max}(f)$ when there is no primary user's reception on f, i.e., $A(f) = 0$. Denote the interference on miniband f at a receiver k, $(k \in \mathcal{V}, k \neq j)$, as $NI_k(f) + \Delta I_{ik}(f)$, where $NI_k(f)$ represents noise plus interference at k before i's transmission, and $\Delta I_{ik}(f)$ represents the additional interference at k caused by i's transmission, i.e., $\Delta I_{ik}(f) = P_i(f) L_{ik} |h_{ik}|^2$.

The second constraint represents the fact that ongoing reception at node k should not be impaired by i's transmission. This can be expressed as

$$\frac{P_k^R(f)}{NI_k(f) + \Delta I_{ik}(f)} \geq \mathrm{SINR}^{th}(BER^*), k \in \mathcal{V}, k \neq j, \quad (4)$$

where $P_k^R(f)$ represents the signal power being received at receiver k. Since this has to be true for every secondary receiver, the constraint can be written as

$$P_i(f) \leq \min_{k \in \mathcal{V}} \frac{\Delta I_k^{max}(f)}{L_{ik} |h_{ik}|^2} \quad (5)$$

where

$$\Delta I_k^{max}(f) = \frac{P_k^R(f)}{\mathrm{SINR}^{th}(BER^*)} - NI_k(f), k \in \mathcal{V}. \quad (6)$$

The inequality in (5) states that the interference generated by i's transmission on each frequency should not exceed the threshold value that represents the maximum interference that can be tolerated by the most vulnerable of i's neighbors.

By combining (3) and (5), we obtain

$$P_i^{max}(f) \triangleq \begin{cases} 0, & A(f) = 1; \\ \min_{k \in \mathcal{V}} \frac{\Delta I_k^{max}(f)}{L_{ik} |h_{ik}|^2}, & A(f) = 0. \end{cases} \quad (7)$$

Hence, for link (i, j), node i's transmit power needs to be bounded on each frequency. The expressions in (2) and (7) define lower and upper bounds, respectively, on the transmit power for each frequency.

C. Link Capacity Maximization Problem

Let C_{ij} represent the capacity for link (i, j) given the current spectrum condition, defined as

$$C_{ij}(f_i, P_i) \triangleq w \cdot log_2 \left[1 + \frac{P_i L_{ij}(f_i) G}{N_j(f_i) + I_j(f_i)} \right]. \quad (8)$$

The achievable values of C_{ij} depend on the spectrum selection f_i, and power allocation P_i. Maximizing the capacity of link (i, j) means selecting spectrum f_i and corresponding transmit power P_i that maximize the capacity under the constraints introduced in (2) and (7).

$$
\begin{aligned}
\mathbf{P1}: Given: \quad & (i,j),\ P_i^{max}(f),\ P_{ij}^{min}(f),\ P^{Bgt} \\
Find: \quad & f_i,\ P_i && (9) \\
Maximize: \quad & C_{ij}(f_i, P_i) && (10) \\
Subject\,to: \quad & \\
& f_{min} \le f_i \le f_{max}; && (11) \\
& P_{ij}^{min}(f_i) \le P_i \le P_i^{max}(f_i); && (12) \\
& P_i \le P^{Bgt}. && (13)
\end{aligned}
$$

where P^{Bgt} represents a constraint on power for each device.

D. Utility Maximization Problem

Our goal is to design decentralized and localized algorithms for throughput maximization through joint cognitive routing and interference-avoiding waveform selection. A desirable solution should adapt to time-varying traffic demands, interference profile, and network topology to locally maximize the achievable data rate while avoiding harmful interference to co-located primary or secondary users.

Here, we define the *utility* U_{ij} for link (i,j) as

$$U_{ij}(t) = C_{ij}(t) \cdot \left(Q_i^{s_{ij}^*}(t) - Q_j^{s_{ij}^*}(t) \right), \tag{14}$$

where

$$s_{ij}^* = \arg\max_s \left\{ Q_i^s - Q_j^s \right\}. \tag{15}$$

In (14), $C_{ij}(t)$ represents the achievable capacity for link (i,j) given the current spectrum condition at time t and the chosen transmission mode, while s_{ij}^* is the session with maximum differential backlog on link (i,j). The achievable capacity for cooperative and direct links under spectrum sharing constraints will be further discussed below.

The utility function is defined based on the principle of dynamic back-pressure, first introduced in [13]. It can be proven [8] that a control strategy that jointly assigns resources at the physical/link layers and routes to maximize the weighted sum of differential backlogs (with weights given by the achievable data rates on the link) is throughput-optimal, in the sense that it is able to keep all network queues finite for any level of offered traffic within the network capacity region.

IV. Decentralized Joint Cognitive Routing and Waveform Selection

A. Joint Cognitive Routing and Waveform Selection

Denote $\mathcal{N}^s(i)$ as the set of feasible next hops for the backlogged session s at node i, i.e., the set of neighbors with positive advance towards the destination of session s. Node m has *positive advance* with respect to i iff m is closer to the destination of session s than i [11]. Every backlogged node i, once it senses an idle common control channel, performs the following joint cognitive routing and waveform selection algorithm:

1) For each candidate next hop, node i estimates the maximum achievable link capacity by optimizing the spectrum and power allocation. For given spectrum f_i, problem $\mathbf{P1}$ is a convex optimization problem, because the objective function is concave and constraints (12) and (13) are all affine functions of the problem variables P_i. Thus, for given spectrum f_i, the link capacity maximization problem can be solved efficiently in polynomial time by using interior point methods [3].
2) Schedule s^* with next hop j^* such that
$$(s^*, j^*) = \arg\max(U_{ij}^s). \tag{16}$$
Note that U_{ij}^s defined in (14) depends on both the capacity and the differential backlog of link (i,j). Hence, routing is performed in such a way that lightly backlogged queues with more spectrum resource receive most of the traffic. The details about above two steps are described in Algorithm 1.
3) The SINR of the link is optimized by the spectrum and power allocation algorithm. The increased SINR can be translated into a lower BER for the same modulation scheme, or a higher transmission rate through a higher order modulation scheme for the same BER. In this work, we adaptively select the modulation based on the expected SINR of the link for a given target BER to increase the transmission rate. We consider the class of M-QAM [12]. Specifically, we consider BPSK and QPSK as the waveform set. The transmitter compares the expected SINR with a set of pre-defined thresholds to choose the best waveform.

Algorithm 1 Joint Routing and Spectrum Selection Algorithm.

At backlogged node i, $U = 0$
for each backlogged session s **do**
  for $j \in \mathcal{N}^s(i)$ **do**
    $C_{ij}^* = 0$
    for each $f \in [f_{min}, f_{max}]$ **do**
      Derive P_i by solving problem $\mathbf{P1}$
      if $C_{ij} > C_{ij}^*$ **then**
        $C_{ij}^* = C_{ij}$
      end if
    end for
    if $C_{ij}^* \cdot (Q_i^s - Q_j^s) > U$ **then**
      $U = C_{ij} \cdot (Q_i^s - Q_j^s)$
      $[f_i^*, P_i^*, s^*, j^*] = [f_i, P_i, s, j]$
    end if
  end for
end for
Return $[f_i^*, P_i^*, s^*, j^*, U]$

The combination of next hops leads to a multi-hop path. The multi-hop path discovery terminates when the destination is selected as the next hop. If the destination is in the transmission range of the transmitter (either a source or an intermediate hop for that session), the differential backlog between the transmitter and the destination is no less than the differential backlogs between the transmitter and any other nodes, because the queue length of the destination is zero. Hence, the destination has a higher probability of being selected as next hop than any other neighboring node of the transmitter. Note that the transmitter may still select a node other than the destination as the next hop even if the destination is in the transmission range. This can happen, for example, if there is no available miniband between transmitter and destination, or if the interference on the miniband at that time is very high, which results in low link capacity between the transmitter and the destination.

B. Decentralized Medium Access Control Mechanism

Once waveform selection, scheduled session s, next hop j have been determined at node i, the probability of accessing the medium is calculated based on the value of U_{ij}. Nodes with higher U_{ij} will get a higher probability of accessing the medium and transmit. Note that U_{ij} is an increasing function of $(Q_i^s - Q_j^s)$, i.e., links with higher differential backlog may have larger U_{ij} , thus have higher probability of being scheduled for transmission.

This probability is implemented by varying the size of the contention window at the MAC layer. The transmitting node i generates a backoff counter BC_i chosen randomly (with a uniform distribution) within the interval $[1, 2^{CW-1}]$, where CW_i is the contention window of transmitter i, whose value is a decreasing function $\Phi()$ of the utility U_{ij} as below

$$CW_i = -\alpha \cdot \frac{U_{ij}}{\sum_{k \in \mathcal{N}_i, k, l \in \mathcal{V}} U_{kl}} + \beta, \;\; \alpha > 0, \beta > 0 \qquad (17)$$

where $\sum_{k \in \mathcal{N}_i, k, l \in \mathcal{V}} U_{kl}$ represents the total utility of the neighboring competing nodes. Scalars α and β can be designed for specific network size and active sessions injected into the network to reduce collision. Note that sender i collects its neighbors' utility values by overhearing control packets on the CCC.

With this mechanism, heavily backlogged queues with more spectrum resources are given higher probability of transmission. For a node i that just has completed transmission on the data channel, the value of $\mathbf{Q}_i$ becomes smaller, which results in a reduced value of U_{ij}, which consequently leads to a lager size of the contention window. In this way, the node's level of priority in accessing spectrum resources is implicitly reduced, which, in turn, improves fairness. Differential backlog-aware routing can reduce the probability of forwarding data through a congested node. A large queue size at an intermediate node is interpreted as an indicator that the path going through that node is congested and should be avoided, while a small queue size at an intermediate node indicates low congestion on the path going through that node. According to the proposed routing algorithm, nodes with a smaller queue size have a higher probability of being selected as next hop. On the other hand, according to our proposed medium access control mechanism as discussed later, links with larger differential backlogs have smaller contention window size, and thus have higher probability of accessing the channel and consequently have higher priority in reserving resources. In this way, congestion is mitigated by the proposed routing and medium access control strategy.

V. Experimental Evaluation

The performance of the algorithm described in the previous sections was evaluated on a wireless testbed composed of software defined radios, whose software architecture is illustrated in Fig. 1.

The testbed architecture consists of a *control plane*, *a decision plane*, and a *data plane*.

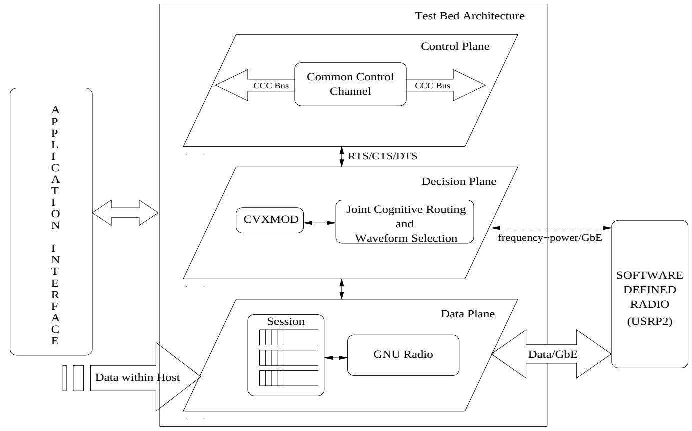

Fig. 1. Testbed architecture.

The *control plane* essentially implements the information exchange among secondary users, i.e., the common control channel. To decouple sharing of information from data-related operations, we implement the CCC over a wired local area network using TCP socket programming, which emulates an out-of-band CCC. RTS (Ready To Send), CTS (Clear To Send), and DTS (Data Transmission reServation) packets are exchanged among the nodes to exchange the spectral information, at a data rate much higher than the data channel. An all-wireless CCC will be the subject of future work.

The *decision plane* executes the algorithm for joint routing and waveform selection. The joint routing and waveform selection algorithm allocates PHY/MAC resources and routes jointly based on the information exchanged among the nodes on the control plane. This plane schedules data sessions and chooses the optimal PHY layer parameters like frequency, power and modulation scheme, as described in Section V-C.

The *data plane* is responsible for controlling physical layer parameters and interacting with the hardware. The decision on channel, power, relay and modulation scheme is made by the decision plane. Based on this decision, the data plane configures the modulation schemes and tunes the hardware to the specified channel and power. The data plane relies on the GNU Radio framework for signal processing operations. GNU Radio provides an interface to the USRP2 software defined radio platform from Ettus research LLC [7] for sending the modulated data on the data channel at a chosen frequency and power.

The experimental evaluation is based on a 3-node setup as shown in Fig. 2. Every node in the testbed setup consists of a host and USRP2. All the nodes are connected to the CCC via a Gigabit Ethernet (GbE) interface.

A. Node Hardware

Every node in the network consists of a PC with Intel processor and two Gigabit Ethernet cards installed on the host PC, one to connect the host and USRP2, and the other one to connect the host to the CCC LAN. The GNU Radio library on Linux is used to provide building blocks of the PHY layer. Digital data is modulated based on an orthogonal frequency division multiplexing (OFDM) scheme. OFDM subcarriers are modulated with either BPSK or QPSK based on the SINR of the chosen link. If the SINR of the link chosen is between 6dB and 9dB, we choose BPSK, while if it is between 9dB and 16dB we choose QPSK. The SINR on each carrier is estimated at the transmitter based on the channel and power information exchanged between the nodes on the CCC.

USRP2 radios consists of a motherboard and a daughter board. The motherboard is based on a Xilinx spartan 3-2000 field programmable gate array (FPGA), 100 MSamples/s analog-to-digital converters (ADC) at 14 bits/sample on both I and Q channels, 400 MSamples/s DAC at 16 bits/sample on both the IQ channels. The FPGA has AeMB 32-bit soft core processor for control activities on USRP2, CORDIC core for DUC/DDC (Digital Upconverter/ Downconverter) implementation, and FIFO queues for sending/receiving data to/from host and daughter board. The daughter board is the radio front end of the USRP2. In our setup, the RFX2400 daughterboard is being used. Although the daughterboard is capable of operating between 2.3GHz and 2.9GHz, the communication is restricted to the ISM band through analog filters. However, the filters can be bypassed for using the entire range of operation.

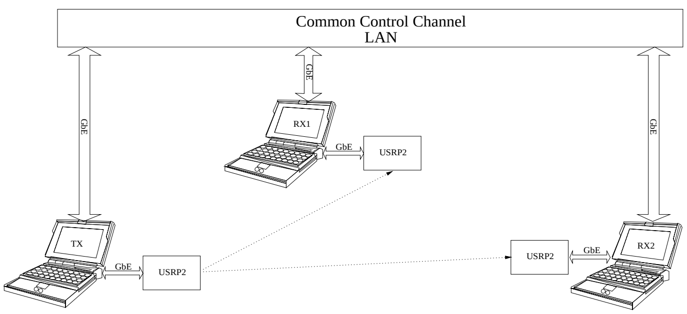

Fig. 2. Experimental Setup.

B. Testbed Operation

The setup consists of three nodes, one transmitter (TX) and two receivers (RX1 and RX2). The testbed is setup for evaluating both dynamic channel allocation and fixed channel allocation. For dynamic channel allocation the interference at the RX1/RX2 and primary user power level information are estimated for each of the five considered center frequencies (2.4, 2.408, 2.410, 2.415 and 2.420 GHz) with 2MHz bandwidth and 200 subcarriers of OFDM. On the other hand for fixed channel allocation, the interference at the RX1 and RX2 and primary user power level information are simulated for center frequency 2.4GHz and 2.408GHz respectively. The utility factor as defined in (14) is evaluated for both dynamic channel allocation and fixed channel allocation.

The decision variables, i.e., the best transmission channel, transmission power, modulation scheme, and next hop are chosen based on the maximum utility factor as defined in (16). These decision variables are communicated between TX and RX1/RX2 by RTS/CTS/DTS exchange over the CCC. We implement the CCC and data channel on different threads of the host such that CCC and data channel can run in parallel independently of each other.

C. Testbed Experimental Results

The results presented in this section report samples of experiments run for 60 seconds. The testbed experimental setup ran for two different scenarios: dynamic channel allocation (DCA) and fixed channel allocation (FCA).

In DCA, the frequency, power and waveform of the link are dynamically allocated as described in Section IV. In FCA, the channel used on each of the links is fixed. However, the power allocation and the waveform are adaptively selected for the given channel conditions.

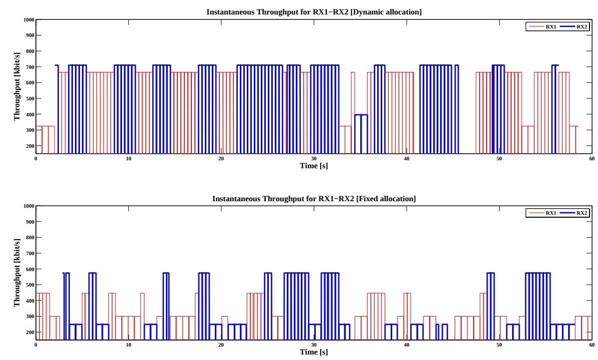

Fig. 3. (a) Dynamic channel allocation throughput (b) Fixed channel allocation throughput.

Figure 3(a)(b) shows throughput vs time for the DCA and FCA scenarios. In our experiments, the throughput is the measure of the PHY layer data rate at the receiver. The results clearly indicate that the average throughput achieved by DCA is higher than that of FCA.

Figure 4(a)(c) shows the SINR vs time for dynamically chosen channels and fixed channels on links RX1 and RX2. It can be observed in Fig. 4(a) that the SINR achieved on each link for the dynamically allocated channels is higher than the SINR achieved on the fixed channel, as shown in Fig. 4(c) at any instant of time.

At any instant of time, the link chosen for transmission is determined by utility factor as defined in (14). The utility factor is governed by the SINR at each receiver and the differential backlog between the transmitter and the receiver. Transmission links are switched between TX-RX1 and TX-RX2 depending on which of the two has the greatest utility

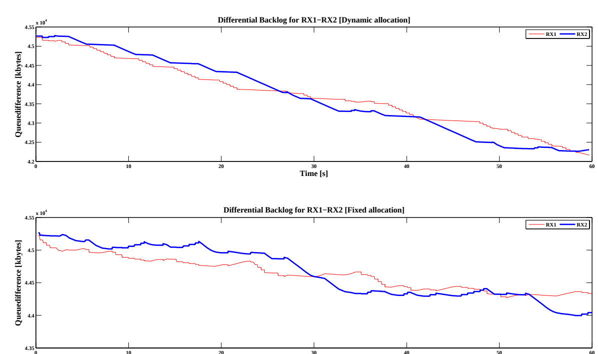

Fig. 5. (a) Session backlog in dynamic channel allocation (b) Session backlog in fixed channel allocation.

The values of differential backlog of the session on each of the links RX1 and RX2 during DCA and FCA are as shown in 5(a)(b). It can be the clearly observed from the plots that

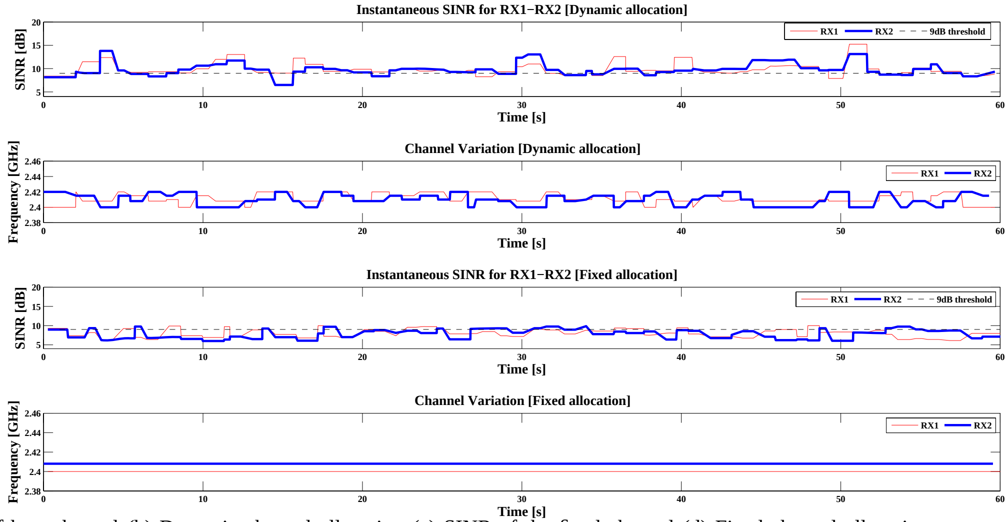

Fig. 4. (a) SINR of best channel (b) Dynamic channel allocation (c) SINR of the fixed channel (d) Fixed channel allocation.

the transmitter session queue is cleared much faster in DCA than the FCA, since the transmission rates are improved by dynamic channel selection.

In our experimental evaluation we are changing the waveforms by varying the modulation schemes between BPSK and QPSK of the OFDM subcarriers. The 9dB threshold on the SINR plot represents the boundary for changing the waveforms between BPSK and QPSK. If the the value of the SINR is between 6dB and 9dB we select a BPSK waveform, while if the SINR is between 9dB and 16dB we select a QPSK waveform. Therefore, we notice that the throughput varies for BPSK and QPSK when the SINR value for the best chosen next hop is above or below the 9dB threshold.

The silence periods in the throughput plot indicate packet losses during the transmission period. Packets may currently be lost due to varying channel conditions, or due to insufficient processing resources at the time of decoding the packets at the receivers.

VI. Conclusion

We proposed a decentralized algorithm for throughput maximization through joint cognitive routing and interference-avoiding waveform selection. The proposed algorithm adapts to time-varying traffic demands, interference profile, and network topology to locally maximize the achievable data rate while avoiding harmful interference to co-located primary or secondary users. Moreover, a prototype implementation based on a software-defined USRP2 platform of the proposed decentralized control algorithm was presented.

To evaluate the performance of joint routing and waveform selection, a testbed setup with three nodes in the network and a CCC implementation on the GbE LAN was described. The algorithm was shown to lead to higher throughput with respect to algorithms that do not rely on dynamic channel allocation.

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