Cognitive Code-Division Channelization with Blind Primary-System Identification

Ming Li, Stella N. Batalama, Dimitris A. Pados†, Tommaso Melodia
Department of Electrical Engineering
State University of New York at Buffalo
Buffalo, NY 14260
E-mail: {mingli,batalama,pados,tmelodia}@buffalo.edu

Michael J. Medley, and John D. Matyjas
Air Force Research Laboratory/RIGF
525 Brooks Rd
Rome, NY 13441
E-mail: {michael.medley,john.matyjas}@rl.af.mil

***Abstract*—We consider the problem of cognitive code-division channelization (simultaneous power and code-channel allocation) for secondary transmission links co-existing with an unknown primary code-division multiple-access (CDMA) system. We first develop a blind primary-user identification scheme to detect the binary code sequences (signatures) utilized by primary users. To create a secondary link we propose two alternative procedures –one of moderate and one of low computational complexity– that optimize the secondary transmitting power and binary code-channel assignment in accordance with the detected primary code channels to avoid "harmful" interference. At the same time, the optimization procedures guarantee that the signal-to-interference-plus-noise ratio (SINR) at the output of the maximum SINR linear secondary receiver is no less than a certain threshold to meet secondary transmission quality of service (QoS) requirements.**

***Index Terms*—Blind user identification, code-channel allocation, code-division multiple-access, cognitive radio, dynamic spectrum access, power allocation, signal-to-interference-plus-noise ratio.**

I. Introduction

With the rapid proliferation of a variety of consumer oriented wireless devices, demand for access to radio spectrum has been growing dramatically and the limited available spectrum is becoming increasingly congested. Ironically, at the same time much of the pre-licensed radio spectrum experiences low utilization [1]. Cognitive radio (CR) is an emerging technology aiming at improving spectrum utilization efficiency by allowing secondary users/networks to opportunistically share radio spectrum originally licensed by primary users/networks without causing "harmful" interference to them [2]-[5].

Cognitive radio networks can be categorized according to two modes of operation: *Cooperation* mode and *coexistence* mode [6]. In cooperation mode, primary users cooperate with secondary users and share information to avoid mutual interference. In coexistence mode, there is no form of cooperation and secondary users must have the ability to detect the presence of primary users [7], [8] and change behavior accordingly to avoid mutual interference.

Past work in the young field of cognitive code-division channelization includes coexistence power control [9] as well as distributed resource allocation of spectral bands, power, and data rates among multiple secondary users for multi-carrier CDMA systems [10]. Cooperation-mode bit rate and spreading factor adjustments for a secondary CDMA system under interference-minimizing code assignments were carried out in [11]. In [12], a secondary maximum signal-to-interference-plus-noise ratio (SINR) code-division link is designed subject to SINR requirements for the primary system which is presumed known (cooperation-mode cognitive radio). Outside the framework of cognitive code-division altogether, interesting work in the form of joint beamforming and power allocation algorithms was reported in [13]-[16]. In particular, in [13] the radio frequency spectrum of interest was divided into a set of multiple orthogonal channels and was shared between primary and secondary networks using orthogonal frequency division multiple access (OFDMA). In [14]-[15], joint spatial-channel and power allocation algorithms for cognitive radio networks were developed. In [16], the authors provide a solution for leasing spectrum for a fraction of time to secondary users based on the idea that secondary nodes can earn spectrum access in exchange for transmission assistance to the primary link (cooperative communication paradigm).

In this work, we focus on coexistence-mode cognitive radio and investigate the problem of establishing a secondary code-division link coexisting with an *unknown* primary CDMA system. In particular, we investigate –to the best of our knowledge for the first time in the context of cognitive radio– the problem of blindly identifying the binary codes/signatures utilized by primary users when neither channel state information nor pilot signaling (training sequence) is available. Then, we study the design of a power and binary-code-channel allocation protocol for the secondary link that will not cause "harmful" interference to the existing primary users. Since post-processing interference sensing is not feasible in coexistence mode cognitive radio, to quantify "harm" we use the periodic-total-square-correlation (PTSC) interference metric in our optimization problem as the mathematical means to protect co-channel primary users [2], [17]. At the same time, to satisfy quality-of-service (QoS) requirements for the secondary link, the power and code-division optimization problem is constrained to have SINR at the output of the maximum SINR linear receiver of the secondary link no less than a certain threshold. We recognize that the above described fundamental cognitive code-division radio formulation is, regretfully, a non-convex NP-hard problem. Yet, using existing SINR-maximization signature design methodologies we are able to develop novel, realizable suboptimum solutions of varying computational complexity with excellent cognitive system performance characteristics as demonstrated by simulation studies included in this paper. The theoretical developments and experiments can be readily extended to cover multiple secondary links alongside the primary CDMA

This work was supported by the U.S. Air Force Research Laboratory under Grant FA8750-08-1-0063. Approved for Public Release; Distribution Unlimited: 88ABW-2010-2300 dated 04 May 2010.

†Corresponding author.

system.

II. System Model and Problem Formulation

In the following, we consider a primary code-division system with a primary transmitter PT and K primary receivers $PR_i, i = 1, 2, \ldots, K$, as shown in Fig. 1. The primary transmitter (for example, base station) PT communicates downlink with the K primary receivers $PR_i, i = 1, 2, \ldots, K$, over distinct code-division channels defined by individual normalized binary codes/signatures $\mathbf{s}_i = \frac{1}{\sqrt{L}}\{\pm 1\}^L$, $i = 1, 2, \ldots, K$, where L is the signature length (system processing gain). We consider also a potential concurrent secondary code-division link in the spectrum band of the primary system between a secondary transmitter ST and receiver SR. The secondary communication link is activated, whenever possible, with a (normalized) binary signature $\mathbf{c} = \frac{1}{\sqrt{L}}\{\pm 1\}^L$ and transmitting power $P > 0$. All transmitted signals, primary and secondary when appropriate, are assumed/modeled to propagate over multipath Rayleigh fading channels and experience additive white Gaussian noise (AWGN).

We first assume that the secondary transmitter ST is quiet and we examine how the signal sent by PT is observed by SR. After carrier demodulation, chip matched filtering and sampling at the chip rate over a presumed multipath extended data bit period of $L_M = L + M - 1$ chips where M is the number of resolvable multipaths, the observed data vector $\mathbf{y}(n) \in \mathbb{C}^{L_M}$ by SR takes the following general form

$$\mathbf{y}(n) = \sum_{i=1}^{K} \sqrt{E_i} b_i(n) \mathbf{H}\mathbf{s}_i + \mathbf{i} + \mathbf{n}, \;\; n = 1, 2, \ldots, \quad (1)$$

where $\mathbf{H} \in \mathbb{C}^{L_M \times L}$ is the multipath channel matrix between PT and SR

$$\mathbf{H} \triangleq \begin{bmatrix} h_1 & 0 & \ldots & 0 & 0 \\ h_2 & h_1 & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ h_M & h_{M-1} & & 0 & 0 \\ 0 & h_M & & 0 & 0 \\ \vdots & \vdots & & \vdots & \vdots \\ 0 & 0 & \ldots & h_M & h_{M-1} \\ 0 & 0 & \ldots & 0 & h_M \end{bmatrix} \quad (2)$$

with entries $h_m \in \mathbb{C}$, $m = 1, \ldots, M$, considered as complex Gaussian random variables to model fading phenomena, $\sqrt{E_i} > 0$ and $b_i(n) \in \{\pm 1\}$ are the amplitude level and nth transmitted bit of primary user i, $i = 1, \ldots, K$, respectively, $\mathbf{i} \in \mathbb{C}^{L_M}$ denotes multipath induced inter-symbol-interference (ISI), and $\mathbf{n}$ is a zero-mean additive white Gaussian noise (AWGN) vector with autocorrelation matrix $\sigma^2 \mathbf{I}_{L_M}$. The information bits $b_i(n)$ are viewed as binary equiprobable random variables that are independent within a user stream (in $n = 1, 2, \ldots$) and across users (in $i = 1, 2, \ldots, K$). Since the effect of ISI is, arguably, negligible for most applications of practical interest where the number of resolvable multipaths is much less than the processing gain, for mathematical convenience we will not consider the ISI terms in our theoretical developments that follow[1]. Thus, the primary users' signal observed by SR in (1) is simplified/approximated by

[1]However, naturally ISI will be considered and accounted for in our simulation studies.

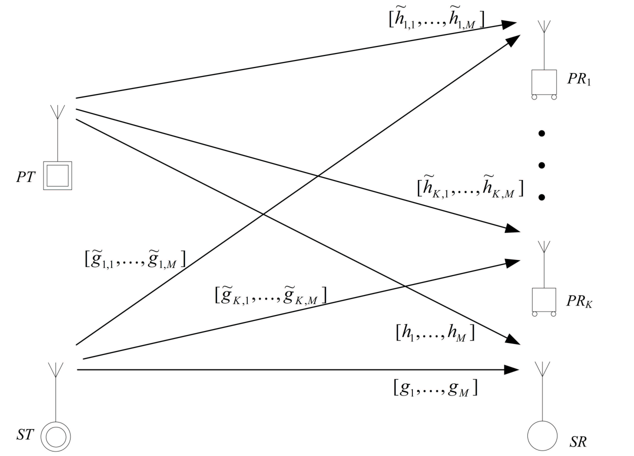

Fig. 1. Primary/secondary code-division system model of a primary transmitter PT, K primary receivers $PR_i, i = 1, 2, \ldots, K$, and a secondary transmitter/receiver pair ST, SR (all received signals exhibit multipath Rayleigh fading).

$$\mathbf{y}(n) = \sum_{i=1}^{K} \sqrt{E_i} b_i(n) \mathbf{H}\mathbf{s}_i + \mathbf{n}, \;\; n = 1, 2, \ldots. \quad (3)$$

In our cognitive system model, the secondary link is taken to be synchronous to the primary network with the same chip rate. Also, without loss of generality and for simplicity in notation, we assume that the multipath channels between PT and PR_i, $i = 1, \ldots, K$, PT and SR, and ST and SR, all have the same number of resolvable paths. Then, when the secondary communication link is activated with a (normalized) binary signature code $\mathbf{c} = \frac{1}{\sqrt{L}}\{\pm 1\}^L$ and transmit power $P > 0$, the aggregate signal vector received by SR can be expressed as

$$\mathbf{r}(n) = \sqrt{P} b(n) \mathbf{G}\mathbf{c} + \mathbf{y}(n), \;\; n = 1, 2, \ldots, \quad (4)$$

where $\mathbf{G} \in \mathbb{C}^{L_M \times L}$ is the ST to SR channel matrix with multipath channel coefficients $g_m \in \mathbb{C}$, $m = 1, \ldots, M$, and $\mathbf{y}(n)$ is given by (3).

Information bit detection at SR is carried out via linear maximum SINR filtering (or, equivalently, minimum mean square error filtering) as follows

$$\widehat{b}(n) = \mathrm{sgn}\left\{\mathfrak{Re}\{\mathbf{w}_{maxSINR}^H \mathbf{r}(n)\}\right\}, \;\; n = 1, 2, \ldots, \quad (5)$$

where $\mathbf{w}_{maxSINR} = c\mathbf{R}^{-1}\mathbf{G}\mathbf{c} \in \mathbb{C}^{L_M}$, $c > 0$, is the maximum SINR filter and $\mathbf{R} = \mathrm{E}\{\mathbf{y}\mathbf{y}^H\}$ is the autocorrelation matrix of the $\mathbf{y}(n)$ signal in (3) that constitutes primary-system disturbance to SR. Practically, $\mathbf{R}$ is estimated by averaging over $N \geq L_M$ observation samples $\mathbf{r}(n)$, when ST is silent ($P = 0$), $\widehat{\mathbf{R}}(N) = \frac{1}{N}\sum_{n=1}^{N} \mathbf{r}(n)\mathbf{r}(n)^H = \frac{1}{N}\sum_{n=1}^{N} \mathbf{y}(n)\mathbf{y}(n)^H$. The output SINR of the filter $\mathbf{w}_{maxSINR}$ can be calculated to be

$$\begin{aligned} \Gamma &\triangleq \frac{\mathbb{E}\{|\mathbf{w}_{maxSINR}^H(\sqrt{P}b\mathbf{G}\mathbf{c})|^2\}}{\mathbb{E}\left\{|\mathbf{w}_{maxSINR}^H \mathbf{y}|^2\right\}} \\ &= P\mathbf{c}^T \mathbf{G}^H \mathbf{R}^{-1} \mathbf{G}\mathbf{c}. \end{aligned} \quad (6)$$

To attain a certain QoS level for the secondary link, we need to jointly design the binary signature $\mathbf{c}$ and the transmitting power P to have the SINR value Γ at the output of the maximum SINR filter $\mathbf{w}_{maxSINR}$ no less than a given threshold $\gamma > 0$, i.e. $\Gamma \geq \gamma$.

At the same time, due to the coexistence of the secondary link with the primary network, interference is introduced to the primary receivers. The secondary link is to be allowed to activate *only if* the interference to each primary receiver is not "harmful." The difficulty is that in cognitive radio networks operating in coexistence-mode, the primary network does not cooperate/talk to secondary users and the latter do not have global knowledge of system parameters, such as the multipath channel coefficients $[\widetilde{h}_{i,1}, \ldots, \widetilde{h}_{i,M}]$ between PT and PRi, or the channel coefficients $[\widetilde{g}_{i,1}, \ldots, \widetilde{g}_{i,M}]$ between ST and PRi, $i = 1, 2, \ldots, K$ (see Fig. 1), or the primary binary signatures $\mathbf{s}_i$, $i = 1, \ldots, K$, in (3) and the filters utilized by each primary user receiver. Therefore, post-processing interference sensing is not feasible.

We recall that the periodic (cyclic) total squared cross-correlation (PTSC) value [17] is a useful measure to evaluate multiple access interference (MAI) when channels exhibit multipath behavior. In this spirit, we propose to use the PTSC value as a metric to evaluate the interference caused by the secondary link. For notational simplicity, let $\mathbf{s}_{i|l}$, $i = 1, \ldots, K$, denote the *cyclic right-shifted* version of $\mathbf{s}_i \in \frac{1}{\sqrt{L}}\{\pm 1\}^L$, by l bit positions when $l = 0, 1, \ldots, L-1$, and *cyclic left-shifted* version of $\mathbf{s}_i$ by l bit positions when $l = 0, -1, \ldots, 1-L$, (hence, $\mathbf{s}_{i|0} = \mathbf{s}_i$). The PTSC between signatures $\mathbf{c}$ and $\mathbf{s}_i$ for multipath shifts up to lag M is defined as

$$\mathrm{PTSC}(\mathbf{c}, \mathbf{s}_i) \triangleq \sum_{l=-M}^{M} |\mathbf{c}^T \mathbf{s}_{i|l}|^2, i = 1, \ldots, K. \tag{7}$$

In this context, we define the *generalized correlation interference* by a secondary link with power $P > 0$ to the ith primary receiver as

$$\mathcal{I}_i \triangleq P \times \mathrm{PTSC}(\mathbf{c}, \mathbf{s}_i), \quad i = 1, \ldots, K. \tag{8}$$

We understand that $\mathcal{I}_i$ serves as a simple "worst-case" measure of the effect of the secondary link on the ith primary user. Then, in this context, the secondary link can be activated by assigning a signature $\mathbf{c}$ and power $P > 0$ if the interference to *every* primary user is less than a threshold $\mathcal{I}_{\mathrm{th}} > 0$: $\mathcal{I}_i < \mathcal{I}_{\mathrm{th}}$ $\forall i = 1, \ldots, K$. If

$$\mathcal{I}_{max} \triangleq max\{\mathcal{I}_i, i = 1, \ldots, K\} \tag{9}$$

is the strongest generalized interference to primary receivers, the activation condition is equivalent to $\mathcal{I}_{max} < \mathcal{I}_{\mathrm{th}}$.

Our objective is to jointly design the binary signature $\mathbf{c}$ and the transmitting power $P > 0$ for the secondary link to minimize $\mathcal{I}_{max}$ under the constraint that the secondary link achieves its pre-determined SINR requirement γ:

$$\underset{P>0,\, \mathbf{c}\in\frac{1}{\sqrt{L}}\{\pm 1\}^L}{\text{minimize}} \quad \mathcal{I}_{max} \triangleq max\{P \times \mathrm{PTSC}(\mathbf{c}, \mathbf{s}_i), i = 1, \ldots, K\}$$

$$\text{s. t. } \Gamma \triangleq P\mathbf{c}^T \mathbf{G}^H \mathbf{R}^{-1} \mathbf{G}\mathbf{c} \geq \gamma. \tag{11}$$

Then, if the resulting minimized $\mathcal{I}_{max}$ is indeed less than $\mathcal{I}_{\mathrm{th}}$, the secondary link can be activated; otherwise, it is kept idle.

In our assumed coexistence mode of operation, the secondary link needs to blindly evaluate the caused interference in the form of $\mathrm{PTSC}(\mathbf{c}, \mathbf{s}_i)$, $i = 1, \ldots, K$, hence blindly detect the number of active primary users K and their binary signatures $\mathbf{s}_i$, $i = 1, \ldots, K$. With respect to the population size identification problem, we can for example utilize the algorithm developed recently in [18]. Due to space limitations, in this paper we do not deal further with this issue and instead assume that K is correctly identified. Then, in the next section, we develop an iterative-least-square (ILS)-based procedure that can blindly detect the primary users' binary signatures $\mathbf{s}_i$, $i = 1, \ldots, K$, from the observed primary signal $\mathbf{y}(n)$.

III. Primary-System Identification

If we denote the (energy inclusive) channel processed signature by

$$\mathbf{v}_i \triangleq \sqrt{E_i}\mathbf{H}\mathbf{s}_i, \; i = 1, 2, \ldots, K, \tag{12}$$

then the observed signal in (3) can be expressed as

$$\mathbf{y}(n) = \sum_{i=1}^{K} \mathbf{v}_i b_i(n) + \mathbf{n} = \mathbf{V}\mathbf{b}(n) + \mathbf{n}, \quad n = 1, 2, \ldots, \tag{13}$$

where $\mathbf{V} \triangleq [\mathbf{v}_1, \ldots, \mathbf{v}_K]$ is the effective signature matrix and $\mathbf{b}(n) \triangleq [b_1(n), \ldots, b_K(n)]^T$ is the vector of bits for all K users at the nth transmission period. If SR is able to collect N observation vectors $\mathbf{y}(n)$, $n = 1, 2, \ldots, N$, then (13) can be rewritten in matrix form as

$$\mathbf{Y} = \mathbf{V}\mathbf{B} + \mathbf{N} \tag{14}$$

where $\mathbf{Y} \in \mathbb{C}^{L_M \times N}$ is the observation matrix, $\mathbf{B} \triangleq [\mathbf{b}(1), \ldots, \mathbf{b}(N)]$ is the $K \times N$ data matrix that contains the N bits transmitted for each of the K primary users, and $\mathbf{N}$ is an $L_M \times N$ Gaussian noise matrix.

To detect the binary signatures $\mathbf{s}_i$, $i = 1, \ldots, K$, we first estimate the channel processed signature set $\mathbf{V}$ from the observation matrix $\mathbf{Y}$. Our approach begins by formulating the signature set estimation problem as a joint detection and estimation problem with the following least squares (LS) solution

$$\widehat{\mathbf{V}}, \widehat{\mathbf{B}} = \arg \min_{\substack{\mathbf{B}\in\{\pm 1\}^{(K\times N)},\\ \mathbf{V}\in\mathbb{C}^{L_M \times K}}} \|\mathbf{Y} - \mathbf{V}\mathbf{B}\|_F^2 \, . \tag{15}$$

The above LS solution is maximum-likelihood optimal as long as $\mathbf{N}$ is white Gaussian. In any case, regretfully, joint detection and estimation by (15) has complexity exponential in NK. We consider this cost unacceptable and attempt to reach a quality approximation of the solution by alternating least squares estimates of $\mathbf{V}$ and $\mathbf{B}$, iteratively, as described below.

The basic idea behind such an iterative least squares (ILS) solution [19]-[21] is to compute an LS update of one of the unknown (matrix) parameters conditioned on a previously obtained estimate of the other (matrix) parameter and continue on until convergence is observed. The iterative least-squares procedure for the solution of our problem in (15) is presented in Table I. Superscripts in Table I denote the iteration index. Derivation details are omitted due to lack of space.

TABLE I
ITERATIVE LEAST-SQUARES PROCEDURE

1) $d = 0$; initialize $\widehat{\mathbf{B}}^{(0)} \in \{\pm 1\}^{K \times N}$ arbitrarily.
2) $d = d + 1$;
$$\widehat{\mathbf{V}}^{(d)} = \mathbf{Y}(\widehat{\mathbf{B}}^{(d)})^T \left[(\widehat{\mathbf{B}}^{(d)})(\widehat{\mathbf{B}}^{(d)})^T\right]^{-1};$$
$$\widehat{\mathbf{B}}^{(d)} = \mathrm{sgn}\left\{\mathfrak{Re}\left[\left[(\widehat{\mathbf{V}}^{(d-1)})^H(\widehat{\mathbf{V}}^{(d-1)})\right]^{-1}(\widehat{\mathbf{V}}^{(d-1)})^H\mathbf{Y}\right]\right\}.$$
3) Repeat Step 2 until $(\widehat{\mathbf{B}}^{(d)}, \widehat{\mathbf{V}}^{(d)}) = (\widehat{\mathbf{B}}^{(d-1)}, \widehat{\mathbf{V}}^{(d-1)})$.

After obtaining an estimated (energy inclusive) channel processed signature set $\widehat{\mathbf{V}}$, we develop another procedure to extract the individual primary binary signatures $\mathbf{s}_i$, $i = 1, \ldots, K$, by decomposition of $\widehat{\mathbf{V}}$. The channel processed signatures can be rewritten as

$$\mathbf{v}_i = \sqrt{E_i}\mathbf{S}_i\mathbf{h},\ i = 1, \ldots, K, \tag{16}$$

where $\mathbf{h} = [h_1, \ldots, h_M]^T$ and

$$\mathbf{S}_i \triangleq \begin{bmatrix} s_i(1) & & \mathbf{0} \\ & \ddots & \\ \vdots & & s_i(1) \\ s_i(L) & & \vdots \\ & \ddots & \\ \mathbf{0} & & s_i(L) \end{bmatrix}_{LM \times M} . \tag{17}$$

If the binary signatures $\mathbf{s}_i$, $i = 1, \ldots, K$, were known, by (16) we could estimate $\sqrt{E_i}\mathbf{h}$ as

$$\widehat{\sqrt{E_i}\mathbf{h}} = (\mathbf{S}_i^T\mathbf{S}_i)^{-1}\mathbf{S}_i^T\widehat{\mathbf{v}}_i,\ i = 1, \ldots, K, \tag{18}$$

where $\widehat{\mathbf{v}}_i$ is the ith column of matrix $\widehat{\mathbf{V}}$. Then, a quality estimate of $\mathbf{h}$ (scaled) could be produced by averaging,

$$\widehat{\mathbf{h}} = \frac{1}{K}\sum_{i=1}^{K}\widehat{\sqrt{E_i}\mathbf{h}}, \tag{19}$$

to create a matrix channel estimate $\widehat{\mathbf{H}}$ by (2). Given $\widehat{\mathbf{H}}$ (and $\widehat{\mathbf{v}}_i$), one could detect the binary signatures can be detected by

$$\widehat{\mathbf{s}}_i = \frac{1}{\sqrt{L}}\mathrm{sgn}\left\{\mathfrak{Re}\{(\widehat{\mathbf{H}}^H\widehat{\mathbf{H}})^{-1}\widehat{\mathbf{H}}^H\widehat{\mathbf{v}}_i\}\right\}, i = 1, \ldots, K. \tag{20}$$

The proposed individual binary signature extraction algorithm from $\widehat{\mathbf{V}}$ is now ready. Initialize $\mathbf{s}_i \in \frac{1}{\sqrt{L}}\{\pm 1\}^L$, $i = 1, \ldots, K$, arbitrarily, and alternate computation between (18), (19), and (20), iteratively. Stop when convergence is observed[2].

To illustrate briefly the proposed primary binary signature detection algorithm, we consider a primary downlink CDMA system with $K = 4$ or $K = 8$ active users that utilize Gold signatures with length $L = 31$. The primary users' signals are transmitted with equal power over a multipath Rayleigh fading channel with $M = 3$ resolvable paths in the presence of additive white Gaussian noise. SR is able to collect $N = 256, 384$, or 512 observation samples and employs our proposed method to extract the primary users' binary signatures. The experiment is repeated 10^5 times with randomly drawn channel coefficients. In Fig. 2, we plot the probability of correct identification of all binary signatures, $\Pr(\widehat{\mathbf{s}}_i = \mathbf{s}_i, \forall i = 1, \ldots, K)$, as a function of SNR. It can be seen that even under low/moderate SNR values the proposed method can correctly extract all signatures with sufficient sample support (secondary receiver observation time interval). It is worth pointing out that, experimentally, when errors do occur only one or two signatures have few chip-bit errors only.

[2]The iterative procedure may be re-executed with distinct initialization if convergence cannot be observed after sufficient iterations.

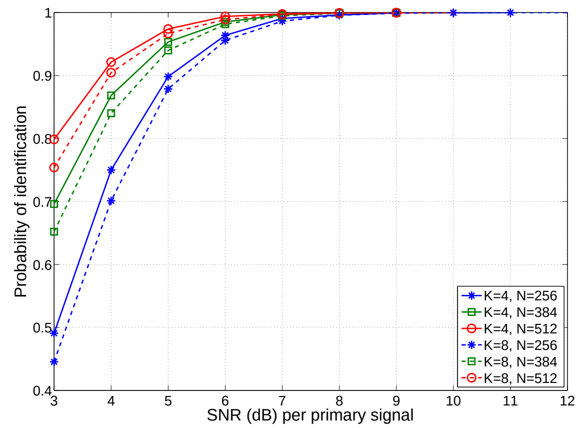

Fig. 2. Performance of blind primary-users identification algorithm: Primary transmitters PT has K downlink users with length $L = 31$ Gold signatures. The transmitted signal propagates over a 3-path Rayleigh fading channel to secondary receiver SR that collects N observation samples to run Table I procedure followed by execution of (18)-(20).

IV. SECONDARY LINK CODE-DIVISION CHANNELIZATION

It is known that the general maximum SINR joint binary signature and power optimization problem under SINR constraints is non-convex NP-hard [12]. We must, therefore, pursue disjoint suboptimal design procedures if we wish to keep the computational complexity manageable. To satisfy that the SINR of the secondary receiver SR at the maximum-SINR linear filter output is no less than the QoS requirement $\gamma > 0$, the power $P > 0$ can be set at

$$P = \frac{\gamma}{\mathbf{c}^T\mathbf{G}^H\mathbf{R}\mathbf{G}\mathbf{c}}. \tag{21}$$

Then, the optimization problem in (11) becomes

$$\begin{aligned} \underset{\mathbf{c}\in\frac{1}{\sqrt{L}}\{\pm 1\}^L}{\text{minimize}}\ \mathcal{I}_{max} &= max\{P \times \mathrm{PTSC}(\mathbf{c}, \mathbf{s}_i), i = 1, \ldots, K\} \\ \text{s. t. }\ P &= \frac{\gamma}{\mathbf{c}^T\mathbf{G}^H\mathbf{R}\mathbf{G}\mathbf{c}}. \end{aligned} \tag{22}$$

The maximum generalized correlation interference $\mathcal{I}_{max}$ is the product of two components, transmit power P and maximum PTSC value. Thus, to minimize $\mathcal{I}_{max}$ we need to design a binary signature $\mathbf{c}$ to minimize the product of the required transmit power $P = \frac{\gamma}{\mathbf{c}^T\mathbf{G}^H\mathbf{R}\mathbf{G}\mathbf{c}}$ times $\underset{i=1,\ldots,K}{max}\{\mathrm{PTSC}(\mathbf{c}, \mathbf{s}_i)\}$. At first, we look at minimizing P *alone*. The binary signature $\mathbf{c}$ that minimizes P maximizes the SR output SINR with unit ST transmit power (denominator of (21)):

$$\mathbf{c} = \arg\max_{\mathbf{c}\in\frac{1}{\sqrt{L}}\{\pm 1\}^L}\mathbf{c}^T\mathbf{A}\mathbf{c} \tag{23}$$

where $\mathbf{A} \triangleq \mathbf{G}^H\mathbf{R}\mathbf{G}$. At this point, the SINR-maximizing binary signature designs of polynomial complexity developed in [22], [23] can be used jointly. We recall that in [22] the binary signature vector is optimized under a rank-2 approximation of the matrix $\mathbf{A}$, while in [23] the arcs of least SINR decrease from the real maximum SINR solution are evaluated. Both algorithms first generate L candidate binary signatures[3], denoted by $\mathbf{q}_j \in \frac{1}{\sqrt{L}}\{\pm 1\}^L$, $j = 1, \ldots, L$, which can provide high output SINR. Then, the signature among them with highest output SINR is selected.

While the highest-SINR signature minimizes the transmitting power required to satisfy any given QoS constraints, it may result to high values of PTSC with respect to primary user signatures and consequently let the secondary link introduce strong interference to the primary system. Therefore, we propose to evaluate next all L binary signatures $\mathbf{q}_j \in \frac{1}{\sqrt{L}}\{\pm 1\}^L$, $j = 1, \ldots, L$ returned by the solver of (23) in [22] or [23] in our interference metric for the ith primary user

$$\mathcal{I}_{j,i} = P_j \times \mathrm{PTSC}(\mathbf{q}_j, \mathbf{s}_i), j = 1, \ldots, L, i = 1, \ldots, K, \quad (24)$$

and find the maximal generalized correlation interference value caused by $\mathbf{q}_j$, $\mathcal{I}_{j,max} = \max\{\mathcal{I}_{j,i}, i = 1, \ldots, K\}$, $j = 1, \ldots, L$. Then, we choose the signature, power pair $(\mathbf{q}_{j^*}, P_{j^*})$ which has the least maximal-interference. If the resulting maximal-interference by $(\mathbf{q}_{j^*}, P_{j^*})$ is introduced to the i^*th primary user, i.e. $\mathcal{I}_{j^*,i^*} = \min\{\mathcal{I}_{j,max}, j = 1, \ldots, L\}$, and still $\mathcal{I}_{j^*,i^*} < \mathcal{I}_{\mathrm{th}}$, the secondary link is allowed to access the channel by assigning signature $\mathbf{c} = \mathbf{q}_{j^*}$ and power $P = P_{j^*}$. We refer to this method of selecting a pair of signature and power from the candidate set as *passive interference suppression* and outline the procedure in Table II.

The secondary link design method in Table II exclusively focuses on transmit power minimization; the PTSC factor is, of course, evaluated and accounted for in (24) but not actively optimized (minimized). To further reduce the maximum interference caused to the primary system and further improve the chances of spectrum sharing, we next propose to iteratively adjust the binary channel signature to actively avoid interference by jointly reducing the PTSC value with the most impacted at each time i^*th primary user's signature $\mathbf{s}_{i^*}$, as well as minimizing the transmit power.

Define $\widetilde{\mathbf{S}}_{i^*} \triangleq \left[\mathbf{s}_{i^*|-M}, \ldots, \mathbf{s}_{i^*|0}, \ldots, \mathbf{s}_{i^*|M}\right]$ and calculate $\mathrm{PTSC}(\mathbf{c}, \mathbf{s}_{i^*}) = \mathbf{c}^T \widetilde{\mathbf{S}}_{i^*} \widetilde{\mathbf{S}}_{i^*}^T \mathbf{c}$. To combine the SINR-optimization problem of (23) with the PTSC suppression task, after executing the procedure in Table II we update $\mathbf{A} = \mathbf{G}^H \mathbf{R} \mathbf{G} - \alpha \widetilde{\mathbf{S}}_{i^*} \widetilde{\mathbf{S}}_{i^*}^T$ where $\alpha > 0$ is an introduced weighting factor. Then, by re-executing the procedure in Table II with the updated $\mathbf{A}$, we obtain a new optimal pair $(\mathbf{q}_{j^*}, P_{j^*})$ and new maximum-interference $\mathcal{I}_{j^*,i^*}$. If the new maximum-interference $\mathcal{I}_{j^*,i^*}$ is reduced, we iteratively update $\mathbf{A} \leftarrow \mathbf{A} - \alpha \widetilde{\mathbf{S}}_{i^*} \widetilde{\mathbf{S}}_{i^*}^T$ and re-execute the algorithm in Table II. This procedure will be stopped when the maximum interference cannot be suppressed further. We outline the procedure in Table III.

TABLE II
SECONDARY LINK SIGNATURE AND POWER DESIGN W/ PASSIVE INTERFERENCE SUPPRESSION

Input $\mathbf{A} := \mathbf{G}^H \mathbf{R} \mathbf{G}$
Obtain $\mathbf{q}_j$, $j = 1, \ldots, L$ as solution candidates for (23) by [22] or [23].
Calculate P_j, $j = 1, \ldots, L$, by (21).
Calculate $\mathcal{I}_{j,i}$, $j = 1, \ldots, L$, $i = 1, \ldots, K$, by (24).
Select j^*, i^* such that $\mathcal{I}_{j^*,i^*} = min\{\mathcal{I}_{j,max}, j = 1, \ldots, L\}$
and $\mathcal{I}_{j,max} = max\{\mathcal{I}_{j,i}, i = 1, \ldots, K\}$.
Output P_{j^*}, $\mathbf{q}_{j^*}$, and $\mathcal{I}_{j^*,i^*}$.
If $\mathcal{I}_{j^*,i^*} < \mathcal{I}_{\mathrm{th}}$,
transmit on channel q_{j^*} with power P_{j^*};
else seize.

TABLE III
SECONDARY LINK SIGNATURE AND POWER DESIGN W/ ACTIVE INTERFERENCE AVOIDANCE

Input $\mathbf{R}$, $\mathbf{G}$, and $\mathbf{s}_i$, $i = 1, \ldots, K$
$d := 0$.
$\mathbf{A} := \mathbf{G}^H \mathbf{R} \mathbf{G}$.
Obtain P_{j^*}, $\mathbf{q}_{j^*}$, and $\mathcal{I}_{j^*,i^*}$ by Table II.
$P^d := P_{j^*}$, $\mathbf{c}^d := \mathbf{q}_{j^*}$, $\mathcal{I}^d_{max} := \mathcal{I}_{j^*,i^*}$.
While $d = 0$ or $\mathcal{I}^d_{max} < \mathcal{I}^{(d-1)}_{max}$
$d := d + 1$;
$\mathbf{A} \leftarrow \mathbf{A} - \alpha \widetilde{\mathbf{S}}_{i^*} \widetilde{\mathbf{S}}_{i^*}^T$;
obtain P_{j^*}, $\mathbf{q}_{j^*}$, and $\mathcal{I}_{j^*,i^*}$ by Table II;
$P^d := P_{j^*}$, $\mathbf{c}^d := \mathbf{q}_{j^*}$, $\mathcal{I}^d_{max} := \mathcal{I}_{j^*,i^*}$.
End
Output $P^{(d-1)}$, $\mathbf{c}^{(d-1)}$, and $\mathcal{I}^{(d-1)}_{max}$.
If $\mathcal{I}^{d-1}_{max} < \mathcal{I}_{\mathrm{th}}$,
transmit on channel $\mathbf{c}^{(d-1)}$ with power $P^{(d-1)}$;
else seize.

V. SIMULATION STUDIES

To illustrate the presented algorithmic developments, we consider a primary multiuser CDMA system with K active users that utilize Gold signatures with length $L = 31$. The primary users' signals are transmitted with equal per-user power $E_1 = E_2 = \ldots = E_K = 10$dB over a multipath Rayleigh fading channel with $M = 3$ resolvable paths in the presence of additive white Gaussian noise. At first, one secondary link attempts to share the spectrum with target receiver filter output SINR $\gamma = 10$dB.

The secondary link code channel and power are optimized by the algorithm in Table II (passive interference suppression) and Table III (active interference avoidance). Specifically, we utilize the rank-2 SINR-maximization binary signature design method [22] and set the weighting factor for the algorithm in Table III to $\alpha = 0.05$. If the resulting maximum generalized correlation interference is less than the threshold $\mathcal{I}_{\mathrm{th}}$, the secondary link is allowed to share the spectrum. The simulation experiment is repeated 10^5 times. With varying primary user population $K = 2, 10, 18$, the probability of coexistence of a secondary link is plotted in Fig. 3 as a function of $\mathcal{I}_{\mathrm{th}}$. While the Table II algorithm behaves -arguably- satisfactorily, it can be observed that the active interference avoidance algorithm of Table III can significantly enhance the opportunity of coexistence of a secondary link. In Fig. 4, we fix the interference threshold at $\mathcal{I}_{\mathrm{th}} = 2, 6$, or 10, and plot the probability of coexistence of a secondary link versus the number of primary users. Similar conclusion can be drawn.

VI. CONCLUSIONS

We considered the general problem of establishing a secondary code-division link alongside a primary code-division multiple-access system. We first developed a novel iterative least square (ILS) based primary-system identification algorithm which can blindly detect the code channels utilized by primary users. Then, we proposed two alternative schemes,

[3] We recall that [23] finds $(LT - T + 1)$ binary sequences that are closest to T arcs of least SINR decrease in the l_2 sense. In this paper, we only consider one slowest descent arc and generate L binary sequences. This is sufficient to closely approximate the performance level reached when all $L - 1$ slowest descent arcs are considered.

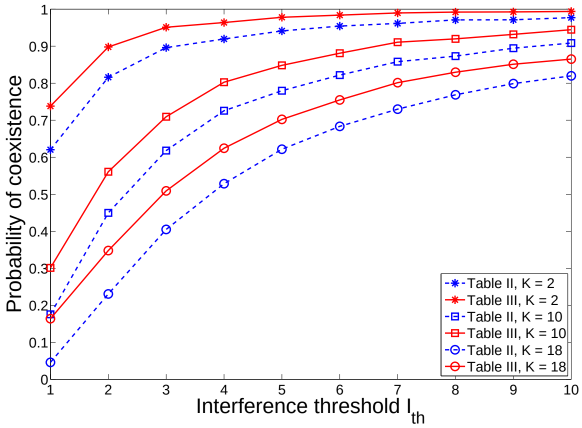

Fig. 3. Probability of coexistence of secondary link versus interference threshold $\mathcal{I}_{\rm th}$.

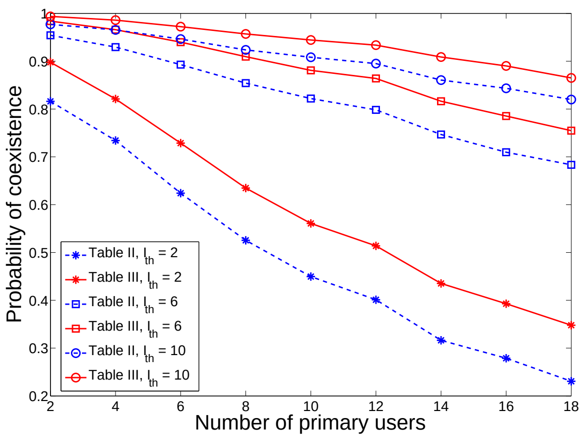

Fig. 4. Probability of coexistence of secondary link versus number of primary users K.

one of low (passive scheme) and one of moderate (active scheme) computational complexity that optimize transmitting power and binary code-channel allocation of the secondary link without causing "harmful" interference to the primary users. At the same time, the signal-to-interference-plus-noise ratio (SINR) of the secondary link at the output of the maximum SINR linear receiver is no less than a certain threshold to meet quality of service (QoS) requirements for the secondary link.

Simulation results demonstrated that the proposed blind identification algorithm can efficiently and effectively detect primary users' code channels and the proposed code-division channelization methods can successfully allow secondary links to opportunistically share the spectrum without causing harmful interference to primary users.

Cognitive code-division radios combine in principle the bandwidth efficiency characteristics of cognitive operation and code-division multiple accessing and are expected to find a place in future communication systems. To that extend, the developments presented in this paper constitute an early contribution that can be helpful in benchmarking future efforts. Since the developed herein coexistence-mode cognitive networks do not require any prior knowledge about the primary networks (such as signatures, transmission energy, channel state information), the secondary networks can be deployed transparently without any modification/upgrade of the existing primary CDMA infrastructure.

REFERENCES

[1] FCC, "US Federal Communications Commission Spectrum Policy Task Force, Report of the Spectrum Efficiency Working Group," Nov. 2002. [Online]. Available: *http://www.fcc.gov/sptf/files/SEWGFinalReport_1.pdf*

[2] FCC, "US Federal Communications Commission Spectrum Policy Task Force, Report of the Unlicensed Devices and Experimental Licenses Working Group," Nov. 2002. [Online]. Available: *http://www.fcc.gov/sptf/files/E&UWGFinalReport.pdf*

[3] J. Mitola and G. Q. Maguire, "Cognitive radio: Making software radios more personal," *IEEE Personal Comm.*, vol. 6, pp. 13-18, 1999.

[4] J. Mitola, *Software Radios: Wireless Architecture for the 21st Century*. New York: Wiley, 2000.

[5] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE Journ. Select. Areas Comm.*, vol. 23, pp. 201-220, Feb. 2005.

[6] J. M. Peha, "Sharing spectrum through spectrum policy reform and cognitive radio," *Proc. of IEEE*, vol. 97, pp. 708-719, Apr. 2009.

[7] G. Ganesan, Y. Li, B. Bing, and S. Li, "Spatiotemporal sensing in cognitive radio networks," *IEEE Journ. Select. Areas Comm.*, vol. 26, pp. 5-12, Jan. 2008.

[8] Z. Quan, S. Cui, A. H. Sayed, and H. V. Poor, "Optimal multiband joint detection for spectrum sensing in cognitive radio networks," *IEEE Trans. Wireless Comm.*, vol. 57, pp. 1128-1140, Mar. 2009.

[9] Y. Xing, C. Mathur, M. A. Haleem, R. Chandramouli, and K. P. Subbalakshmi, "Dynamic spectrum access with QoS and interference temperature constraints," *IEEE Trans. Mobile Comp.*, vol. 6, pp. 423-433, Apr. 2007.

[10] Q. Qu, L. B. Milstein, and D. R. Vaman, "Cognitive radio based multi-user resource allocation in mobile Ad Hoc networks using multi-carrier CDMA modulation," *IEEE Journ. Select. Areas Comm.*, vol. 26, pp. 70-82, Jan. 2008.

[11] M. Kashef, M. Abdallah, A. Elezabi, and M. Khairy, "System parameter selection for asymmetric underlay CDMA networks with interference-minimizing code assignment," in *Proc. IEEE 10th Workshop on Signal Proc. Advances in Wireless Comm.*, Perugia, Italy, Jun. 2009, pp. 722-726.

[12] K. Gao, S. N. Batalama, D. A. Pados, and J. D. Matyjas, "Cognitive code-division channelization," in *Proc. Asilomar Conf. Signals, Syst., and Comp.*, Pacific Grove, CA, Nov. 2009, pp. 672-676.

[13] A. T. Hoang and Y.-C. Liang, "Downlink channel assignment and power control for cognitive radio networks," *IEEE Trans. Wireless Comm.*, vol. 7, pp. 3106-3117, Aug. 2008.

[14] R. Zhang and Y.-C. Liang, "Exploiting multi-antennas for opportunistic spectrum sharing in cognitive radio networks," *IEEE Journ. on Select. Topics in Signal Proc.*, vol. 23, pp. 88-120, Feb. 2008.

[15] R. Zhang, F. Gao, and Y.-C. Liang, "Cognitive beamforming made practical: Effective interference channel and learning-throughput tradeoff," *IEEE Trans. Comm.*, vol. 58, pp. 706-718, Feb. 2010.

[16] O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini, and R. Pickholtz, "Spectrum leasing to cooperating secondary Ad Hoc networks," *IEEE Journ. Select. Areas Comm.*, vol. 26, pp. 203-213, Jan. 2008.

[17] H. Ganapathy and D. A. Pados, "Optimal binary signature sets under cyclic shifts," in *Proc. IEEE Military Comm. Conf. (MILCOM)*, Boston, MA, Oct. 2005, vol. 2, pp. 890-896.

[18] M. Li, S. N. Batalama, and D. A. Pados, "Population size identification for CDMA eavesdropping," in *Proc. IEEE Military Comm. Conf. (MILCOM)*, Orlando, FL, Oct. 2007.

[19] S. Talwar, M. Viberg, and A. Paulraj, "Blind seperation of synchronous co-channel digital signals using an antenna array - part I: Algorithms," *IEEE Trans. Signal Proc.*, vol. 44, pp. 1184-1197, May 1996.

[20] M. Gkizeli, D. A. Pados, S. N. Batalama, and M. J. Medley "Blind iterative recovery of spread-spectrum steganographic messages," in *Proc. IEEE Intern. Conf. on Image Proc. (ICIP)*, Genoa, Italy, Sept. 2005, vol. 2, pp. 1098-1101.

[21] M. Li, S. N. Batalama, D. A. Pados, and J. D. Matyjas, "Multiuser CDMA signal extraction," in *Proc. IEEE Military Comm. Conf. (MILCOM)*, Washington D.C., Oct. 2006.

[22] G. N. Karystinos and D. A. Pados, "Rank-2-optimal adaptive design of binary spreading codes," *IEEE Trans. Inform. Theory*, vol. 53, pp. 3075-3080, Sept. 2007.

[23] L. Wei, S. N. Batalama, D. A. Pados, and B. W. Suter, "Adaptive binary signature design for code-division multiplexing," *IEEE Trans. Wireless Comm.*, vol. 7, pp. 2798-2904, July 2008.