The Throughput Potential of Cognitive Radio: A Theoretical Perspective

Sudhir Srinivasa and Syed Ali Jafar
Electrical Engineering and Computer Science
University of California Irvine, Irvine, CA 92697-2625
Email: *sudhirs@uci.edu, syed@uci.edu*

Abstract

Cognitive radios are promising solutions to the problem of overcrowded spectrum. In this article, we explore the throughput potential of cognitive communication. Different interpretations of cognitive radio that underlay, overlay and interweave the transmissions of the cognitive user with those of the licensed users are described. Considering opportunistic communication as a baseline, we investigate the throughput improvements offered by the overlay methods. Channel selection techniques for opportunistic access such as frequency hopping, frequency tracking and frequency coding are presented. The tradeoff between regulation and autonomy inherent in the design and performance of cognitive networks is examined through a simple example, which shows that the optimal amount of licensing is proportional to the duty cycle of the traffic arrivals.

I. INTRODUCTION

The widespread acceptance of wireless technologies has triggered a huge demand for bandwidth that is expected to grow well into the future. Spectrum licensing has been the traditional approach to ensure co-existence of diverse wireless systems. However, after many years of spectrum assignment to meet the ever increasing demand, the FCC's frequency allocation chart [1] now shows a heavily crowded spectrum with most frequency bands already assigned to different licensed (primary) users for specific services. A natural question is to explore if there is room in the licensed spectrum bands to accommodate secondary (unlicensed) wireless devices without disrupting the communications of the primary (licensed) users of the spectrum. In a broad sense, the term 'cognitive radio' refers to various solutions to this problem that seek to overlay, underlay or interweave [2] the secondary user's signals with that of the primary users in such a way that the primary users of the spectrum are as unaffected as possible.

The 'underlay' approach allows concurrent primary and secondary transmissions in the manner of Ultrawideband (UWB) systems. Underlay systems protect primary users by enforcing a spectral mask on the secondary signals so that the interference generated by the secondary devices is below the acceptable noise floor for the primary users of the spectrum. The spectral mask constraints are compensated by access to a wide bandwidth over which the secondary signal can be spread and de-spread to provide useful SNR (signal to noise ratio) for secondary communications. However, the interference power constraints associated with underlay systems allow only short range communications.

The 'overlay' approach also allows concurrent primary and secondary transmissions. The enabling premise for overlay systems is that the secondary users can use part of their power for secondary transmissions and the remainder of the power to assist (relay) the primary transmissions. By careful choice of the power split, the increase in primary user's SNR due to the assistance from secondary relaying is exactly offset by the decrease in primary user's SNR due to the interference caused by the remainder of the secondary transmit power that is used to communicate secondary data. Contingent on availability of sufficient side information, sophisticated coding techniques such as dirty paper coding can also be used to mitigate interference seen by the secondary users.

The 'interweaving' approach is based on the idea of *opportunistic communication*, derived from J. Mitola's doctoral thesis [3]. Recent studies conducted by the FCC [4] and industry show that a major part of the spectrum is not utilized most of the time. In other words, there exist temporary frequency 'voids', referred to as *spectrum holes* that are not in use by the licensed owners. These gaps change with time and geographic location, and can be used for communication by the secondary users. Consequently, the utilization of the spectrum is improved by opportunistic frequency re-use over the spectrum holes. An opportunistic cognitive radio is therefore an intelligent wireless communication system that periodically monitors the radio spectrum, intelligently detects occupancy in the different parts of the spectrum and then opportunistically communicates over spectrum holes with minimal interference to active primary users.

In this article, we are interested in the throughput potential of cognitive radio technology as revealed by several recent research efforts. In particular, we focus on the overlay and interweave interpretations of cognitive radio and describe conceptual frameworks for secondary communication based on these techniques. In the presence of multiple unoccupied frequency bands, different frequency selection techniques that can be used for opportunistic communication are presented. Numerical results comparing the theoretical throughput limits of the secondary users in the overlay and interweave approaches complement the discussion. With an illustrative example, we explore the tradeoff between licensing and opportunism that arises in cognitive radio systems with multiple primary and secondary users.

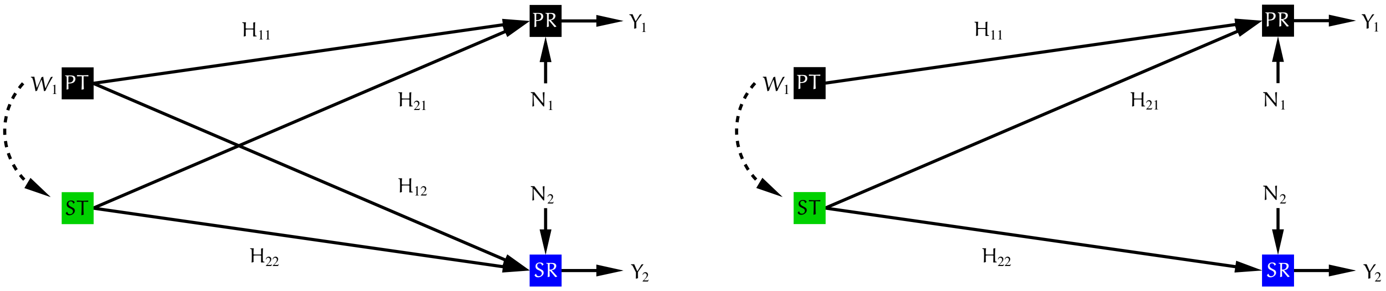
II. COGNITIVE RADIO MODELS

Since its introduction in [3], the definition of cognitive radio has evolved over the years to make the radio more capable and more powerful. Consequently, different interpretations of cognitive radio and different visions for its future exist today. In this section, we describe a few communication models that have been proposed for cognitive radio. We broadly classify them into *overlay* or *known interference* models and *underlay* or *interference avoidance models*.

A. Overlay (Known Interference) Models

The defining assumption for these models is that the secondary transmitter has *a priori* (non-causal) knowledge of the primary user's transmissions. Consider the communication scenario shown in Figure 1(a), where the primary transmitter (PT) and secondary transmitter (ST) wish to communicate over the same frequency band with the primary receiver (PR) and the secondary receiver (SR), respectively. All the channel gains are known to both the transmitters and both the receivers. The defining assumption in the overlay models is that the secondary transmitter has *a priori* knowledge of the primary user's transmissions, i.e., the primary message W_1 is non-causally known to the secondary transmitter. In such a scenario, there are two interesting strategies the secondary transmitter can pursue:

- **Selfish approach**: This is a greedy approach wherein the secondary transmitter uses *all* the available power to send its own message to the secondary receiver. The secondary transmitter uses the knowledge of the primary message to effectively null the interference at the secondary receiver by using a dirty paper coding technique [5]. The secondary receiver is therefore oblivious to the presence of the primary user, as shown by the equivalent channel model in Figure 1(b). While the selfish approach violates the cognitive radio principle of protecting the primary users, it provides a theoretical upperbound on the maximum throughput achievable by the secondary users.



(a) Modified Interference Channel (b) Selfish Approach

Fig. 1: PT and PR represent the primary transmitter and receiver. ST and SR represent the secondary counterparts. The dotted line indicates a priori knowledge of the primary message W_1 at the secondary transmitter

- **Selfless approach**: In this approach, the secondary transmitter allocates a part of its power to *relay* the primary user's message to the primary receiver. The remaining power is used to transmit the secondary user's message. The power distribution is calculated so that the SNR at the primary receiver remains the same with or without the secondary user [6]. The primary receiver is therefore virtually unaware of the existence of the secondary user. Since accurate knowledge of the primary user's message is available, the secondary transmitter applies dirty paper coding on its own message to eliminate interference at the secondary receiver. Figure 2 shows the resulting equivalent model. The capacity of the secondary user in the low interference gain case ($|H_{21}| \geqslant |H_{22}|$) is characterized in [6].

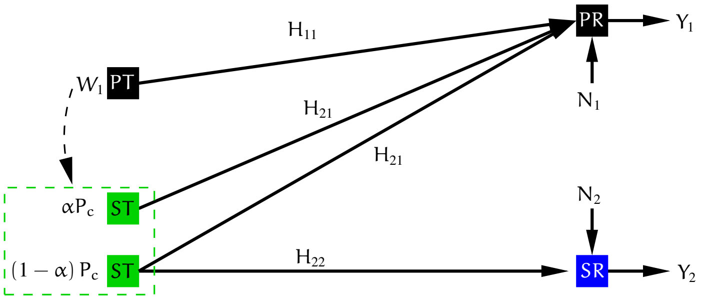


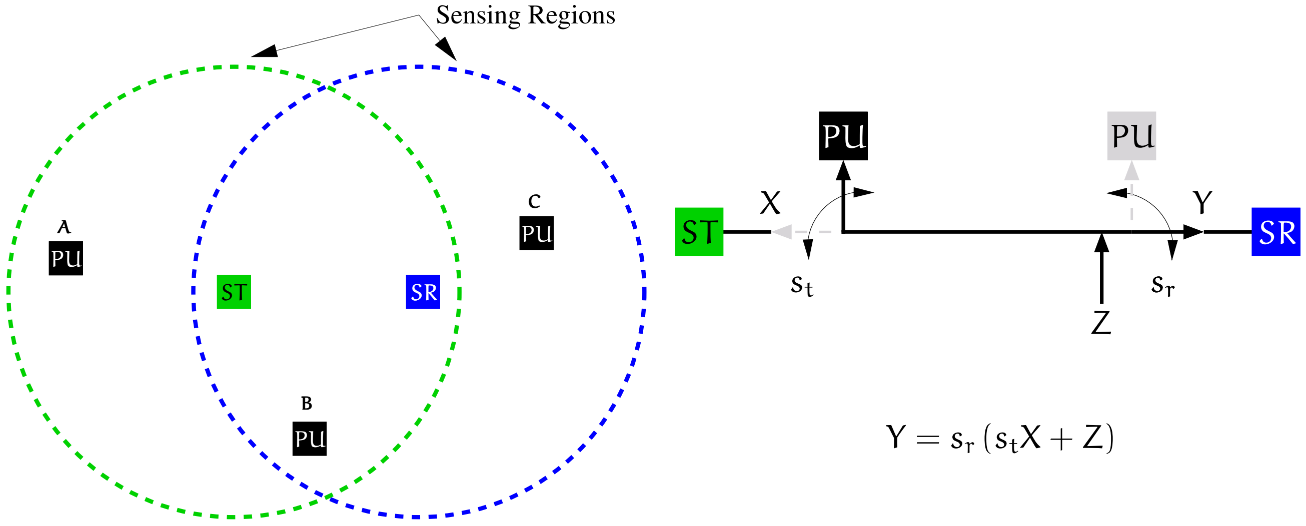
Fig. 2: Overlay Models: Selfless Approach.

Overlay models are especially useful as they characterize the ultimate limits of cognitive radio with access to side information and sophisticated coding techniques. Further, the hidden terminal problem is completely avoided - by allowing the secondary user to simultaneously transmit in the *same* frequency band as that of the local primary user, there is no interference caused to surrounding primary users who are assigned orthogonal frequency bands by the licensing arrangement.

B. The Interweave (Interference Avoidance) Model

The overlay approach requires non-causal knowledge of the interference, which is difficult to obtain when the transmitters are not in close proximity of each other or when they do not share codebooks. In such scenarios, concurrent primary and secondary user operation is invariably associated with interference at the primary receiver, which is not desired. The best solution is to try to completely *avoid* this interference by allowing the secondary user to transmit only over spectral segments unoccupied by primary radios. In this section, we describe the *two switch* interweave model proposed in [7].

1) The Two Switch Model: Consider a conceptual depiction of a cognitive radio link with a secondary transmitter (ST) and a secondary receiver (SR) in the presence of primary users(PU) A, B and C located as shown in Figure 3(a). The dotted regions around the secondary transmitter and receiver represent their respective *sensing regions* - primary transmissions can only be detected within these regions. Cognitive transmitter ST can therefore only sense whether or not primary users A or B are active, i.e., ST detects spectral holes when both A and B are inactive. Similarly, the cognitive receiver SR can only sense whether or not primary users B or C are active, i.e., SR detects spectral holes when B and C are inactive. As a consequence, the spectral holes (communication opportunities) detected at the secondary transmitter and receiver are not identical.



(a) Conceptual Model

(b) Two Switch Model

Fig. 3: The different perspectives on local spectral activity at the secondary radio transmitter ST and receiver SR are depicted in 3(a). Nodes marked A, B and C represent the primary users (PU) of the spectrum. The dotted circles represent the corresponding sensing regions. 3(b) represents the corresponding two switch model where the primary user occupancy processes are captured in the switch states s_t and s_r.

The conceptual model of Figure 3(a) reveals that the spectral environment is *distributed* and *dynamic*. These fundamental characteristics are described as follows.

- **Distributed**: Due to the physical separation between the secondary transmitter and receiver, the primary user activity detected in the vicinity of the cognitive transmitter differs from that detected around the cognitive receiver. Moreover, the secondary transmitter ST does not automatically have full knowledge of the primary user activity in the vicinity of the receiver SR. Similarly there is an uncertainty at the secondary receiver about the primary user activity at the transmitter. The higher the separation between the secondary transmitter and receiver, the lesser the overlap in their respective sensing regions, the more *distributed* the spectral environment, and consequently the higher the uncertainties at the transmitter and receiver.
- **Dynamic**: The primary users' activity is *dynamic* - over time, different primary users can become active/inactive in different segments of the spectrum. Therefore the primary user activity sensed at the secondary transmitter and receiver change with time. This increases the uncertainty at either end of the link about the communication opportunities sensed

at the other end. As the primary users become more dynamic, the spectral activity changes faster and is consequently less predictable.

The conceptual model of Figure 3(a) can be reduced to a *two switch* mathematical model shown in Figure 3(b). The communication opportunities sensed at the secondary transmitter are modeled using a two-state switch $s_t \in \{0,1\}$. The transmitter switch state $s_t = 0$, i.e., the transmitter switch is open, whenever the cognitive transmitter perceives that a primary user is active in its sensing region. The transmitter switch state $s_t = 1$ when no primary user is detected at the secondary transmitter. Similarly, the receiver switch state s_r is 0 or 1 depending on whether or not an active primary user is detected in the sensing region of the secondary receiver.

The switch state s_t is known only to the transmitter while the switch state s_r is known only to the receiver. The *correlation* between the transmitter state s_t and the receiver state s_r is a measure of the distributed nature of the system - if the transmitter and receiver are far apart, the more distributed the primary activity and therefore the lower the correlation. The dynamic nature of the primary user activity is reflected in the rate at which the switches change state.

The relationship between the input signal X_s at the secondary transmitter and the signal output Y_s at the secondary receiver is described in Figure 3(b). Notice that the knowledge of both the switch states s_t and s_r completely characterizes the communication channel. However, s_t is known only to the secondary transmitter and s_r only to the secondary receiver, i.e., the secondary transmitter and receiver only have *partial* channel knowledge. Opportunistic cognitive radio therefore corresponds to communication with *partial side information* - this abstraction is explored from an information theoretic perspective in [7].

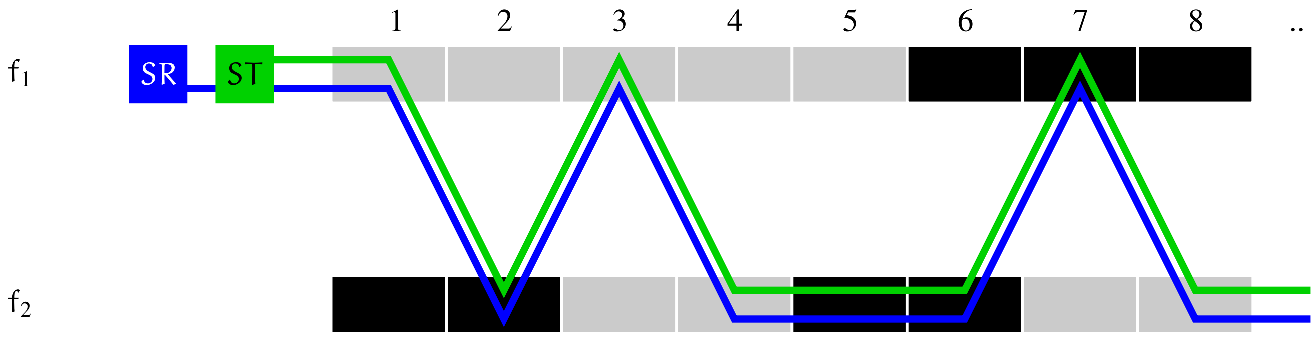
2) Opportunistic Channel Selection: The two switch cognitive radio model hides the details of opportunistic channel (frequency) selection. The choice of the frequency band(s) that can be used for communication is dictated by the type of secondary transceiver - narrowband or wideband.

- **Narrowband Techniques**: With a narrowband transmitter and receiver, the frequency band to be used for transmission can be predetermined, or dynamically chosen based on the primary user occupancy. This gives rise to two different frequency selection techniques:
  - *Frequency Hopping*: In the frequency hopping scheme, the secondary transmitter and receiver simultaneously hop across multiple frequencies according to a predetermined hopping sequence as shown in Figure 4(a). The secondary transmitter and receiver are *always* matched to the same frequency band. Frequency hopping is a very simple scheme - it does not exploit the knowledge of the past and present channel availabilities. As an illustrative example, consider Figure 4(a), which depicts a frequency hopping scheme with two frequencies. In practice, the transmissions of the primary user are not bursty, i.e., frequency bands that are free in a given time slot are highly likely to be free even in the following time slot. Instead of hopping from frequency band f_1 to frequency band f_2 during time slot $n = 2$ (f_2 is occupied by a primary user in time slot $n = 2$) as dictated by the hopping sequence, the secondary transmitter-receiver pair could have continued to communicate over f_1 (which is unoccupied even in time slot $n = 2$). It may, therefore, be possible to use primary user occupancy information of the past to predict future channel availabilities. Consequently more communication opportunities can be identified to obtain higher throughputs. This directly leads us to the frequency tracking scheme.
  - *Frequency Tracking*: In the frequency tracking scheme, the secondary transmitter, based on a given strategy, chooses *one* (if any) of the free frequency bands for transmission. The secondary receiver, based on past received signals, chooses the best channel to listen to so that the probability that the transmitter and receiver are matched to the same channel is maximized.

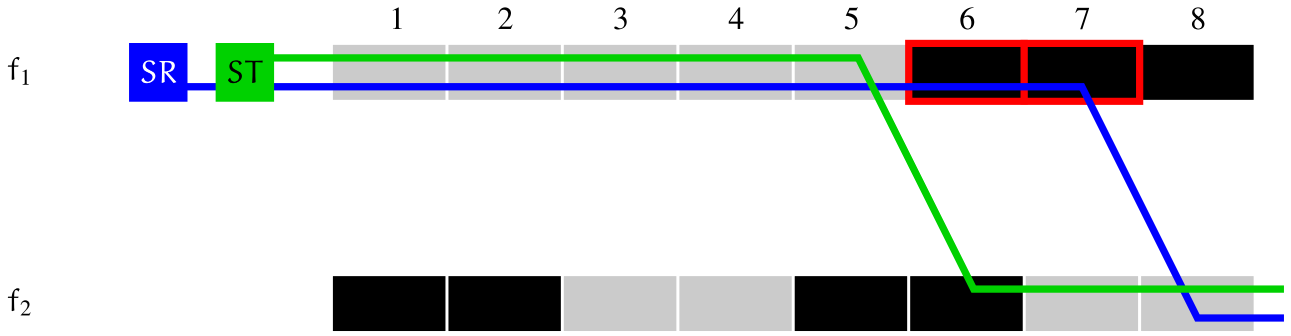
    Notice that frequency tracking is a significant departure from the conventional communication model. Traditionally, the receiver has knowledge of the frequency band used for transmission and can wait till the end of transmission to decode the message. However, in the tracking problem, the receiver must make *real time* choices to stay matched with the transmitter. After each transmission, the receiver must determine whether each observed symbol corresponds to a matched scenario (i.e. the secondary transmitted symbol is received) or a mismatch (i.e. received signal is independent of the secondary transmitted symbol).

    Figure 4(b) shows a simple frequency tracking scheme with two frequencies f_1 and f_2. The transmitter stays in the same channel (frequency band) as long as it is unoccupied while the receiver tries to *track* the frequency the transmitter is on. Unlike frequency hopping, the secondary transmitter and receiver are *not always matched to the same channel* as is evident from Figure 4(b).
- **Wideband Technique** - *Frequency Coding*: With a wideband secondary system, the cognitive transmitter can transmit over *multiple* frequency bands that are detected to be unoccupied, i.e., codewords are sent over several frequencies. The receiver monitors all the frequencies that are detected to be available at its end. Notice that unlike frequency hopping, such a *frequency coding* scheme requires the channel availabilities in *all* the different frequency bands *before* every transmission.

Recent results [7], [8] suggest that, in highly dynamic primary activity environments, frequency hopping outperforms frequency tracking for narrowband systems. Further, in such scenarios, the throughput benefits of frequency coding over



(a) Frequency Hopping



(b) Frequency Tracking (ST stays on the same frequency till it is occupied by PU)

Fig. 4: Simple examples showing frequency hopping (Figure 4(a)) and frequency tracking (Figure 4(b)) over two frequency bands f_1 and f_2. Grey boxes represent spectrum holes in the corresponding frequency at *both* ST and SR. Black boxes indicate that the corresponding frequency is occupied at the ST and/or SR. In Figure 4(b), the red borders indicate that the secondary receiver has made errors in trying to track the secondary transmitter state in the corresponding time slots.

frequency hopping are found to be very small. On the other hand, when the primary user switches ON/OFF much slowly, frequency tracking utilizes the memory in the primary occupancy process and provides higher throughputs than frequency hopping.

III. DESIGN CHALLENGES AND LIMITATIONS

While the software defined radio platform envisioned for cognitive radio technology is available now, the development of cognitive radio is still at a conceptual stage, due to the multitude of challenges in providing quality of service (QoS) assurances for primary users, spectrum sensing and estimation/feedback of channel/side information. In this section, we highlight a few practicalities of the overlay and interweave communication approaches and discuss solutions proposed by recent research to overcome them.

A. Overlay Approach - Obtaining Side Information

a) Primary Message Knowledge: : The overlay models discussed previously assume a priori knowledge of the primary message at the secondary transmitter. In practice, this non-causal knowledge can be obtained if the primary and secondary transmitters are located in close proximity to one another, as illustrated in Figure 1(a). In such scenarios, the SNR of the primary signal is higher at the secondary transmitter than at the primary receiver. As a result, the capacity, C_{ps}, of the $PT-ST$ link is higher than the capacity, C_{pp}, of the $PT-PR$ link. The secondary transmitter can therefore decode the primary message in a fraction $\nu = \frac{C_{pp}}{C_{ps}}$ of the time it takes the primary receiver to decode the same message. Therefore for a fraction $(1-\nu)$ of the time, the primary users transmitted signal is non-causally known to the secondary transmitter. The cost of acquiring this non-causal interference knowledge is the fraction of time ν that must be spent listening to the primary users transmissions.

b) Channel Knowledge: : Another challenge to cognitive communication via the overlay approach is the problem of obtaining channel information at the secondary terminals. Dirty paper coding at the secondary transmitter is possible only when knowledge of all the channel gains is available. An algorithm wherein the primary and secondary systems collaborate and exchange channel estimates is presented in [6].

B. Interweave approach - Robust Primary User Detection

The fundamental constraint governing opportunistic communication is that no interference should be caused to the active primary users. Accurate detection of the presence of primary systems is therefore extremely crucial to cognitive radio operation. This task is rendered especially difficult due to degraded primary signals at the secondary detectors caused by fading and shadowing effects. In the presence of fading, robust detection of the primary users mandates very sensitive detectors on the secondary user, which in turn forces infeasibly long sensing times [9]. Analysis of detection times in scenarios with noise uncertainty [9] reveals that in some cases detection may not be possible, even with infinite sensing times. The solution to this problem is, fundamentally, to take a collaborative approach to sensing [9]–[11]. Multiple secondary users have to independently monitor primary user activity and then exchange spectrum availability estimates to infer the presence of the primary users. However, there has been limited research into designing suitable protocols for information exchange between the sensing nodes in the dynamic cognitive radio environment.

IV. OVERLAY AND INTERWEAVE MODELS: A QUANTITATIVE COMPARISON

In this section, we numerically compare the throughput limits of the secondary user in the overlay and interweave models discussed previously. The communication scenario we consider has the primary and secondary transmitter-receiver pairs located as shown in Figure 5. For every link in Figure 5, we assume a path-loss exponent of 4 and unit variance AWGN noise. The channel gains are assumed to be globally known at all instants. The primary user activity follows an i.i.d Bernoulli process with an average on-time of 40%. We consider a short term power constraint of $P_p = 10$ at the primary transmitter and P_s at the secondary transmitter. For the sake of simplicity, we assume that the secondary users detect the primary user activity perfectly (no sensing errors).

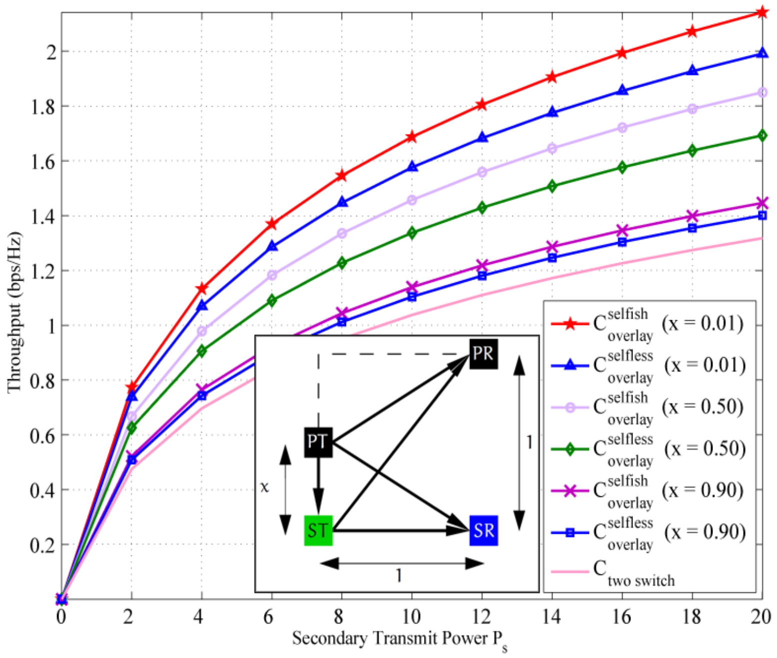


Fig. 5: Throughput comparison of the overlay and interweave models. The inset shows the communication model considered.

Figure 5 plots the throughputs achieved by the secondary user for the overlay and interweave models of Section II. For the overlay models, the cost of obtaining the primary message (dependent on the fractional decoding time ν) is included in the throughput calculations. Since the transmitter in the two switch interweave model does not transmit when the primary user is active, the achievable throughput $C_{twoswitch}$ is independent of x. The potential throughput improvements from interference knowledge and dirty paper coding techniques are captured by the $C^{overlay}_{selfless}$ and $C^{selfish}_{overlay}$ curves, which depend on the distance x between the primary and secondary transmitters. As $x \to 1$, $C_{pp}(x) \to C_{ps}$ and $1 - \nu(x) \to 0$. The fraction of overlay transmission time therefore decreases to 0 and both $C^{selfish}_{overlay}$ and $C^{selfless}_{overlay}$ approach $C_{twoswitch}$. However, when the primary and secondary transmitters are located close to each other ($x \approx 0$), the secondary transmitter is able to obtain the primary message sooner and therefore $C^{selfless}_{overlay}$ and $C^{selfish}_{overlay}$ increase. Since all the available power in the selfish approach is used for secondary transmissions, the $C^{selfish}_{overlay}$ curves represent an upperbound on the secondary users capacity.

Figure 5 indicates that the overlay approaches can provide a significant throughput improvement over the opportunistic interweave approach. However, this improvement rapidly disappears as the distance x between the primary and secondary transmitters increases.

V. How much licensing is optimal?

The question of regulation versus autonomy is fundamental to many areas of systems and control theory. The generality of this tradeoff is evident through an analogy with traffic control: Too much regulation/licensing (traffic lights at every intersection) and the system becomes inefficient. Too much autonomy/opportunistic behavior (no traffic lights) and the system becomes self-disruptive (collisions). In wireless networks, where we have the option of licensing spectrum or autonomous sharing of spectrum on an opportunistic basis, the natural question that arises is: *How much licensing is optimal*? We provide a simple example that scratches the surface of this involved question.

Consider a certain channel resource with N users (transmitter-receiver pairs). Delay intolerant traffic arrives at each user in an i.i.d fashion with a probability of arrival p. Suppose we divide the users into two groups - we randomly pick $n < N$ users and allocate (license) $\frac{1}{n}^{th}$ of the total resource to each user. Whenever the users in this group (primary users) have data to transmit, they can reliably transmit up to their licensed channel capacity, i.e., $\frac{1}{n}$ of the overall channel resource capacity. The remaining $(N - n)$ form the group of secondary users, who can only access the channel opportunistically. For the sake of simplicity, we assume that the secondary users can perfectly sense the presence/absence of primary users, so that secondary transmissions cannot occur in licensed bands where the corresponding primary users are active. The delay intolerant data of the secondary users is considered lost if either multiple secondary users select the same unoccupied licensed channel (i.e., when a *collision* occurs) or if no free channel is available for secondary transmissions. The performance metric of interest, which we refer to as the *goodput*, is the total amount of data that is successfully delivered normalized by the data arrival rate. Figure 6 plots the goodput with increasing number of licensed users for different primary user duty cycles. Notice that neither full regulation ($\frac{n}{N} = 1$) nor fully autonomous operation ($\frac{n}{N} = 0$) is optimal. Instead the optimal amount of licensing is an intermediate value that increases with the data arrival rate p. Consistent with intuition, we observe that licensing is good for highly active (always ON, $p \to 1$) data transmission while opportunistic operation is more suited for highly bursty traffic with low duty cycle (rarely ON, $p \to 0$). Interestingly, it turns out that the optimal fraction of licenses is equal to the traffic arrival rate p and seems to be insensitive to the total number of users N.

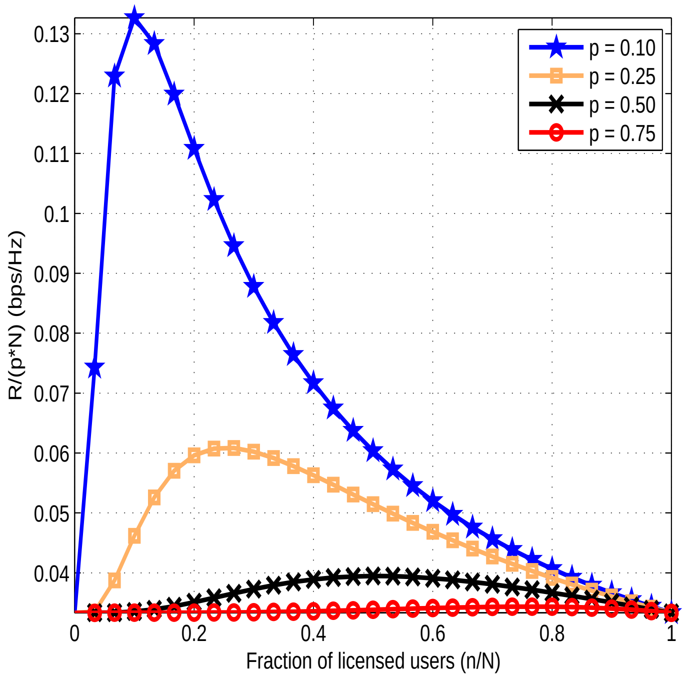


Fig. 6: The normalized goodput ($\frac{R_{sum}}{(pN)}$) versus the fraction of licensed users ($\frac{n}{N}$) with $N = 30$ users for different values of p.

VI. Conclusion

Cognitive radio refers to the different solutions to the problem of congested and inefficient licensed spectrum that seek to overlay and interweave secondary transmissions with the primary users' signals. In the opportunistic interweave technique, the secondary users monitor the spectrum and navigate through unused frequency segments. Concurrent primary and secondary transmissions in the overlay technique can potentially provide a higher secondary throughputs. However, this improvement quickly disappears as the distance between the primary and secondary transmitters increases and is contingent on the availability of complicated coding techniques at the secondary user. Various channel selection techniques such as frequency hopping, frequency tracking and frequency coding can be used for opportunistic spectrum access. While frequency hopping is optimal in scenarios where the primary user activity is highly dynamic, frequency tracking is more suited for relatively static cases. Frequency coding appears to have no significant throughput advantage over frequency hopping in spite of the non-causal knowledge of the spectrum holes.

Overall, the fundamental question for the coexistence of heterogeneous wireless devices is one of autonomy versus regulation. While licensing is found to be best suited for high duty cycle traffic, opportunistic access is optimal for bursty, low duty cycle traffic. In general, the optimal amount of licensing is proportional to the traffic duty cycle and lies between the two extremes of fully licensed and fully opportunistic operation.

References

[1] National Telecommunications and Information Administration (NTIA), "FCC Frequency Allocation Chart," 2003. Download available at www.ntia.doc.gov/osmhome/allochrt.pdf.

[2] Paul J. Kolodzy, "Cognitive Radio Fundamentals," *SDR Forum, Singapore*, April 2005.

[3] Joseph Mitola, "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio," *PhD Dissertation, KTH, Stockholm, Sweden*, December 2000.

[4] Federal Communications Commission Spectrum Policy Task Force, "Report of the Spectrum Efficiency Working Group," *Technical Report 02-135*, no. November, 2002. Download available at http://www.fcc.gov/sptf/files/SEWGFinalReport_1.pdf.

[5] Natasha Devroye, Patrick Mitran and Vahid Tarokh, "Achievable Rates in Cognitive Radio Channels," *IEEE Transactions on Information Theory*, vol. 52, pp. 1813–1827, May 2006.

[6] Aleksandar Jovičić and Pramod Viswanath, "Cognitive Radio: An Information-Theoretic Perspective," *Submitted to the IEEE Transactions on Information Theory*, April 2006. Available online at http://www.ifp.uiuc.edu/ pramodv/pubs/JV06.pdf.

[7] Syed Ali Jafar and Sudhir Srinivasa, "Capacity Limits of Cognitive Radio with Distributed and Dynamic Spectral Activity," *To appear in the IEEE Journal on Selected Areas in Communications*, First Quarter 2007.

[8] Sudhir Srinivasa, Syed Ali Jafar and Nihar Jindal, "On the Capacity of the Cognitive Tracking Channel," *IEEE International Symposium on Information Theory*, January 2006.

[9] Anant Sahai, Nigel Hoven, Shrishar Mubaraq Mishra, and Rahul Tandra, "Fundamental Tradeoffs in Robust Spectrum Sensing for Opportunistic Frequency Reuse," *Technical Report*, March 2006. Available online at http://www.eecs.berkeley.edu/∼sahai/Papers/CognitiveTechReport06.pdf.

[10] Amir Ghasemi and Elvino S. Sousa, "Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments," *IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, pp. 131–136, November 2005.

[11] Ghurumuruhan Ganesan and Ye Li, "Agility Improvement through Cooperative Diversity in Cognitive Radio," *IEEE Global Communications Conference*, vol. 5, November - December 2005.