Contention-Sensing and Dynamic Spectrum Co-Use in Secondary User Cognitive Radio Societies

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***Abstract*—Emerging standards in Cognitive Radio seek to alleviate the problem of spectrum scarcity by leveraging spectrum under-utilization through dynamic spectrum access (DSA). Unlicensed users ("secondary") may opportunistically make use of channels during times when the licensed ("primary") user is absent. The "open access" paradigm proposed by FCC mandates the study of primary-secondary dynamics, as well as secondary-secondary dynamics to better understand the implications of uncoordinated competition for limited number of resources between secondary users. In this paper, we consider long term etiquette between secondary users engaged in spectrum co-use. In order to maximize throughput, by avoiding over-crowded channels, we propose a novel approach wherein secondary users have the ability to "sense" very approximate contention levels at a single spectrum band at each point in time. System performance under the contention-sensing paradigm is compared to two schemes: first, a previously defined non-cooperative game model; second, a new model which allows for spectrum foraging, but without providing secondary users the ability to sense contention in a band. Through simulation experiments, we show that the contention-sensing paradigm results in significantly better co-use of spectrum resources. Additionally, our experiments demonstrate that the proposed contention-sensing paradigm continues to outperform when the ratio of secondary users to spectrum bands is increased. Thus, the new schemes described here may be of critical importance in a future where we expect the number of secondary users to grow exponentially and thus require a scalable mechanism for opportunistic scavenging of unused spectrum.**

***Index Terms*—Cognitive radio networks, self-coexsitence, dynamic spectrum access, contention-sensing.**

I. Introduction

Cognitive Radio [4] has emerged as a promising technology for dynamic spectrum access (DSA) networks. The significant increase in wireless service demands has resulted in spectrum scarcity [11], and yet although few segments of spectrum remain for new services, the licensed spectrum appears to be underutilized. Specifically, the Federal Communication Commission (FCC) reports that licensed, or "primary", users are leaving their bands idle for a significant fraction of time [6]. During periods when a band is unused by its primary user (PU) – referred to as a "spectrum hole" [2] – the band may be legally used in an opportunistic manner by one or more unlicensed "secondary" users (SU), provided the SUs relinquish the band when the PU returns.

Because FCC regulations mandate that secondary users not interfere with primary user transmission, most prior research has focused on the interaction of primary users with secondary users. Since there are multiple secondary users, each secondary user decision to transmit in a band potentially impacts other secondary users, since channel bandwidth degrades as greater numbers of SUs share a channel.

Relatively few researchers have looked at the implications and issues surrounding SU-SU interactions [9], [7], [17]. In [10] Tan et. al. consider secondary coexistence in 802.22 networks as a non-cooperative mixed-strategy game; in [9], they consider minority game variations. Evolutionary game theoretic formulations of spectrum sharing have also been recently considered [7]. Indeed, non-cooperative game theory has been used extensively in prior work, to model the competition between secondary users over a limited amount of resources [8], [9]. Unfortunately (see Xu et. al [13] and others), a frequent limitation of these approaches is that *the game is repeatedly played for just one step*. In contrast, here we advance the performance of non-cooperative mixed-strategy approaches [10] when applied to *dense CR societies of secondary users that play the game continuously over long time intervals*. Achieving this requires the development of new behavioral models of SU spectrum co-use etiquette, outlined below, and subsequently analyzed in Sections II, IV, and VI, below.

To capture the transmission state of primary users, a two state Markov Chain with on and off states has often been used [12]. We use a similar Markov Chain approach in this work to represent the historical trajectory of a secondary user across spectrum bands. In our model SUs can either be transmitting in a spectrum band (i.e. in the consume state) or seeking a spectrum band with less contention (i.e. in the forage state). When an SU is transmitting, it receives a utility mitigated by channel interference due to the contention with other SUs also opportunistically using the same band. Every time an SU switches bands, transmitter reconfiguration necessitates an associated cost. We show that allowing secondary users to forage for spectrum (even without precise sensing of contention levels), yields significantly better utilization of spectrum resources. Then, we extend our model by allowing

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SUs to sense contention levels in a spectrum band prior to making independent decentralized decisions on transmission frequency. The model which incorporates this augmented set of SU capabilities is shown to exhibit dramatic improvement in the mean SU utility achieved over time.

Applications. The use-case for our investigation is the LTE deployments of radio spectrum at picocell (200 m) through microcell (2 km) scales [15]. The communication architecture considered is one in which SUs seek to transmit opportunistically via a base station controller. While most prior work on SU-SU dynamics considers relatively low ratios of SUs to bands (upto 6:1), in anticipation of future device-rich environments, we present means for efficient spectrum co-use in scenarios where the ratio is much higher (upto 40:1). For simplicity, pairwise communication between SUs is assumed uniformly random, and since SUs communicate through a base station that operates a software defined radio across multiple frequencies simultaneously, coordinating channel selection between pairs of communicating SUs is not required.

This article is organized as follows: In Section II we present the mathematical model. In Section III, we describe the model of SU behavior put forth by Tan et. al [10], which is the starting point of this work. Section IV, presents a novel model of foraging/consuming SUs, its benefits shown in Section V. Then, in Section VI, contention-sensing capabilities are added, and evaluated in Section VII. In most of the paper, simulations use settings identical to Tan et. al [10] to facilitate comparison. In Section VIII, we lift this restriction and consider the performance of our approach across a wide range of settings.

II. Mathematical Model

We consider a discrete time stochastic system of n secondary users $S = \{s_1, s_2, ..., s_n\}$ and m orthogonal spectrum bands $B = \{b_1, b_2, ..., b_m\}$. At each discrete time step t, each $s \in S$ commits to precisely one of the m spectrum bands $\alpha_t(s) \in B$, implicitly defining an infinite family of maps $\alpha_t : S \to B$, indexed by discrete time, which assign SUs to bands. By choosing band $\alpha_t(s)$, the secondary user s enjoys a communication rate or "reward" at time t of

$$R(k) \stackrel{def}{=} B \cdot log_2 \left(1 + \frac{G_s P_s}{\sum_{i=1}^{k} G_i \, P_i + \omega}\right) \tag{1}$$

where $k \stackrel{def}{=} |\{s' \in S | \alpha_t(s') = \alpha_t(s)\}|$ is the number of SUs sharing the band with s. This definition of reward (1) is drawn from information theoretic considerations, and is consistent with a significant body of prior work on spectrum sharing [5]. In expression (1), the transmission power for SU s (resp. i) are denoted P_s (resp. P_i); B is the channel bandwidth; G_s represents the channel gain for the transmissions by s, and ω is the power level of the ambient white Gaussian noise. **Assumptions:** To isolate the impact of the proposed paradigm, we do not consider path losses, we assume a homogeneous network wherein all SUs send (to the base station) at the same power P and experience the same channel gain G.

System-wide performance metrics are defined as the total reward obtained by all SUs at time t :

$$W_t \stackrel{def}{=} \sum_{i=1}^{m} k_t(b_i) R(k_t(b_i)) \tag{2}$$

where $k_t(b_i) \stackrel{def}{=} |\alpha_t^{-1}(b_i)|$ is the occupancy in band b_i at time t. Following previous research [1], [3], we assume a fixed cost c is incurred by an SU switching transmission bands. We denote the set of SUs that switched transmission band at $t \geqslant 2$ as

$$M_t \stackrel{def}{=} \{s \in S | \alpha_t(s) \neq \alpha_{t-1}(s)\}, \tag{3}$$

so the total switching cost incurred is $C_t \stackrel{def}{=} c|M_t|$, from which we deduce that the average instantaneous utility (per SU) obtained at time step t is

$$I_t \stackrel{def}{=} \frac{1}{n}(W_t - C_t). \tag{4}$$

The average utility (per SU per unit time) up to time T is

$$U_T \stackrel{def}{=} \frac{1}{T} \sum_{t=1}^{T} I_t. \tag{5}$$

In what follows, we consider various novel parametrized models of secondary user etiquette; we will use the above defined U_T to (experimentally) determine optimal parameter settings, as well as to evaluate relative merits of the proposed models as schemes for SU spectrum co-use.

III. Previous Approaches

Our work takes as a point of departure the model of secondary-secondary dynamics developed by Tan, Sengupta, and Subbalakshmi [10]. In what follows, we will refer to this as the "TSS" model, a natural formulation of SU strategy in response to PU departure, within the framing context of SU-SU dynamics. A distributed DSA network is assumed where multiple homogeneous SUs can share the same spectrum band. In addition, it is assumed that all SUs are in the same range considering the same bands. In the model, at time 1, all secondary users $s \in S$ start in the same spectrum band $\alpha_1(s) = b_1$. Tan et. al. then consider the situation where at time $t = 2$, the primary users of bands b_2 through b_m all simultaneously stop transmitting, leaving these $m - 1$ bands free to be used by secondary users S, who are assumed to be playing a mixed strategy game. At time step 2, each SU chooses with probability p to switch to a different spectrum band $b_i \neq b_1$ (chosen at random), or with probability $(1 - p)$ decides to stay in band b_1. Once each SU has made its stochastic choice, the utility U_2 can be computed, as defined in (5). Of particular interest is the strategically optimal p^* that maximizes the expected utility for the SUs at time $t = 2$:

$$p^* = \arg\max_{p \in [0,1]} (E[U_2^{TSS}]). \tag{6}$$

We know by elementary probability that $p^* \sim \frac{1}{m} = 0.20$.

Tan et. al. go on to explore the impact of "parochialism"

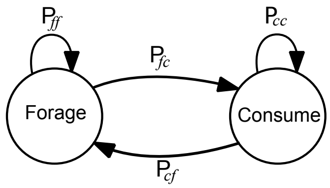

Fig. 1. Finite state machine

– local deviation from the homogeneous adoption of game-theoretically optimal strategies. In their simulation experiments, they consider concrete scenarios in which $n = 30$ SUs compete over $m = 5$ spectrum bands, each having bandwidth $B = 20$MHz. The transmission power $P = 4$W, Gaussian noise $\omega = 0.05$W and switching cost $c = 0.3 \cdot B$. The channel gain was obtained through simulation of a 10 transmitter and 10 receiver wireless system. Although we will not be considering parochialism or non-cooperative games here, our experiments will use the parameter settings of Tan et. al. [10] above to facilitate comparison with TSS and elucidate trade offs. Later, in Section VIII, we will evaluate the universality of the conclusions drawn in earlier sections, by varying the number of secondary users n, channel bandwidth B, and the cost of switching transmission bands c over a broad range of settings.

IV. The Forage-Consume Model

In our forage-consume (FC) model, each SU operates via the probabilistic finite state machine (FSM) shown in Figure 1; this FSM has two states $Q = \{q_c, q_f\}$ and one state variable, the band of interest (BoI). In state q_c (called "consume"), the SU has committed to transmitting in its BoI, which is one of the m spectrum bands $b \in B$. By doing so, it receives a reward $R(k)$ as defined in (1). In state q_f (called "forage"), an SU is merely "observing" some BoI $b \in B$ as a precursor to making a commitment consume (by moving to the consume state q_c). An SU receives a reward of 0 while in state q_f since s is not able to transmit.

Each SU's decision to move from state q to state q' is governed by an independent Markov process with the transition matrix $P_{qq'}$ where $q, q' \in Q$ and $\sum_{q'} P_{qq'} = 1$. To keep track of instantaneous state, in addition to the function $\alpha_t : S \to B$ described in Section II, we introduce time indexed functions

$$\gamma_t : S \to \{q_f, q_c\} \tag{7}$$

where $\gamma_t(s)$ indicates the state of SU s at time t.

We can now describe precisely the choices that each SU s faces at time t. Note that because we assume the secondary users are following a homogeneous strategy, the same logic applies to all SUs.

If $\gamma_t(s) = q_c$ and $\alpha_t(s) = b_i$, then s makes one of the following two choices at time $(t + 1)$:

- C_0: With probability P_{cc}, s can stay in q_c, using band b_i, i.e. $\gamma_{t+1}(s) = \gamma_t(s)$ and $\alpha_{t+1}(s) = \alpha_t(s)$.
- C_x: With probability P_{cf}, s moves to q_f, i.e. $\gamma_{t+1}(s) = q_f$ and $\alpha_{t+1}(s) = b_j$ $(j \neq i)$ chosen uniformly from B.

If $\gamma_t(s) = q_f$ and $\alpha_t(s) = b_i$, then s makes one of the following two choices at time $(t + 1)$:

- F_0: With probability P_{ff}, s stays in q_f, i.e. $\gamma_{t+1}(s) = \gamma_t(s)$ and $\alpha_{t+1}(s) = b_j$ $(j \neq i)$ chosen uniformly from B.
- F_x: With probability P_{fc}, s commits to band b_i by moving to q_c, i.e. $\gamma_{t+1}(s) = q_c$ and $\alpha_{t+1}(s) = b_i$.

At each time step t an s is associated with some band b, i.e. $\alpha_t(s) = b$, regardless of its state $\gamma_t(s) \in Q$. However, since the reward $R(k)$ is only obtained when s is in the consume state q_c, we must revise the utility function U_T by modifying k_t to only include SUs in the consume state q_c $k'_t(i) = |\alpha_t^{-1}(i) \cap \gamma_t^{-1}(q_c)|$. The reward at t for all SU is

$$W'_t = \sum_{i=1}^{m} k'_t(i) R(k'_t(i)). \tag{8}$$

When an SU switches transmission bands on entering (or re-entering) q_c, transmitter reconfiguration is required. We assume this to be an expensive operation compared to the receiver reconfigurations required upon entering (or re-entering) q_f. To capture this, our model charges each SU a fixed cost c whenever it switches transmission bands by moving from the forage state q_f to the consume state q_c. Function M_t captures the number of SUs charged for switching at time t

$$M'_t = \{s \in S \mid \gamma_{t-1}(s) = q_f \wedge \gamma_t(s) = q_c\} \tag{9}$$

so the switching cost of the system at time t is $C'_t = c|M'_t|$ and the instantaneous average utility (per SU) at time t is

$$I'_t = \frac{1}{n}(W'_t - C'_t) \tag{10}$$

and the average utility (per SU per unit time) up to time T is

$$U'_T = \frac{1}{T} \sum_{t=1}^{T} I'_t. \tag{11}$$

Note that even though the SUs that are in the forage state are excluded from W', the utility function implicitly incorporates a zero reward for each SU in the forage state since in (10), the quantity $(W' - C')$ is divided by n, the total number of SUs in the system.

Interpreting TSS within FC. It is easy to see that setting $P_{fc} = 1$ in the FC model yields behavior that is equivalent to the TSS model. When $P_{fc} = 1$, SUs pass through the forage state but are not able to remain there, and are thus effectively forced to immediately switch and commit to a new randomly chosen band, as is the case in the TSS model. We will refer to this formal rendering of the TSS model as a special case of the FC model, as TSS^*.

Experimental Evaluation of TSS^*. We ran 10 simulations with $T = 10^5$. To facilitate comparison, we use the original parameters used by Tan et. al. [10] – presented also here at the end of Section III – for the reward function $R(k)$, the number of SU n, the number of bands m, and the probability $P_{cf} = p^* = 0.20$ as presented in (6). We observed the average utility (per SU per unit time) in TSS^* to be $U'_T = 6.58$. This number is the baseline against which we

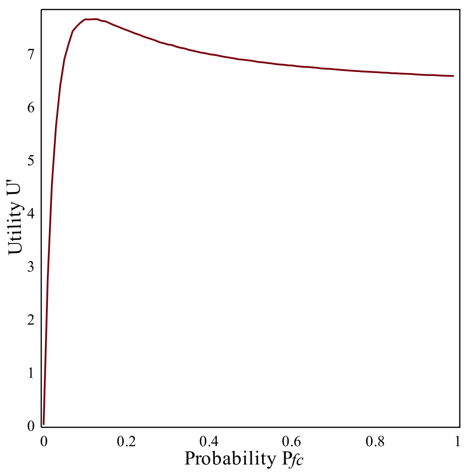

Fig. 2. Average utility as a function of probability to transition to consume.

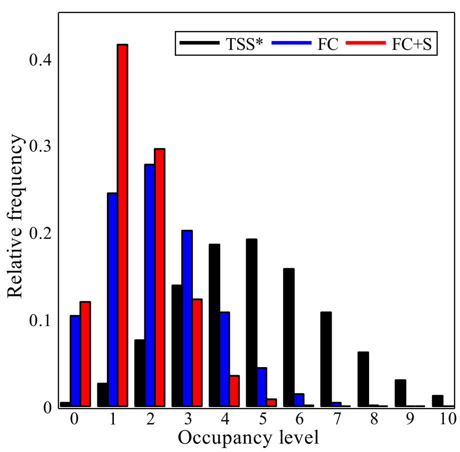

Fig. 3. Frequency of channel occupancy level

evaluate the performance of our new approaches, below.

V. Evaluating the FC Model

In this section we lift the restriction $P_{fc} = 1$ (which renders the TSS model as a degenerate case of the FC model), and allow ourselves to consider the entire range of possibilities $0 \leqslant P_{fc} \leqslant 1$. In order to have a controlled experiment, we fix the same parameters settings as in Section III for the reward function $R(k)$, the number of SUs n, the number of bands m, simulation time T, and probability P_{cf}. Then, through simulation, we find optimal $P_{fc} \in [0, 1]$ that maximizes U_T':

$$P_{fc} = \arg\max_{p\in[0,1]}(E[U_T{}'(FC)]). \tag{12}$$

Figure 2 presents the intermediate results of this optimization process, by showing how U_T' varies for different choices of P_{fc}. We see immediately that the utility is not maximized at $P_{fc} = 1$, but rather when $P_{fc} = 0.12$. At this setting the utility $U_T{}'(FC)$ reaches its peak at 7.66, a 16% increase over the 6.58 achieved by TSS^* (where $P_{fc} = 1$).

TABLE I
A comparison of TSS^*, FC and $FC{+}S$

Model	P_{fc}	P_{cf}	ϵ	τ	U'	U^c	time in q_c	time in q_f
$TSS*$	1.00	0.20	-	-	6.58	7.9	83%	17%
FC	0.12	0.20	-	-	7.66	21.3	36%	64%
$FC{+}S$	0.12	0.20	0.05	0	8.49	32.7	26%	74%

Table I compares various metrics of TSS^* and FC. To understand the difference in utility U' achieved in TSS^* and FC we first consider U^c, the utility that each SU receives (on average) when in the consume state q_c. We can see that in TSS^*, utility $U^c = 7.9$ while in FC, utility $U^c = 21.3$, an increase of 270%. Also from Table I, we observe that in TSS^* (where $P_{fc} = 1$) an SU spends 83% of the time in q_c, while in FC (where $P_{fc} = 0.12$) it spends only 36% of its time consuming. The lower "duty cycle" of FC ensures that SUs obtain higher utility when consuming, and take turns (stochastically) transmitting data.

Thus, the notable difference in utility between TSS^* and FC rests upon the steep falloff in the utility curve $R(k)$ as $k \gg 0$. Since SUs stay in the forage state 17% of the time in TSS^* but 64% of the time in FC, there is less contention among consumers in the latter model. This is confirmed in the histogram depicted in Figure 3, which shows the fraction of time that an SU experiences contention between $0 - 10$ other SUs in each of the two schemes, TSS^* and FC; note that the histogram does not include the time spent in forage. The histogram is skewed to the left for FC (mean 1.8) relative to TSS^* (mean 4.8), confirming that in the FC model, each SU experiences less contention while consuming resources.

VI. Adding Sensing Capabilities $FC{+}S$

In the FC model of the previous section, each SU is said to "observe" a random sequence of bands while it is in the forage state q_f, but the model renders the SU powerless to acquire any useful information about the current transmission characteristics of the band. Here we extend the FC model to support contention-sensing; that is, we allow each SU s while both foraging ($\gamma_t(s) = q_f$) and consuming ($\gamma_t(s) = q_c$) some band of interest $\alpha_t(s)$, to additionally "sense" the approximate number of SUs consuming the band. Rather than requiring exact measurement, we simply permit the SU to make a 1-bit measurement–that is, to determine whether the band has "low" occupancy: $(k_t{}'(\alpha_t(s)) \leqslant \tau)$, or "high" occupancy: $(k_t{}'(\alpha_t(s)) > \tau)$ for a fixed system-wide integer **contention threshold parameter** τ. This knowledge can be obtained in distributed manner or through a centralized entity. There are a number of existing strategies to implement this sensing capability [7], [14], [16], [17], beyond the scope of this paper. Contention-sensing capabilities described above augment the forage-consume (FC) model by modifying the transition probabilities in the FSM of Figure 1. This augmented model is referred to as $FC{+}S$ to indicate the inclusion of contention-sensing. FSM probabilities are altered as follows. When an SU is in state q_c and consuming band $\alpha_t(s) = b$:

C_x^-: The probability of moving from q_c to q_f is lowered to $(P_{cf} - \epsilon)$ if the occupancy of band b is low ($k'_t(b) \leqslant \tau$),

C_x^+: The probability of moving from q_c to q_f is raised to $(P_{cf} + \epsilon)$ if the occupancy of band b is high ($k'_t(b) > \tau$).

When an SU is in state q_f and observing band $\alpha_t(s) = b$:

F_x^-: The probability of moving from q_f to q_c is raised to $(P_{fc} + \epsilon)$ if the occupancy of b is low ($k'_t(b) \leqslant \tau$),

F_x^+: The probability of moving from q_f to q_c is lowered to $(P_{fc} - \epsilon)$ if the occupancy of b is high ($k'_t(b) > \tau$).

Clearly, the choice of the **contention bias parameter** ϵ must satisfy $0 \leqslant \epsilon \leqslant min(P_{cf}, P_{fc})$, and serves to control how sensitive or apathetic the secondary users are towards the possibility of contention with other SUs at spectrum holes. If ϵ is high or τ is low, the SUs will be more selective and spend more time scanning for low occupancy bands; they will also be equally reluctant to leave low occupancy bands. The values of τ and ϵ must be chosen carefully in order to obtain maximized utility. This selection process is the subject of the experiments described in the next section.

VII. Evaluating $FC+S$

In Table I, we compare the utility U' for all three models TSS^*, FC and $FC+S$. In considering $FC+S$ we take $\epsilon = 0.05$ and $\tau = 0$, indicating that an SU will increase (or decrease) its probabilities of moving to forage (or consume) state by 5% based on whether there are other users in the current band. We can see that in $FC+S$ the utility $U' = 8.49$, an 11% improvement over FC (where $U' = 7.66$) and a 30% improvement over TSS^* (where $U' = 6.58$). Thus, we observe that even with a relatively small τ and ϵ, there is a significant increase in average utility per SU. Although the time spent in the consume state has decreased to 26% in $FC+S$, the amount of time spent in consume is heavily influenced by the threshold τ. Table II (rows 2-5) reports on the differences in utility U' and duty cycle for different values of τ. As is apparent, taking $\tau = 0$ maximizes mean system utility (per user per unit time). The histogram in Figure 3 also shows that $FC+S$ (with $\epsilon = 0.05$ and $\tau = 0$) exhibits a distribution of occupancy numbers that is further shifted to the left (mean 1.1) from FC (mean 1.8). Hence, the performance improvement from contention-sensing is explained by lower mean congestion over resources while consuming, and this in turn is made possible by contention-sensing because SUs are able to be ϵ-biased against transmitting in bands that are have occupancy exceeding τ, and be ϵ-biased in favor of transmitting in bands that are have occupancy τ or lower. In other words, at any given point in time the number of active transmitters is lower for $FC+S$ compared to the previously defined models.

VIII. Scalability of Experimental Results

In previous sections, our experiments have used identical parameter settings to those used by Tan et. al. [10] in order to facilitate comparison. Here, we lift this assumption, and determine the extent to which conclusions drawn in earlier sections continue to hold in settings with different numbers of secondary users n, channel bandwidth B, and switching cost c. We continue throughout to assume a fixed $m = 5$ spectrum bands, transmission power, channel gain and Gaussian noise.

TABLE II
Varying contention threshold parameter τ

row	P_{fc}	P_{cf}	ϵ	τ	U'	U^c	time in q_c	time in q_f
1	0.12	0.20	-	-	7.66	21.3	36%	64%
2	0.12	0.20	0.05	0	8.49	32.7	26%	74%
3	0.12	0.20	0.05	1	8.18	24.8	33%	67%
4	0.12	0.20	0.05	2	7.84	19.6	40%	60%
5	0.12	0.20	0.05	3	7.66	18.2	42%	58%

To begin, in Figure 4, we look at $\partial U/\partial n$ on a log-linear graph. For these experiments, $B = 20$MHz and $c = 0.3 \cdot B$. When the ratio of users to bands is less than 4 SUs per band, both FC and $FC+S$ under perform, providing users with only 44% and 64% of the utility enjoyed by TSS^*. As the ratio of SUs to bands exceeds 4:1 both FC and $FC+S$ outperform TSS^*. When the ratio of SUs to bands is 40:1, i.e. 200 SUs are competing over 30 bands, $FC+S$ ($U'_T = 0.77$) leads, providing 1724% of the mean utility of TSS^* ($U'_T = 0.045$) and 122% what is achieved by FC ($U'_T = 0.636$). Even with the increase of the SUs to channel ratio, the occupancy level at each channel is governed by τ.

Varying the bandwidth B results in a linear growth of the expected utility for all three schemes where $FC+S$ outperforms both FC and TSS^*. For these experiments, $c = 6$ and there are $n = 30$ secondary users. The slope of the three lines is close, but $FC+S$ is able to harness additional bandwidth slightly more efficiently (slope 0.44) compared to FC (slope 0.40) and TSS^* (slope 0.38).

Finally, we investigate how expected utility is affected by increases in switching cost. In these experiments, bandwidth $B = 20$MHz and there are $n = 30$ secondary users. Here again, we get a linear dependency, indicating that as switching cost increases, expected utility is proportionately decreased– but the proportionality constants differ considerably across the three models. Even with 0 switching cost, the $FC+S$ model outperforms FC by 10% and TSS^* by 20%. Where the $FC+S$ (resp FC) model continues to deliver positive utility until switching cost $c = 7.2 \cdot B$ (resp. $5.3 \cdot B$), the TSS^* model fails to provide positive utility once the switching cost c goes above $2.2 \cdot B$. By switching less frequently, and by favoring bands which are "low" occupancy, the $FC+S$ scheme is less vulnerable to performance losses when the switching cost is increased. The utility obtained by $FC+S$ is governed as $U'_T = -0.06 \cdot c + 8.9$ while for TSS^* it is given by $U'_T = -0.17 \cdot c + 7.6$ The difference between the two expressions is $0.11 \cdot c + 1.3$. This residual surplus utility is available to be allocated to the cost of contention-sensing if needed (by comparison, in this paper we assumed that contention-sensing costs were negligible). It follows that the maximum **channel contention-sensing cost** c_s for $FC+S$ to maintain a performance advantage over TSS^* is $c_s \leqslant 0.11 \cdot c + 1.3$. This

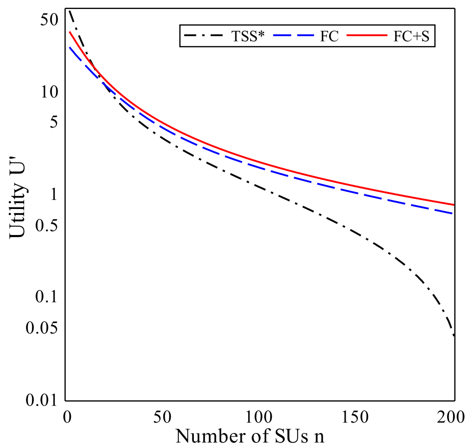

Fig. 4. Varying the number of secondary users n

means that asymptotically, channel contention-sensing costs must remain below 11% of the channel switching cost c—which is to say less than 3% of channel bandwidth B—in order for $FC{+}S$ to continue to be a justifiable SU etiquette. This 3% bound is on the actual cost of making 1-bit measurements of band contention levels, not on the "opportunity cost" of not transmitting while in forage state, since the latter is already fully accounted for in (10), which assigns SUs who are in foraging state a 0 reward in the computation of mean SU utility.

IX. Conclusion and Future Work

We have presented a paradigm for secondary spectrum co-use in DSA networks that is built on an extended SU capability of "sensing" channel occupancy levels. Through simulation, we demonstrate that the new $FC{+}S$ contention-sensing model frequently provides a significant (up to 1724%) higher average (per user per unit time) utility when compared to earlier models of SU etiquette such as TSS^*, and a noticeable improvement (122%) over foraging schemes without contention-sensing. This performance advantage is present as long as the ratio of SUs to bands exceeds 4, and continues to be exhibited as ever greater numbers of SUs fight for a fixed number of resources. Although our experiments have assuming zero cost for contention-sensing, the $FC{+}S$ continues to provide better utility and be a better SU etiquette even with non-zero contention-sensing costs, as long as instantaneous contention-sensing cost remains below 3% of total channel bandwidth.

Future extensions of this work presently underway include:

-Validate these simulation results in a hardware testbed implementation: We hope to implement the $FC+S$ model within a cognitive radio testbed consisting of laptops with Orinoco 802.11 PCMCIA cards based on the Atheros 5212 (802.11 a/b/g) chipset.

-Choosing τ and ϵ dynamically by estimating the number of secondary users n. At present, it is assumed that all secondary users know the value of n, the static constant number of SUs, and so can set optimal values of FSM transition probabilities, τ and ϵ. In practice this is unlikely to be the case. For these types of scenarios, it will be necessary for SUs to run a parallel process which estimates the current value of n, on the basis of which they each independently set their behavioral parameters vis-a-vis FSM transition probabilities, τ and ϵ.

-Validating robustness of the scheme by varying simulation parameters and incorporating SU diversity.

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