Abstract—In this paper we develop a cellular cognitive radio network based on MC-CDMA, which is able to coexist with a number of legacy RANs in a shared band. Using the simple-to-obtain knowledge of RF environment, namely the bandwidth and frequency location of each legacy system, the cognitive MC-CDMA transmitter mitigates the interference in the corresponding receivers by adaptive transmission. We will develop an algorithm for calculating the adaptive transmission parameters and elaborate on error performance of this approach analytically and numerically.

I. INTRODUCTION

The explosive growth of wireless applications along with the increasing demand for higher data rates imposes a challenge to develop more efficient spectrum utilization schemes. The future wireless systems should be able to efficiently coexist with many other wireless technologies in a heterogeneous environment, including many legacy Radio Access Networks (RAN).

The idea of Cognitive Radio (CR) developed by Mitola [1] is a promising way to tackle this problem. Initial definition of CR provisioned a wide range of capabilities for such autonomous radios, for instance RF environment sensing, model-based reasoning, learning and acting according to this knowledge [1]. However, two major shifts of focal point in the field of CR are currently happening. The first one is a narrower focus on the intelligent spectrum utilization, for example using opportunistic/secondary spectrum access [2]. The other major change is the shift from autonomous CR operation, which makes it more suitable for ad hoc networking scenarios, to cooperative approaches and structured networking architectures, as manifested in IEEE 802.22 standard [3].

An important consideration for CRs to utilize the idle bands is the fact that although at any given time and location it might not be easy to find a big chunk of idle spectrum, e.g., several MHz of bandwidth, it is relatively easier to identify several smaller idle bands. Hence, if the CR can use spectrum aggregation techniques, e.g., by using multi-carrier modulations, an efficient secondary spectrum access can be leveraged. In this paper, we develop a CR design for a wide-band cellular system, based on Direct-Sequence Multi-Carrier CDMA (DS MC-CDMA), so that it would be able to coexist with a number of legacy RANs in a specific band. Depending on the type of the acquired information by the CR, which can be referred to as knowledge level, different transmission strategies can be provisioned. If the interfering signals of legacy transmitters are completely known (from an information theory point of view) methods like dirty paper coding can be a powerful coexistence solution [4]. However, developing practical means of obtaining this level of knowledge might increase the complexity of CR implementation significantly. Here, we assume rather simple-to-obtain information, namely bandwidth and frequency location of the legacy systems, are known by the proposed cognitive MC-CDMA system.

The rest of the paper is organized as follows. In the next section, we introduce the notion of cognitive MC-CDMA system. In section III different aspects of transmission, reception and an algorithm to evaluate necessary parameters are presented. In section IV system performance is investigated and some numerical results are provided in section V. Finally section VI concludes the paper.

II. PROBLEM DEFINITION

To successfully deploy a CR network in heterogeneous wireless environments, two elements are necessary. First, a spectrum monitoring mechanism, which can sense and/or gather information regarding the interfering signals (similar to the “genie” concept in [4]), and then an adaptive transceiver architecture, which can exploit this knowledge. The cognitive information acquisition is out of the scope of this paper. Many spectrum sensing or resource information sharing solutions can be envisioned or might be found in literature and adapted to this problem, e.g., see [5]. We will elaborate on developing the adaptive transceiver design.

There exist two MC-CDMA schemes. One approach is using DS CDMA to spread the data over a series of disjoint carrier frequencies [6], the other method uses OFDM [7] to spread and modulate the data over a number of orthogonal carriers. In this paper, we will propose a solution based on DS MC-CDMA method. In the rest of the paper we use the term MC-CDMA to denote DS MC-CDMA, unless otherwise stated. In our scenario we assume that each legacy system uses fixed operating frequency and bandwidth within the shared band, but they can be randomly (in time/location)
present in the channel. The variation of available signals in the channel happens in a much longer time interval than resource allocation period of the MC-CDMA system. These assumptions are in line with IEEE 802.22 standard [3]. The proposed cognitive MC-CDMA system identifies the legacy systems and tries to mitigate to make interference on them or receive interference from them. Obviously, there is a minimum duration of time \((t_{\text{min}})\) for CR operations, including sensing, evaluating the new transmission parameters, informing the cognitive receivers of the new parameters and adaptively tuning the transmitter/receivers, during which the channel interference pattern is assumed static.

Many adaptive MC-CDMA (and OFDM) based transmitters use sub-band deactivation technique to avoid interfering with the primary system [8]. That is, no energy is transmitted in the sub-band, where the primary signal is detected. However, this approach is not spectrally efficient because the primary signal might have only occupied a small fraction of a sub-band. We propose an approach to both alter the transmission power and bandwidth of sub-bands of MC-CDMA system, so that the transmitted signal is tailored to the channel condition. This method is illustrated in Fig. 1.

III. SYSTEM MODEL

Upon receiving the information of RF environment, the cognitive MC-CDMA BS adaptively changes its transmission parameters, and informs CR users about the changes in impulse modulator, chip wave-shaping filters and RF modulators. In the following, we describe in detail the adaptive procedure of our cognitive MC-CDMA system.

A. Transmitter

The cognitive MC-CDMA transmitter is forming the data to be sent for users, where the total number of active users is assumed to be \(K\). For each sub-band there is a different spreading code for each user (i.e. signature sequence). This is due to variation of sub-band bandwidth and, hence, spreading code length, which makes it impossible to use the same spreading code for a user in all sub-bands. The chips of the signature sequence have the same chip duration \(T_{c,s}\), \(s = 1, 2, \ldots, S\), in each sub-band for all users, where \(S\) is the number of sub-bands. Therefore, in total \(K \times S\) codes per cell are needed. We assume perfect codes with required length exist and hence no discussion regarding code book is presented in this paper.

The spreaded data symbols modulate an impulse train with energy per chip equal to \(E_c\). Chip wave-shaping filter with impulse response \(h_s(t)\) for the \(s^{th}\) sub-band, creates proper pulse shape from modulated impulse train. We assume the waveform \(h_s(t)\) has root raised-cosine shape with rolloff factor of \(\alpha_s\) \((0 \leq \alpha_s \leq 1)\), i.e., \(x_s(t)\) is defined as

\[
x_s(t) = F^{-1}\{|H_s(f)|^2\},
\]

where \(F^{-1}\) means inverse Fourier transform. Then, \(x_s(f) = |H_s(f)|^2\) satisfies the Nyquist criterion. Also we assume \(f^{-\infty} |H_s(f)|^2 df = 1\). As mentioned earlier the bandwidth of each sub-band \((BW_s)\) might be different and will change proportional to the bandwidth and location of interfering signals. Sub-band bandwidth is related to the chip duration and rolloff factor of pulse shape as follows,

\[
BW_s = (1 + \alpha_s) \frac{1}{T_{c,s}}, \quad s = 1, 2, \ldots, S.
\]

The bandwidth of sub-bands should satisfy the constraint \(\sum_{s=1}^{S} BW_s = BW_T\), where \(BW_T\) is the bandwidth of the shared band, which is assumed fixed as shown in Fig. 1. After detection of legacy signals in the band, the cognitive multi-carrier system modifies the bandwidth of the sub-bands, accordingly as shown in Fig. 1. Indexing sub-bands in the ascending order, starting from the lowest frequency and accounting for the location of interfering signals, we denote by the set \(G\), the set of indices of \(M\) sub-bands where interfering signals are located. Then, we can formulate the transmitted signal of cognitive MC-CDMA as

\[
S_{MC}(t) = \sum_{k=1}^{K} \sum_{s=1}^{S} \sum_{n=-\infty}^{+\infty} \sum_{i=1}^{N_s} A_s d_k(n)c_{k,s}(i) \times h_s(t - iT_{c,s}) \cos(\omega_s t + \theta_s),
\]

where \(d_k(n)\) represents the \(n^{th}\) data symbol of the \(k^{th}\) user (using BPSK signaling), \(c_{k,s}(i)\) is the \(i^{th}\) chip of the \(s^{th}\) sub-band’s spreading code (signature sequence), where \(i = 1, 2, \ldots, N_s\). Also, \(N_s\) is the number of chips per symbol and is calculated by

\[
N_s = \frac{T_{\text{symbol}}}{T_{c,s}}, \quad s = 1, 2, \ldots, S \text{ and } s \notin G,
\]

where \(T_{\text{symbol}}\) is symbol duration.

B. Channel Characteristics

A slow-varying, frequency selective Rayleigh fading channel with delay spread of \(T_m\) and coherence bandwidth \((\Delta f)_c\) is assumed. Each band’s chip duration should be greater than the delay spread to achieve minimal ISI distortion i.e., \(T_m \leq \)
bands are fading independently, i.e., $BW_s \geq \langle \Delta f \rangle_c$, $s = 1, 2, \ldots, S$ and $s \notin G$. It is assumed that the sub-bands are fading independently, i.e., $BW_s \geq \langle \Delta f \rangle_c$, $s = 1, 2, \ldots, S$ and $s \notin G$. Therefore, the rolloff factor should satisfy,

$$
\alpha_s \geq \left( \frac{T_{c,s}}{T_m} - 1 \right), \quad s = 1, 2, \ldots, S, \quad \text{and} \quad s \notin G,
$$

(6)

Hence, in order to keep $0 \leq \alpha_s \leq 1$ it is necessary that $T_{c,s} \leq 2T_m$ which results in,

$$
T_m \leq T_{c,s} \leq 2T_m, \quad s = 1, 2, \ldots, S, \quad \text{and} \quad s \notin G.
$$

(7)

With the above assumptions, the lowpass equivalent impulse response of the $s^{th}$ channel seen by the $k^{th}$ user is

$$
e_s(t) = \alpha_{k,s} \exp(j\beta_{k,s}) \delta(t),
$$

where $\alpha_{k,s}$ and $\beta_{k,s}$ are, respectively, i.i.d Rayleigh random variables with a unit second order moment and i.i.d uniform random variables over $[0, 2\pi)$.

C. Receiver

The received signal is a combination of MC-CDMA signal, legacy interfering signals plus AWGN with a double-sided psd of $\frac{N_0}{2}$. The receiver uses a bank of band-pass filters matched to the corresponding wave-shaping filter in the transmitter. This means that the receiver should be able to vary the pass-band size and center frequency of each sub-band filter according to the changes in the transmitter. The required adjustable filters for both the transmitter and the receiver should have a steep cut-off. Novel solutions for practical implementation of such adaptive and adjustable filters have been vigorously studied, for example using RF-MEMS [9]. Another solution to avoid interference due to practical filtering limitations is to consider guard-bands between the legacy signals and the cognitive MC-CDMA sub-bands, which is not considered here. Also, we assume that the receiver obtains the information of center frequency and bandwidth of sub-bands through signaling channels from the transmitter, accurately and instantly. The output of band-pass filter for the $s^{th}$ sub-band ($s \notin G$) can be written as

$$
y_s(t) = \sum_{k=1}^{K} \sum_{n=-\infty}^{\infty} \sum_{i=1}^{N_s} \{\sqrt{2TE_cA_s} \alpha_{k,s} d_k(n) \delta_{k,s}(i)} \times \tilde{x}_s(t - iT_{c,s} - \tau_k) \cos(\omega_s t + \theta_{k,s}) \} + BP\{\tilde{n}_w(t)\},
$$

(8)

where $BP\{\cdot\}$ stands for band-pass filtering operation, $\tilde{x}_s(t)$ is defined in (1), $\tilde{n}_w(t)$ is AWGN and $\theta_{k,s} = \theta_s + \beta_{k,s}$ is the received phase. As (8) shows the legacy interfering signals have been removed at the output of the band-pass filter in the receiver.

D. Parameter Calculation

Since the cognitive transmitter saves a portion of its transmission power by avoiding interference zones, we should propose an algorithm for distributing the excess power in non-interfered sub-bands. The maximum transmission power of the cognitive MC-CDMA system, i.e., $P_{total}$, is usually limited by requirements of standards or regulations. Hence, $\frac{P_{symbol}}{T_{symbol}} \leq P_{Total}$ should be satisfied, where $E_b$ is the energy symbol. Usually in non-adaptive transmissions, the given $E_b$ is uniformly distributed amongst all sub-bands. If before modifications due to legacy interfering signals, the spectrum partitioning has $S'$ sub-bands, then each sub-band’s energy should be $\frac{E_b}{S'}$. Hence, the relation $\sum_{s'=1}^{S'} (\frac{A_s^2}{2}E_cN_{s'}) = E_b$ must hold, where $A_{s'}$ is the initial sub-band amplitude. For such conventional MC-CDMA, in which all the sub-bands have the same bandwidth, $A_{s'} = A$ and $N_{s'} = N$, we can calculate energy per chip as

$$
E_c = \frac{2E_b}{A^2 \times N \times S'}.
$$

(9)

After sub-band adaptation to avoid legacy signals, keeping energy per chip as (9), we should have

$$
\sum_{s'=1}^{S'} (\frac{A_{s'}^2}{2}E_cN_{s'}) \leq P_{Total}.
$$

Therefore, we can derive the amplitude of sub-bands by

$$
A_s = \sqrt{\frac{2T_{symbol} \times P_{Total}}{E_cN_{s}(S-M)}}, \quad s = 1, 2, \ldots, S, \quad \text{and} \quad s \notin G.
$$

Assuming the legacy transmitters in the channel will vary much slower than resource allocation period of the cognitive MC-CDMA (e.g., TV signals in IEEE 802.22 case follow a similar pattern), the BS can perform Transmit Power Control...
techniques to adjust the power level of each user based on its channel condition. Using the flowchart shown in Fig. 2 and the parameters evaluated above, the cognitive MC-CDMA transmission is possible.

IV. SYSTEM PERFORMANCE

We now focus on the performance analysis of the proposed system assuming single user detection with Maximum Ratio Combining (MRC) at the receivers. Without any loss of generality we assume the receiver belongs to the first user (\( k = 1 \)) and \( \tau_1 = 0 \). Multiplying (8) by \( \sqrt{2} \cos(\omega_s t + \theta'_s) \), lowpass filtering and sampling, we can formulate the resulting discrete-time signal at the output of the correlator for the \( s^{th} \) branch, where \( s \notin G \), as \( Z_s = S_{Z_s} + I_{Z_s} + N_{Z_s} \), where

\[
S_{Z_s} = \sum_{n=-\infty}^{\infty} \sum_{i=1}^{N_s} \sqrt{E_c} A_s c_{1,s}(i) d_1(n) \times c_{1,s}(i') x_s((i - i') T_{c,s}),
\]

\[
I_{Z_s} = \sum_{k=2}^{\infty} \sum_{n=-\infty}^{\infty} \sum_{i=1}^{N_s} \sqrt{E_c} A_s c_{1,s}(i) d_k(n) \times c_{k,s}(i) c_{1,s}(i') x_s((i - i') T_{c,s} - \tau_k),
\]

and

\[
N_{Z_s} = \sum_{i'=1}^{N_s} c_{1,s}(i') [L P\{N_{y,1}(t) \sqrt{2} \cos(\omega_s t + \theta'_s)\}]_{i'=i'} T_{c,s}.
\]

Also \( \xi_{k,s} = \alpha_{k,s} \cos(\theta'_s - \theta'_s) \) and the operator \( L P\{\} \) denotes low-pass filtering. The output of the correlators, after multiplication by their corresponding branch gain (\( g_{1,s} \)), are summed. The branch (equalization) gain for MRC is equal to fading amplitude of channel \( g_{1,s} = \alpha_{1,s} \) for \( s = 1, 2, \ldots, S \) and \( s \notin G \) [6]. For slow varying fading channel \( \alpha_{1,s} \) can be estimated with sufficiently high accuracy.

To analyze the performance, the SNR at the output of MRC should be used, which is given by [10],

\[
SNR_z = \frac{[E(Z | a'_1)]^2}{2 Var(Z | a'_1)},
\]

where \( a'_1 \) is the vector of fading amplitudes. Considering randomness and orthogonality of signature sequences, we assume \( [d_k(n)c_{k,s}(i), k = 2, 3, \ldots, K; i = 1, 2, \ldots, N_s, s = 2, 3, \ldots, S; s \notin G] \) are independent random binary sequences. On the other hand, signature code for the first user is deterministic (since this is the first user’s receiver) and, therefore, nominator of (10) can be evaluated as,

\[
E(Z | a'_1) = \sqrt{E_c} \sum_{s=1}^{S} \sum_{n=1}^{N_s} (\pm N_s A_s c_{1,s}).
\]

To calculate the conditional variance in (11) we can write

\[
Var(Z \mid \alpha_{1,s}) \equiv \sigma^2_s = Var(S_{Z_s} \mid \alpha_{1,s}) + Var(I_{Z_s} \mid \alpha_{1,s}) + Var(N_{Z_s} \mid \alpha_{1,s}).
\]

It is clear that \( Var(S_{Z_s} \mid \alpha_{1,s}) = 0 \). Also, we can write

\[
Var\{N_{Z_s} \mid \alpha_{1,s}\} = Var\{N_{Z_s}\} = \sum_{i=1}^{N_s} \sum_{i'=1}^{N_s} c_{1,s}(i)c_{1,s}(i') \times R_{N_{y,s}}((i - i') T_{c,s}) = \frac{N_s^2 \sigma_{N_{y,s}}}{2},
\]

where \( R_{N_{y,s}} \) is the auto-correlation function of \( I_{y,s} \). Therefore, the Signal-to-Noise Ratio (SNR) is

\[
SNR_z = \frac{E_c \sum_{s=1}^{S} A_s^2 \sum_{s' \in G} \sigma^2_{z,s} + \sum_{s=1}^{S} \sigma^2_{\alpha_{1,s}}}{2 \sum_{s=1}^{S} \sigma^2_{z,s} + \sum_{s \notin G} \sigma^2_{\alpha_{1,s}}} = \frac{E_c}{2} \sum_{s=1}^{S} \sigma^2_{\alpha_{1,s}},
\]

where \( \sigma^2_{\alpha_{1,s}} = \sum_{s' \in G} \sigma^2_{z,s} + \sigma^2_{\alpha_{1,s}} \) and \( \sigma^2_{z,s} = \sigma^2_{\alpha_{1,s}} \). For the large number of users, MAI can be assumed to have Gaussian probability density function (pdf), based on the central limit theorem [10]. Hence, we can evaluate the probability of bit error as, [10],

\[
P_b = Q(\sqrt{2 \gamma_b})
\]

where \( \gamma_b = SNR_z \) is the SNR per bit. Since \( P_b \) is a function of \( \gamma_b \), a better insight to the performance of system can be achieved by computing average probability of error \( P_e \) from

\[
P_e = \int_0^{\infty} P_b(\gamma_b) f_{\gamma_b}(\gamma_b) d\gamma_b,
\]

where \( f_{\gamma_b}(\gamma_b) \) is the pdf of \( \gamma_b \). Given the channel fading coefficients \( \alpha_{1,s} \) have Rayleigh distribution, \( q_s / \)has exponential distribution, i.e.,

\[
f_{q_s}(q_s) = c^2_s \exp(-c^2_s q_s).
\]

The moment generation function of \( \gamma_b \) is multiplication of moment generation functions of \( q_s \), hence, its pdf can be formulated as

\[
f_{\gamma_b}(\gamma_b) = F^{-1}\{ \prod_{s=1}^{S} \frac{c^2_s}{c^2_s - \gamma} \}.
\]

Using partial fraction expansion, we can calculate (13) as

\[
f_{\gamma_b}(\gamma_b) = F^{-1}\{ \sum_{s=1}^{S} \frac{B_s}{c^2_s - \gamma} \} = \sum_{s=1}^{S} B_s e^{-c^2_s \gamma_b},
\]

where \( B_s = \prod_{s' \in G} \frac{c^2_{s'}}{c^2_{s'} - c^2_s}, s = 1, 2, \ldots, S \) and \( s \notin G \). Then, noting that chernoff bound for \( P_b \) given by \( Q(\sqrt{2 \gamma_b}) \leq e^{-\gamma_b} \), we can calculate an upper bound for \( P_e \) as,

\[
P_e \leq \int_0^{\infty} (e^{-\gamma_b}) \left( \sum_{s=1}^{S} A_s e^{-c^2_s \gamma_b} \right) d\gamma_b
\]

\[
= \sum_{s=1}^{S} e^{-(1+c^2_s \gamma_b)} d\gamma_b = \sum_{s=1}^{S} \frac{B_s}{1+c^2_s \gamma_b}.
\]

V. NUMERICAL RESULTS

In this section a simulation analysis of the performance of the proposed cognitive MC-CDMA system is presented. We assume a total of 5 MHz bandwidth is available for cognitive MC-CDMA operation. Channel delay spread (\( T_m \)) equals 1 \( \mu \)sec and the total transmit power is 50 mW. Spreading factor for a 1 MHz channel is 32. We have assumed a legacy
system with bandwidth of 1 MHz is operating in the band co-located with the second sub-band of MC-CDMA system. It is assumed that the legacy signals, i.e., interference for the cognitive MC-CDMA system, have a flat power spectral density in its bandwidth, where its psd (denoted by “inter” in Fig. 3) is increased from $10^{-6}$ to $10^{-4}$. In these simulations, 15 active users are involved. As the simulation results in Fig. 3 shows, the bit error performance of conventional MC-CDMA deteriorates severely as the power of the narrow-band interferer increases compared with cognitive MC-CDMA. In low SNR region and low interference powers, the performance of both cognitive and non-cognitive methods is comparable since the dominant factor is the noise rather than the interference. The effect of the number of users on the performance of cognitive MC-CDMA method, with a single interfering band, is shown in Fig. 4 with similar assumption as scenario of Fig. 3. Clearly the performance degrades as the number of users increases both for cognitive and conventional operations. This is due to MAI interference. Finally, we investigate the effect of maximum transmission power, as shown in Fig. 5, with similar assumptions as Fig. 3. Here, the maximum power is varied from 50 to 200 and 500 mW, while the interference level is fixed at $10^{-6}$. The performance improvement, as a result of increasing the maximum transmission power of the system, is not very significant. This is due to the fact that the interfering effect of the other active users also increases and, hence, limits the overall performance in the system.

VI. CONCLUSIONS

As the need for more efficient utilization of spectrum increases, more dynamic solutions must emerge to fulfill the demands. In this paper, we investigated the benefits of exploiting CR in downlink transmission of a MC-CDMA based cellular system. We derived an algorithm for such a cognitive environment and analyzed the system performance in terms of probability of error. Examining the system performance under different circumstances, we showed that the cognitive MC-CDMA can effectively coexist with a number of legacy systems in a shared band.

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