# Backward-Compatible Dynamic Spectrum Leasing for 802.11-Based Wireless Networks

Robert Murawski and Eylem Ekici
Department of Electrical and Computer Engineering
The Ohio State University
Columbus, OH, USA
Email: {murawskr,ekici}@ece.osu.edu

***Abstract*—Dynamic spectrum access (DSA) is proposed to deal with the growing shortage of available leased spectrum for wireless communication. We investigate a subset of DSA referred to as Dynamic Spectrum Leasing (DSL). At its core, DSL allows spectrum lease holders and cognitive radios to cooperate in an effort to leverage spatial diversity to improve channel utilization for both parties. In this research, cognitive radios offer their services as an intermediate relay node in an effort to improve throughput of primary users utilizing a 802.11-based channel access mechanism. In return, the cognitive radio 'piggy-backs' some of its own data while acting as a relay. In this paper, a simple coordination scheme is introduced that allows a network of Secondary Users to coordinate with a Primary User network's access point. This scheme does not require any modification to the primary users' 802.11-based protocol stack as our protocol is implemented only at the access point and the secondary users. Analytical insights into the overhead required for this coordination and the optimization of the overhead are presented. It is shown that, given sufficient relay channel conditions, forwarding packets through a secondary relay channel can be beneficial to both parties in terms of saturation throughput.**

***Index Terms*—Cognitive Radio Networks; Dynamic Spectrum Leasing**

## I. INTRODUCTION

Due to the static allocation and sparse usage of licensed spectrum [1], there has been a recent surge in the research of cognitive radio technologies. Cognitive radios are devices that have the ability to adapt their communication parameters to the current spectral environment. In general, these devices are envisioned to operate on the underutilized licensed spectrum without interfering with the licensed users. This generic description of the requirement has lead to several interpretations.

One means of avoiding interference with licensed spectrum owners, referred to as Primary Users (PUs), is called overlay communications [2], [3]. Cognitive radios, referred to as Secondary Users (SUs), observe the local spectral environment, and adapt their communication parameters such that the interference they generate though communication remains below some pre-defined threshold. In general, PUs are oblivious to the presence of SUs and see their communications as noise. However, independent of the modulation and coding schemes employed, the probability of SUs interfering with a PUs is always non-zero without a priori knowledge of PU behavior. Furthermore, this model restricts the access of SUs in case PUs fully utilize the channel. In this paper, we will argue that, even under full PU utilization of wireless resources, it is possible to accommodate SUs at no expense to PUs. On the contrary, PUs stand to improve their throughput via SUs following the methods proposed here.

The above mentioned goals are achievable through *Dynamic Spectrum Leasing* (DSL). Instead of scavenging unused wireless resources, cognitive radios cooperate with PUs and negotiate on-the-fly a deal whereby SUs help improve PU throughput in return for channel access. This basic concept can, in theory, alleviate the two aforementioned problems inherent with overlay cognitive radio communications. By negotiating for available spectrum, rather than blindly attempting to avoid interfering with PU transmissions, the cognitive radios can offer greater assurances of non-interference. Also, whereas excessive PU activity decreases the ability of SUs to gain channel access, we will see how DSL allows SUs to operate even under high PU traffic.

In this paper, we introduce the concept of backward-compatible dynamic spectrum leasing. The authors in [4], [5] investigate utilizing power control as a means of cooperation between local PUs and SUs. However, this cooperation requires SUs and PUs to be involved in the coordination process. The authors in [6], [7] utilize relay communication channels between secondary users to improve the capacity of the secondrary user network. Here, we propose an enhancement to the 802.11 infrastructure mode, which would allow a network of PUs to coordinate spectrum leasing with SUs, while remaining completely oblivious to their presence. All coordination efforts are negotiated between a centralized access point and individual SUs. This eliminates any burden on PUs by requiring no knowledge of the coordination.

## II. SYSTEM MODEL

Our system model consists of $P$ PUs communicating with a centralized access point (AP). The AP is the sink for all traffic PUs and SUs generate. All PUs utilize the standard 802.11 protocol with distributed control function (DCF). $S$ SUs are also placed among PUs. All users communicate via a single communication channel that is reserved for use by the PU network. Since SUs have channel access rights, they must

---

This work has been supported by NSF under grant number CCF-0914912 and by Dayton Area Graduate Studies Institute (DAGSI) under contract number RY9-OSU-08-4.

978-1-4244-5638-3/10/$26.00

either transmit 'around' the local PU transmission (overlay) or must explicitly be given permission to communicate by the central AP. Here, we assume that all PUs operate in saturation, that is, each PU has an infinite backlog of packets ready for transmission. Therefore, opportunities for access to the channel via overlay communications are severely limited, limiting the SU network to access through dynamic spectrum leasing.

Through DSL, an SU offers to relay the PU data to the centralized access point in return for some channel utilization for its own purposes. Before this relay can take place, however, two basic conditions must be met. First, the utility of the relay channel, PU to SU ($C_{ps}$) and SU to AP ($C_{sa}$), must be at least equal to that of the direct communication channel, PU to AP ($C_{pa}$), for the PU to agree to the channel lease. Secondly, there must be sufficient channel capacity to allow the SU to utilize some of the relay channel for its own purposes, or the SU would not agree to assist the PU. In this paper, we measure the utility of the relay and direct communication channels in terms of throughput. When utilizing a relay channel, the original PU data packet is appended with the SU data on the second hop (SU to AP) to allow the SU some access to the data channel. To satisfy both requirements, the throughput of the relay channel, with the additional SU data, must be greater than that of the direct communication channel. To accomplish this, we opportunistically utilize the relay communication paths with favorable channel gains. We exploit the random nature of a fading communication channel to utilize the relay paths when the communication through the relay node is sufficient to meet the above requirements.

## III. PROTOCOL OVERVIEW

To facilitate DSL, first, some degree of coordination is required between the PU and SU networks. To this purpose, we have designed a coordination mechanism that works with the standard 802.11 protocol to achieve backward compatibility. PUs need not be aware of the coordination, or even that they are relaying packets through SUs. The decision of which SU, if any, is used in a relay communication channel, is handled purely by the Access Point. To make this decision, the access point must first gather the channel state information (CSI) from all potential SUs.

### A. *Initialization*

The transmission of channel state information to the access point from all potential SUs is triggered when a PU announces its intention to transmit a data packet via a request to send (RTS) control packet. SUs that overhear this transmission then transmit a request to cooperate (RTC) message to the AP in a slotted-CSMA manner. That is, each SU randomly selects a slot in which it will transmit its RTC message. In the slots preceding their selected transmission slot, SUs listen to the communication channel for other SU activity. If an RTC transmission is detected, the remaining RTC slots are deferred until this transmission is completed. The slotted-CSMA mechanism is illustrated in Figure 1.

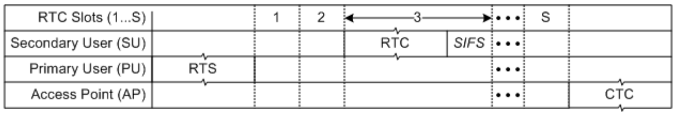


Fig. 1. 802.11 Relay Initialization Overview

*1) Initialization Overhead:* The information exchange between SUs and AP adds overhead to the exchange of packets between the PU and AP, whether or not a SU is selected as a relay node. Here, we analyze the coordination initialization to determine, $t_{coordinate}$, the expected time required for the RTC packet transmission given a network of $S$ SUs utilizing the slotted-CSMA with $K$ time slots.

The probability that a given timeslot $k$ is idle ($P_{idle}$) or busy ($P_{busy}$)is given by

$$P_{idle} = \left(1 - \frac{1}{K}\right)^S, \;\; P_{busy} = 1 - P_{idle}. \qquad (1)$$

The probability that $i$ time slots are idle ($0 \leq i \leq K$) is

$$P_i = \binom{K}{i} \left(P_{busy}\right)^i \left(1 - P_{busy}\right)^{K-i}, \qquad (2)$$

The expected numbers of busy and idle time slots are

$$E\left[K_{busy}\right] = \sum_{i=1}^{K} i P_i = K - E\left[K_{idle}\right]. \qquad (3)$$

With these expectations, we can calculate the expected overhead of the RTC message exchange. We assume the duration of an idle time slot, $t_{idle}$, is only one SIFS as defined in the 802.11 standard, giving other SUs sufficient time to listen and react to the current state of the communication channel. The duration of busy time slots, $t_{busy}$, is sufficiently long to allow the transmission of the collected CSI data and other control data. The duration of the entire RTC packet exchange can be calculated as:

$$T_{RTC} = \left(E\left[S_{idle}\right] t_{idle}\right) + \left(E\left[S_{busy}\right]\left(t_{RTC} + SIFS\right)\right) \quad (4)$$

*2) Initialization Success:* The probability that an arbitrary SU will successfully transmit its RTC packet can be computed based on $S$ and $K$. We assume that if two or more SUs select the same transmission time slot, the transmissions will collide. Therefore, an RTC transmission is successful iff the transmitting SU selects a unique time slot in the current RTC message exchange. The probability, $p(S,K)$, that an arbitrary time slot contains exactly one RTC message transmission is:

$$p(S,K) = \binom{S}{1} \left(\frac{1}{K}\right) \left(1 - \frac{1}{K}\right)^{K-1}, \qquad (5)$$

where $\frac{1}{K}$ is the probability that an SU selects one time slot out of $K$ time slots. We define $m(S,K)$ as the maximum number of nodes that can be discovered in a single RTC message exchange given there are $S$ SUs competing for $K$ slots. $m(S,K)$ is defined as

$$m(S,K) = \begin{cases} K-1 & \text{if } S > K \\ S & \text{if } S \leq K. \end{cases} \qquad (6)$$

The probability of exactly one successful RTC transmission from the $S$ SUs is given as

$$q_1(S,K) = \binom{K}{1}\; p(S,K)\; l(S-1,K-1), \tag{7}$$

where $l(S-1,K-1)$ is the probability that the none of the remaining $S-1$ timeslots contain a successful RTC transmission. Therefore, the probability $q_i(S,K)$ of discovering $i$ nodes ($1 \le i \le m(S,K)$) in one RTC message exchange is

$$q_i(S,K) = \begin{cases} 1 & \text{if } S = 1 \\ 0 & \text{if } S \le K \\ & \text{ and } i = K-1 \\ \binom{K}{i} \left[\prod_{j=0}^{i-1} p(S-j,K-j)\right] & \\ \times l(S-i,K-i) & \text{Otherwise} \end{cases} \tag{8}$$

which is used to calculate the probability mass function (PMF) of the number of successful RTC transmissions in one RTC message exchange. $l(S-i,K-i)$ is the probability that none of the remaining $(K-i)$ time slots contain a successful RTC transmission:

$$\begin{aligned} l(S-i,K-i) &= q_0(S-i,K-i) \\ &= 1 - \sum_{a=1}^{m(S-i,K-i)} q_a(S-i,K-i). \end{aligned} \tag{9}$$

Finally, for a given SU, we calculate the probability of successfully transmitting an RTC packet, $p_{rtc}(S,K)$ as

$$p_{rtc}(S,K) = \frac{\sum_{i=0}^{s} i \cdot q_i(S,K)}{S}. \tag{10}$$

*3) Overhead Optimization:* Both the expected overhead and probability of success for a given RTC packet exchange are dependent on the number of local SUs and the number of RTC times lots utilized. In our system model, we cannot directly control the number of SUs that are allowed to advertise their willingness to cooperate, we can only adjust the number of RTC time slots utilized to optimize the expected overhead for the given network environment. If we were to reduce the RTC time slots to zero, the overhead would be eliminated and the throughput would be similar to that of the standard 802.11 protocol. However, no SUs could transmit RTC messages, and thus, there would be no opportunities to exploit DSL. Conversely, if the number of RTC packets is increased to $\infty$, all SU RTC transmissions would be successful, however, no data communications would be possible. To select an optimal value, we define $\epsilon$ as the target success probability for a given SU RTC transmission. Therefore, the optimal number of RTC slots, $K_{opt}$, is given by

$$K_{opt} = \min(k) \text{ s.t. } p_{rtc}(s,k) \ge \epsilon. \tag{11}$$

### *B. Protocol Runtime*

After the AP collects the RTC message transmissions from all local SUs, it makes a decision as to which SU, if any, is selected for packet relay. This decision will be based on whether the relay communication channel through a given SU $s$ can support a higher throughput than the direct communication path between the PU and AP. A detailed analysis of the system throughput will be given in the following section.

Immediately following the RTC message exchange, the AP announces with a clear to coordinate (CTC) message its decision on which, if any, SU will act as a relay. This decision is based on the the expected throughput of the relay and direct communication channels. Based on the current channel conditions, the AP computes the throughput of the direct channel as well as all relay channels for the current transmission request, accounting for the overhead associated with relaying SUs' data and the handshaking overhead. The channel with the highest throughput (either direct or through a SU relay) is chosen and indicated in AP's response (CTC).

Here, we further discuss the timing of the protocol operation. Since PUs are not required to change their 802.11 protocol operation, any RTC-CTC exchange would lead to the expiration of the PU timers. Therefore, whenever SUs report their channel conditions and send RTC messages, PUs will be forced to transmit their RTS messages once again. When the RTS retransmission occurs, either the AP (in the case of direct communication) or the selected SU (in the case of relay communications) will respond with a clear to send (CTS) message. In the case of direct communication, the remaining handshake and packet exchange will happen according to the 802.11 standard. For relay communication, a store and forward protocol operates in three steps:

1) PU sends its data packet to the relay SU
2) SU appends its data to the original data packet
3) SU sends the modified data packet to the AP

## IV. ANALYSIS

In this section, we analyze the throughput gain via DSL. To improve the overall PU system throughput requires sufficient signal quality on the relay communication channel such that the 802.11 data rate can be increased. In general, higher data rates are achieved by either utilizing a more complex modulation scheme, or by increasing the forward error correction (FEC) coding rate. In each case, the data rate increase is dependent on the signal to noise ratio (SNR) of the communication channel. In this paper, we consider the 802.11a data rates for the following modulation schemes:

1) $r_1$: binary phase shift key (BPSK)
2) $r_2$: quadrature phase shift key (QPSK)
3) $r_3$: quadrature amplitude modulation (QAM-16)
4) $r_4$: QAM-64 (6 bits/symbol)

For any given communication channel, the SNR of the channel determines which of these modulation schemes can be utilized. In this research, for each SNR calculated, we utilize the best modulation scheme while keeping the bit error rate (BER) of the channel below $10^{-5}$. For this research we use well-known BER curves [8] for each modulation scheme.

Each relay communication channel, $C_{re}(r_i, r_j)$, consists of two distinct point-to-point communication channels. Furthermore, the amount of data transmitted on the second hop of the

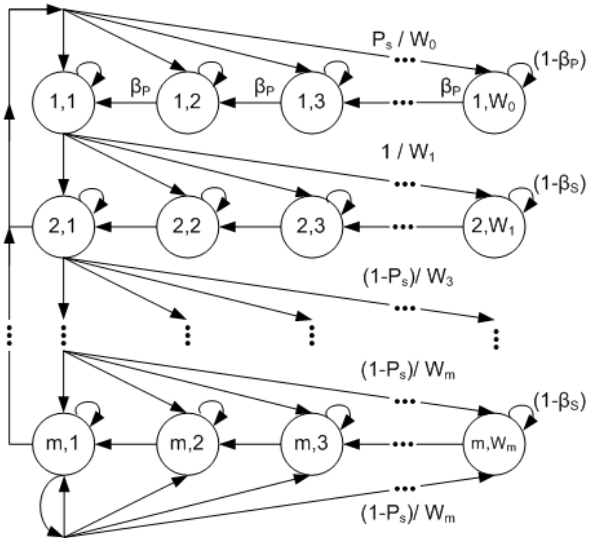


Fig. 2. Modified 802.11 DCF Backoff Model

relay channel is increased due to the additional SU data. The cooperative channel throughput for the $x^{th}$ PU transmission attempt is calculated as

$$Th_c^{(x)} = \max\left\{Th_d(r_1), Th_r(r_2,r_3)^{(s)},\ s=1,\cdot,S\right\}, \quad (12)$$

where $S$ is the number of SUs, $Th_d(r_1)$ is the throughput of the direct channel at rate $r_1$, and $Th_r(r_2,r_3)^{(s)}$ the throughput of the relay channel through SU $s$ at rates $r_2$ and $r_3$.

The saturation throughput of a standard 802.11 network has been thoroughly studied in [9]. In this paper, we make several modifications to this study to account for the overhead associated with dynamic spectrum leasing. To calculate the expected throughput for a given data rate, we utilize a Markov Chain analysis of the distributed coordination function (DCF) backoff mechanism as shown in Figure 2. Each row in the 2-dimensional Markov Chain represents a backoff stage for an arbitrary PU. When the backoff counter for a given PU reaches zero, represented by state 0 in any of the $m$ backoff stages, the PU will attempt transmission by transmitting an RTS packet. In this paper, we assume that all PUs utilize the RTS/CTS handshaking for all communications. Therefore, the probability that an arbitrary PU attempts transmission is

$$\tau = \sum_{i=0}^{m} p(i,0), \quad (13)$$

where $p(i,j)$ is the steady state probability that the backoff counter is equal to $j$ in backoff stage $i$. Following the analysis in [9], we calculate the steady state probability of $\tau$ as

$$\tau = \frac{1-P^{L+1}}{\left(\sum_{j=0}^{L}\left[1+\frac{1}{P_{trans}}\sum_{k=1}^{W_j-1}\right]P^j\right)(1-P)}, \quad (14)$$

where $L+1$ is the maximum number of retransmissions before dropping the packet, $P$ is the probability that one of the $N$ PUs attempt a transmission, and $W_j$ is window size in backoff stage $j$. The probability $P$ is calculated as

$$P = 1-(1-\tau)^N, \quad (15)$$

where $N$ is the number of contending PUs.

In our research, the probability $\tau$ differs from that found in [9] in that the probability of a backoff counter transition, $P_{trans}$, is not 1. According to the 802.11 standards, a user's backoff counter will freeze if interference is detected on the communication channel during DCF backoff. The user's backoff will then only continue after the medium has remained idle for DIFS time (50$\mu$s). During periods when no PUs are transmitting data, PUs can decrement their backoff counters unimpeded. However, during successful transmissions, there are two sources of interference that can freeze a PU's backoff counter, local primary and secondary users. During the idle periods of a successful transmission, the transition probability, $P_{PUtrans}$, is determined by the steady state probability of being in state $I1$ of the Markov Chain model in Figure 3(a). This represents the probability that either an idle time slot occurs immediately following a backoff transition, or that there are three sequential idle time slots following a period of activity.

In the same manner, while SUs are exchanging their RTC control packets, there is a probability, $P_{SUtrans}$, that there are sufficient idle RTC time slots to allow local PUs to reduce their backoff counters. This is the steady state probability of the Markov Chain shown in Figure 3(b) being in state $I1$ (see Section III-A1 for $P_{busy}$ and $P_{idle}$ definitions). In general, the probability, $P_{trans}$, of a PU decrementing its backoff counter is

$$\begin{aligned} P_{trans} =& P_s\left(\frac{P_{SUtrans}\cdot t_{coord}+P_{PUtrans}\cdot t_{idle(2)}}{t_{total}}\right) \\ &+(1-P_b), \end{aligned} \quad (16)$$

where $P_s$ is the probability of successfully transmitting a message, and $P_b$ is the probability that the medium is busy due to a PU transmission.

Given the probability that an arbitrary PU is transmitting a packet, we can calculate $P_b$ that the medium is busy due to PU activity as

$$P_b = 1-(1-\tau)^N, \quad (17)$$

and the conditional success probability of a PU transmission as

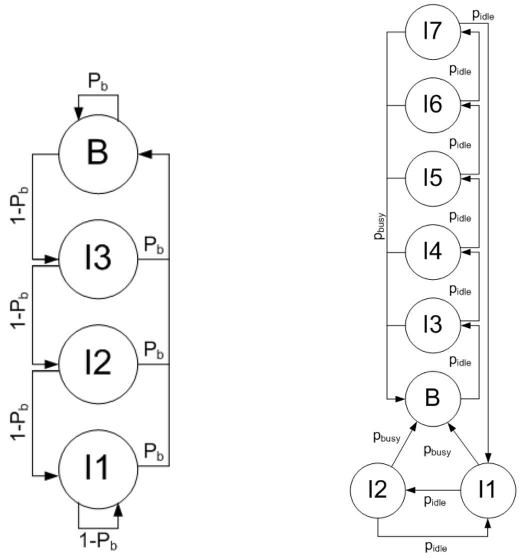
$$P_s = N \times \tau\,(1-\tau)^{N-1} \quad (18)$$

where $N$ is the number of local PUs.

Using these probabilities, we calculate the expected throughput of an arbitrary PU as

$$Th = \frac{P_s\cdot E[D]}{P_sT_s+(1-P_s)T_c}, \quad (19)$$

where $P_s$ is the probability of successfully transmitting a packet, $T_s$ is the time required to transmit a successful packet, $T_c$ is the time required to detect a packet collision, and $E[D]$ is the expected size of the PU data in a packet exchange.



(a) Primary User (b) Secondary User

Fig. 3. Backoff Model for Transition Probabilities

In Equation 19, we see that the PU throughput is dependent on the total duration of the packet exchange. In Figure 4, three possible durations for a packet exchange are shown. Given a successful packet transmission, the data traffic will either be routed through a secondary relay user or sent directly to the access point, depending on the current channel conditions for the primary and secondary users. If the backoff counter in two or more PUs expires at the same time, multiple RTS packets will be sent, resulting in a collision. In this case, duration of the packet exchange is significantly shortened, though no useful information is sent.

In Figure 4, the values of $t_{cts}$, $t_{rts}$, and $t_{ack}$ are the times required to transmit the CTS, RTS, and acknowledgement (ACK) control messages at the base 802.11 data rate of 1 Mbps, respectively. $t_{coord}$ refers to the coordination delay, as calculated in Section III-A of this paper. After the coordination is complete and prior to the PU's RTS retransmission, the medium will be idle for $t_{idle(1)}$ as the PU's backoff counter decrements to zero:

$$t_{idle(1)} = (E[slot] - E[transition]) \times t_{slot}, \qquad (20)$$

where $E[slot]$ is the expected number of backoff transmissions required before the PU will retransmit an RTS message, $E[transition]$ is the expected number of backoff slot transitions during the SU coordination phase, and $t_{slot}$ is the duration of one backoff slot according to the 802.11 DCF standards.

User data is transmitted at the maximum available data rate, as determined by the current communication channel conditions. Based on the available data rates, we calculate the transmission time for the direct communication channel ($t_{data(d)}$), first hop ($t_{data(1)}$) and second hop ($t_{data(2)}$). Finally, after the current transmission ends, the medium will be idle for $t_{idle(2)}$ before another packet transmission will be attempted and is calculated as $t_{idle(2)} = \frac{1}{P} - 1$.

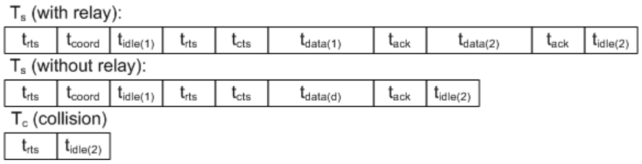


Fig. 4. Modified 802.11 Time Slot Overview

By varying the transmission rate at which the primary and secondary user data are sent, we can calculate the total time required for one packet exchange. In the following section, we show that the expected PU throughput, as calculated in Equation 19, can be increased given sufficient SU relay channel conditions. Furthermore, we show that the expected throughput of PUs can remain above that of the baseline 802.11 protocol with adaptive rate selection even with additional data originating from SUs. As such, both PUs as well as SUs benefit from DSL.

## V. SIMULATION RESULTS

In this section, we present numerical results obtained through Monte-Carlo simulations of the DSL system. To this end, we consider a system consisting of 10 PUs and $S$ randomly placed SUs that may help increase the PU throughput within the DSL framework. In return, they are allowed to piggy-back their data equivalent to a certain fraction of the PU payload. In all our simulations, PUs send 1500 bytes of data through either the direct or relay communication channels in a packet. The amount of data sent by SUs while utilizing the relay communication channel varies as indicated on the result graphs. We use the optimization technique of Section III-A3 to select the minimum amount of overhead with a success probability of 70% for RTC transmissions.

In our throughput analysis, we use the base data rate of 1Mbps for all physical layer header information. Control and data packet information at higher layers is sent at the maximum sustainable data rate as determined by the instantaneous channel conditions as determined by the free-space attenuation and the Rayleigh fading ($\sigma = 3$) as described in Section IV. We assume a base symbol rate of 1 mega-symbol per second as in [8], which, due to the symbol data rates, results in data rates 1Mbps (BPSK), 2Mbps (QPSK), 4Mbps (16-QAM), and 6Mbps (64-QAM). For each PU transmission attempt, we compute the throughput of the PU and (if applicable) the relay SU according to our DSL framework. We also calculate the throughput of the PU under the baseline 802.11 model for comparison. Presented results reflect averages of 10000 transmission attempts.

In Figure 5, we show the expected throughput of DSL and baseline 802.11 channels with varying amounts of SU data. The percentage for these results refer to the size of the SU data package as compared to the 1500 byte PU data packet. These

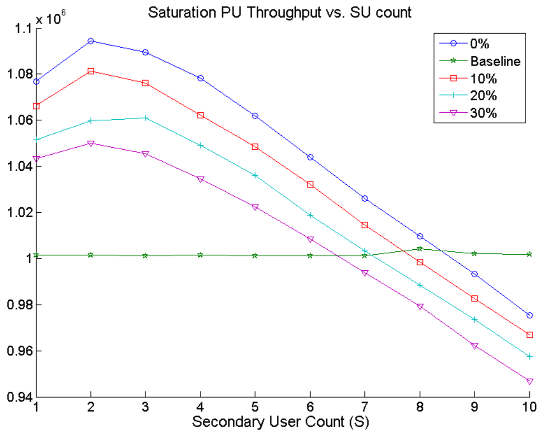


Fig. 5. Expected PU Saturation Throughput

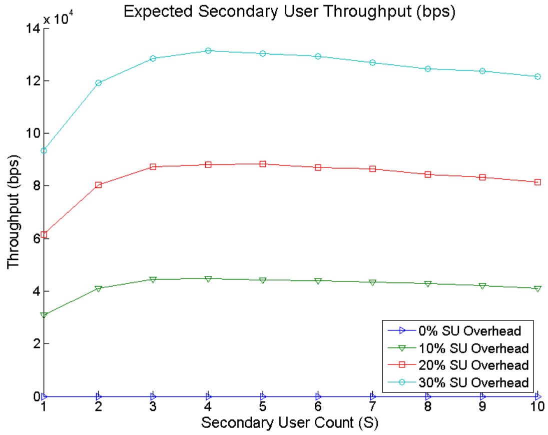


Fig. 6. Expected SU Throughput

results show the throughput from the perspective of the PU. As we can see, the throughput of the cooperative channel initially increases due to the increased probability of finding a SU with sufficient channel conditions to support relay communication. However, the improved throughput through this channel is quickly diminished as the initialization overhead resulting from a higher number of SUs increases the communication overhead, and consequently reduces the achievable throughput, even below the performance of baseline 802.11 implementation that ignores channel diversity. We observe that increasing the number of SUs is not necessarily advantageous from PUs' perspective due to increased overhead. In Figure 6, we see the expected throughput of the SU network under DSL. As expected, SU throughput is significantly less than that of the PUs and increases as more resources are allotted for SUs. This, however, comes at the expense of reduced PU throughput. The effect of increasing SU number is also detrimental beyond a certain point for SU throughput, as well, though it is not as pronounced as for the PU throughput. These results suggest that limiting the number of SUs participating in the RTC-CTC phase is very important to attain highest level of benefits from DSL. To this end, one might consider not allowing SUs with low channel quality to participate in the process, or make their attempt probabilities an increasing function in expected PU throughput as seen from the SUs' perspective. Both approaches will be considered in our future studies.

## VI. CONCLUSIONS AND FUTURE WORK

In this work, we presented a 802.11-backward-compatible protocol that facilitates Dynamic Spectrum Leasing. Under the DSL framework, PUs are still oblivious to the presence of SUs, but the access points are not. Moreover, PUs do not change their implementation of the 802.11 protocol. The main idea behind DSL is to capitalize on diversity in different channels in the network. SUs provide possible relay points to PU data so as to improve the throughput of PUs. In return, SUs are granted permission to piggy-back their own data to the relayed PU data. The AP in the system collects the channel conditions from SUs via a specialized handshaking message sequence and selects the direct or relay path with highest expected throughput. Although ideally DSL is guaranteed not to perform worse than the baseline system without SUs, any practical implementation is bound to induce overhead, which is further exacerbated by backward compatibility requirements of the protocols. We provided analytical tools to scrutinize the performance of the proposed protocols and showed through simulations that our proposed protocol improves the PU throughput above the 802.11 baseline and provides SUs to transmit their own data, without requiring PUs to change their protocol implementations. In our future work, we aim to validate our DSL protocol with a proof-of-concept implementation and test alternative methods to reduce the contention among SUs by eliminating and discouraging SU with poor channel conditions. Furthermore, we will carefully analyze the security aspects of the proposed approach and try to incorporate data privacy and defenses against malicious SU operations.

## REFERENCES

[1] FCC, "Report of the spectrum efficiency working group," tech. rep., FCC Spectrum Policy Task Force, Nov. 2002.

[2] R. Pereira, R. Souza, and M. Pellenz, "Overlay cognitive radio with multiple secondaries and its application to wireless mesh networks," in *VTC 2009, IEEE*, pp. 1–5, April 2009.

[3] W. Guo and X. Huang, "Maximizing throughput for overlaid cognitive radio networks," in *Military Communications Conference, 2009. MILCOM 2009. IEEE*, pp. 1–7, Oct. 2009.

[4] S. Jayaweera and T. Li, "Dynamic spectrum leasing in cognitive radio networks via primary-secondary user power control games," *Wireless Communications, IEEE Transactions on*, vol. 8, pp. 3300–3310, June 2009.

[5] S. K. Jayaweera, K. Hakim, and C. Mosquera, "A game-theoretic framework for dynamic spectrum leasing (dsl) in cognitive radios," in *GLOBECOM Workshops, 2009 IEEE*, pp. 1–6, 30 2009-Dec. 4 2009.

[6] L. Ding, T. Melodia, S. Batalama, and J. Matyjas, "Distributed routing, relay selection, and spectrum allocation in cognitive and cooperative ad hoc networks," in *IEEE SECON*, June 2010.

[7] J. Jia, J. Zhang, and Q. Zhang, "Cooperative relay for cognitive radio networks," in *INFOCOM 2009, IEEE*, pp. 2304–2312, 19-25 2009.

[8] J. C. Bicket, "Bit-rate Selection in Wireless Networks," Master's thesis, Massachussetts Institute of Technology, February 2005.

[9] G. Bianchi, "Ieee 802.11-saturation throughput analysis," *Communications Letters, IEEE*, vol. 2, pp. 318–320, Dec 1998.