Underlay Cognitive Radio Wireless Networks using Repetition Coding and Spread Spectrum

Saed Daoud, David Haccoun, and Christian Cardinal

Department of Electrical Engineering
École Polytechnique de Montréal
Montréal, QC, Canada
Email: saed.daoud@polymtl.ca, david.haccoun@polymtl.ca, christian.cardinal@polymtl.ca

***Abstract*—In this paper, we investigate the use of repetition coding (RC) in conjunction with code division multiple access (CDMA) spread spectrum (SS), as a means to spread the signal power of a secondary (cognitive) underlay system, operating at the same time and on the same frequency band with a primary system. First, we consider single user (SU) systems, where we find the bit error rate (BER) at the secondary receiver (SR), satisfying a given quality of service (QoS) requirement for the primary system. Then, we find the maximum coding rate required to satisfy the QoS of both systems. Also, we investigate the combination of RC and SS in multiuser (MU) systems, where SS is used as a means to separate the signals from each others. Simulation results show that, using RC with low coding rate, can maintain the interference level at the primary receiver (PR) below the maximum allowed level, while, at the same time, improving the BER performance of the secondary system. Furthermore, the largest coding rate required to satisfy both systems' QoS grows fast, as the transmit power of the primary system gets larger than the minimum value for the secondary system to operate. Finally, it is shown that, in some cases, dividing the bandwidth between RC and SS is a better option than allocating the whole bandwidth to SS only.**

Keywords–Bit error rate, cognitive radio, repetition coding, quality of service, spread spectrum.

I. Introduction

Future wireless communication systems will require ever increased data rate (or equivalently, bandwidth), required by the demanding multimedia applications. This is challenging as most of the electromagnetic (EM) spectrum is licensed to primary users. However, close investigations reveal that, the EM spectrum can be utilized more efficiently, by making the transmissions' parameters adaptable to the surrounding environment, as well as to the users' demands [1]–[4].

These findings have triggered huge research activities on developing techniques on how to access the spectrum more efficiently, resulting in the so-called *dynamic spectrum access* (DSA) techniques. In the literature, two models of DSA are mainly studied: interweave and underlay models [5]. In the interweave model, a cognitive secondary unlicensed system uses only the white spaces, i.e., the portions of the spectrum that are not currently utilized by the primary system, to whom the spectrum is licensed, and hence has priority in using it. This model, however, involves detection and tracking of the white spaces, which are complex to implement, and could lead to false detection. As a consequence, the quality of service (QoS) of the primary system is sometimes jeopardized, or white spaces can be gone unused by ready-to transmit secondary users. Furthermore, the required white spaces are not guaranteed to be found at the time a secondary system is ready to transmit. On the other hand, in underlay model, which is our focus, there are no temporal or spatial constraints, but there are interference power constraints imposed by the primary users, which has to be maintained below a given noise floor, in order to maintain a given QoS. These interference constraints can be met in one of two ways: using beamforming in multiple antenna systems by focusing the signal power toward the secondary receivers, and away from the primary receivers, or spreading the signal power over large bandwidth, to decrease the interference level within the primary users' bandwidth of interest [5].

In this paper, our focus is on the underlay model, where we investigate the usage of repetition codes (RC) as a means to spread the signal power, with possibly spread spectrum (SS) techniques for multiuser systems, i.e., code division multiple access (CDMA) [6]. In particular, we consider a secondary system operating at the same time and on the same frequency band with a primary system. First, we consider single user (SU) systems, and we set a QoS limit on the primary system in terms of the largest bit error rate (BER) allowed at the primary receiver (PR), and derive the BER performance at the secondary receiver (SR) for different coding rates. Then, we set a QoS requirement at the secondary system in terms of the maximum BER tolerable at the SR for a satisfying service, and find the maximum coding rate required to satisfy the QoS of both systems. We then consider multiuser (MU) systems, where the primary system uses orthogonal spreading codes such as Walsh-Hadamard (WH) codes [7], where the cross-correlation between the spreading codes is zero, as a means to spread and separate the primary signals, while the secondary system uses a combination of RC and WH codes to spread and distinguish the secondary signals. Simulation results show that RC with low coding rate can be used as a simple means to spread the signal power to satisfy the QoS of both the primary and secondary systems. Furthermore, in MU systems, it is shown that, in some cases, dividing the total available bandwidth between RC and SS is a better option in terms of BER at SRs than allocating the whole available bandwidth to SS only.

To the best of the authors' knowledge, the above proposed systems haven't been considered in the literature. The rest of the paper is organized as follows: In Section II, the system and channel model are presented, in Section III, the performances of SU and MU systems are investigated, in Section IV, simulation results are presented and discussed, and finally in Section V, a conclusion is provided.

II. System Model

A. SU Systems

First, we consider a secondary (cognitive) system consisting of one secondary transmitter (ST) and one SR, which operates at the same time and over the same frequency band as a primary system consisting of one primary transmitter (PT) and one PR. All channels are assumed to be additive white Gaussian noise (AWGN) channels, where the additive noise at the front-end receivers is assumed to have a single-sided power spectral density (PSD) N_0 Watts/Hz, and both systems use binary phase shift keying (BPSK) modulation with the same bit rate R_b bits/sesond, and thus both systems have the same baseband bandwidth, $W = R_b$ Hz, where rectangular pulse shaping is assumed, and null-to-null bandwidth is considered. Both systems are assumed to be synchronous. The power received at the front-end receivers is noted to be P from the PT and S from the ST. The QoS of the primary system is protected by setting a maximum BER value τ_p allowable at the PR. This implies that the minimum data bit energy-to-interference-plus-noise PSD allowed at the PR, denoted by $\eta_{p,\min}$, is given by [8]

$$\eta_{p,\min} = \frac{Q^{-1}(\tau_p)^2}{2}, \tag{1}$$

where $Q(.)$ is the Q-function given by $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-u^2/2}\, du$, and $Q^{-1}(.)$ is its inverse. From (1), it is implied that the interference is approximated as a white Gaussian random process. The secondary system uses a RC scheme with coding rate $R_c = 1/N$, as a means to spread its signal power over a wider bandwidth. At the SR, the majority logic detection is used for decoding, where a bit is declared $1(0)$, if the majority of decoded bits are 1s(0s). The secondary system might have its own QoS requirement in terms of maximum allowable BER at the SR, denoted by τ_s.

B. MU Systems

In multiuser systems, we consider a secondary system with N_s transmitter-receiver (Tx-Rx) pairs operating simultaneously with a primary system with N_p Tx-Rx pairs, where all transmissions are assumed to be synchronous at both the bit and chip levels. WH codes are used in both systems as a means to spread and separate the signals from different transmitters in a given system. It is assumed that the primary signals are spread over the entire available bandwidth, with a spreading factor (SF) G_p. For the secondary system, first a RC with coding rate $R_c = 1/M_s$ is used, and then each coded bit is spread by a SF Q_s, where $Q_s = G_p/M_s$, such that the signal after coding and SS occupies the total available bandwidth, i.e., $M_s Q_s = G_p$. The above description implies that, each user, whether in the primary or secondary system, has a transmission rate of $G_p R_b$ chips/second at the channel input, where R_b is the information bit rate measured in bits/second. Since WH code matrices are squared matrices with dimensions of power 2, and for mathematical convenience, we assume that the parameters G_p, N_p, and M_s are also variables of power 2, i.e., $G_p = 2^{g_p}$, $N_p = 2^{n_p}$, and $M_s = 2^{m_s}$, where g_p, n_p, and m_s are all non-negative integers. Also, it is assumed implicitly that $N_p \leq G_p$ and $N_s \leq Q_s$. Finally, all receivers are assumed to receive a power P from all PTs, and power S from all STs. The other parameters are the same as in SU systems.

III. Performance Analysis

A. SU Systems

Let that the PSD of the primary signal be denoted J_p, and that of the secondary signal J_s. Then we have $P = J_p W$ and $S = J_s W$. In SU case, since RC coding with coding rate $R_c = 1/N$ is used, the secondary signal is spread by a factor N, i.e., the bandwidth and PSD after coding are given by NW and J_s/N, respectively. Thus, the signal-to-interference-plus-noise ratio (SINR) at the PR is given by

$$\frac{J_p W}{\frac{J_s}{N} \times W + N_0 W} = \frac{P}{\frac{S}{N} + N_0\, W}, \tag{2}$$

where $N_0 W$ is the noise power within the primary signal's bandwidth, and the corresponding data bit energy-to-interference-plus-noise PSD is given by [9]

$$\eta_p = \frac{\gamma_p}{\frac{\gamma_s}{N} + 1}, \tag{3}$$

where $\gamma_p = (E_b)_p/N_0$ and $\gamma_s = (E_b)_s/N_0$ are the interference-free signal-to-noise ratio (SNR) at PR and SR, respectively, where $(E_b)_p = P/W$ and $(E_b)_s = S/W$. To satisfy the QoS requirement of the primary system, we need

$$\eta_p = \frac{\gamma_p}{\frac{\gamma_s}{N} + 1} \geq \eta_{p,\min}, \tag{4}$$

which results in

$$\frac{\gamma_s}{N} \leq \frac{\gamma_p}{\eta_{p,\min}} - 1. \tag{5}$$

At the input of the SR, and following the same logic as done above for the PR, the SINR can be found to be

$$\frac{S}{P + N_0 N W}, \tag{6}$$

and the corresponding coded bit energy-to-interference-plus-noise PSD is given by

$$\eta_{s,c} = \frac{\gamma_s/N}{\frac{\gamma_p}{N} + 1}. \tag{7}$$

For the majority logic detector at the SR, the BER is given by

$$\mathtt{BER}_s = \sum_{k=L}^{N} \binom{N}{k} \mathtt{BER}_{s,c}^k \left(1 - \mathtt{BER}_{s,c}\right)^{N-k}, \tag{8}$$

where $L = \lfloor N/2 \rfloor + 1$, and

$$\mathtt{BER}_{s,c} = Q\left[\sqrt{2\,\eta_{s,c}}\,\right], \tag{9}$$

is the BER per coded bit.

If the secondary system also has a QoS requirement, then we aim to find the largest coding rate, or equivalently, the smallest value of N that is required to satisfy the QoS of both systems. Toward that end, the BER at the SR needs to be simplified as a function of N. It can be upper bounded, for $\mathtt{BER}_{s,c} \ll 1$, by [10]

$$\mathtt{BER}_s \leq \left[2\sqrt{\mathtt{BER}_{s,c}}\,\right]^N \leq 2^{N/2} \exp\left(-\frac{N}{2}\eta_{s,c}\right), \tag{10}$$

where the second inequality is due to the Chernoff upper bound of the Q-function: $Q(x) \leq \frac{1}{2}\exp\left(-\frac{x^2}{2}\right)$. To make sure that $\texttt{BER}_s$ is less than a predefined maximum BER τ_s, we need to satisfy the following inequality

$$2^{N/2}\exp\left(-\frac{N}{2}\eta_{s,c}\right) \leq \tau_s, \tag{11}$$

or equivalently

$$\frac{N}{2}\ln 2 - \frac{\gamma_s}{2\left[\frac{\gamma_p}{N}+1\right]} \leq \ln\tau_s, \tag{12}$$

where $\ln(.)$ is the natural logarithm. Solving (12) for γ_s yields

$$\gamma_s \geq 2\left[\frac{\gamma_p}{N}+1\right]\left[\frac{N}{2}\ln 2 - \ln\tau_s\right]. \tag{13}$$

Combining (5) and (13) results in

$$2\left[\frac{\gamma_p}{N}+1\right]\left[\frac{N}{2}\ln 2 - \ln\tau_s\right] \leq \gamma_s \leq N\left[\frac{\gamma_p}{\eta_{p,\min}}-1\right]. \tag{14}$$

Since

$$2\left[\frac{\gamma_p}{N}+1\right]\left[\frac{N}{2}\ln 2 - \ln\tau_s\right] \leq N\left[\frac{\gamma_p}{\eta_{p,\min}}-1\right], \tag{15}$$

and assuming that $N \geq 1$, we can solve (15) for N, which yields the following quadratic function

$$N^2\underbrace{\left[\frac{\gamma_p}{\eta_{p,\min}}-1-\ln 2\right]}_{A} + N\underbrace{\left[2\ln\tau_s - \gamma_p\ln 2\right]}_{B} + \underbrace{2\gamma_p\ln\tau_s}_{C} \geq 0. \tag{16}$$

Using the general quadratic solution formula, N can be found to be

$$N \geq \frac{-B \pm \sqrt{B^2-4AC}}{2A}, \tag{17}$$

and thus, denoting the minimum *real* value in the right hand side of (17) that is grater than or equal to 1 by $N_{\min}$, the maximum RC coding rate that satisfies the QoS of both the primary and secondary systems is given by $R_{c,\max} = 1/N_{\min}$.

B. MU Systems

In MU systems, it can be shown that the SINR at each PR is given by [11]

$$\frac{P}{N_s\,S + \sigma^2_{n,p}}, \tag{18}$$

where $\sigma^2_{n,p} = N_0 G_p W$ is total noise power at the front-end of the PR. Then, the bit-energy-to-interference-plus-noise PSD at each PR after despreading is given by [11]

$$\eta_p = \frac{\gamma_p}{\frac{N_s}{G_p}\gamma_s + 1}. \tag{19}$$

Hence, we need that

$$\eta_p = \frac{\gamma_p}{\frac{N_s}{G_p}\gamma_s + 1} \geq \eta_{p,\min}, \tag{20}$$

to satisfy the QoS of the primary system, which, when solved for γ_s, yields

$$\gamma_s \leq \frac{G_p}{N_s}\left[\frac{\gamma_p}{\eta_{p,\min}}-1\right]. \tag{21}$$

In (21), we have found the maximum allowable power that each SR can receive from the corresponding STs, which will be used next to evaluate the BER at each secondary receiver for different values of M_s, and N_s. Using the majority logic detection for $(M_s,\,1)$ RC, the BER at each SR is given by

$$\texttt{BER}_{s,\text{RCSS}} = \sum_{k=\lfloor\frac{M_s}{2}\rfloor+1}^{M_s}\binom{M_s}{k}\varepsilon^k_{s,\text{RC}}\left(1-\varepsilon_{s,\text{RC}}\right)^{M_s-k}, \tag{22}$$

where $\varepsilon_{s,\text{RC}}$ is the BER per coded bit, which is given by [8]

$$\varepsilon_{s,\text{RC}} = Q\left[\sqrt{2\eta_{s,\text{RC}}}\right], \tag{23}$$

where $\eta_{s,\text{RC}}$ is the secondary system's coded bit energy to interference-plus-noise PSD, and can be shown to be [9]

$$\eta_{s,\text{RC}} = \frac{\gamma_s/M_s}{\frac{N_p}{G_p}\gamma_p + 1}. \tag{24}$$

Note that if the secondary users are spread the same way as the primary users, i.e., if $N_s \leq G_p$ secondary users are spread over the entire bandwidth using a WH code matrix of dimension $G_p \times G_p$, then nothing would change for the primary receivers. However, the BER at the secondary receivers will differ, as the BER in this case will be given by

$$\texttt{BER}_{s,\text{SS}} = Q\left[\sqrt{\frac{2\gamma_s}{\frac{N_p}{G_p}\gamma_p + 1}}\right]. \tag{25}$$

In next section, we will compare the performance of coded SS (using RC and WH codes), and uncoded SS (when only WH codes are used).

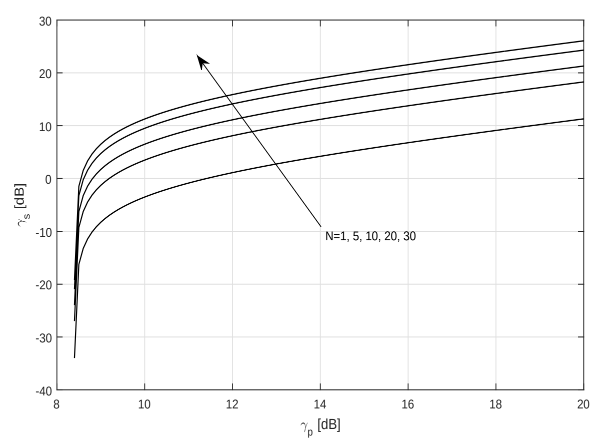

Figure 1. SNR at SR γ_s in dB vs. SNR at PR γ_p in dB for $\tau_p = 10^{-4}$ and $N = 1,\,5,\,10,\,20,\,30$.

IV. SIMULATION RESULTS

In this section we evaluate the analytical results we derived in the previous sections. First we show the results for SU systems, when only the primary system has to meet a QoS requirement, and then when both the primary and secondary systems have to meet their respective QoSs. Then we illustrate the performance of MU systems, and compare coded SS with uncoded SS systems. All simulations were conducted using MATLAB program version R2015a.

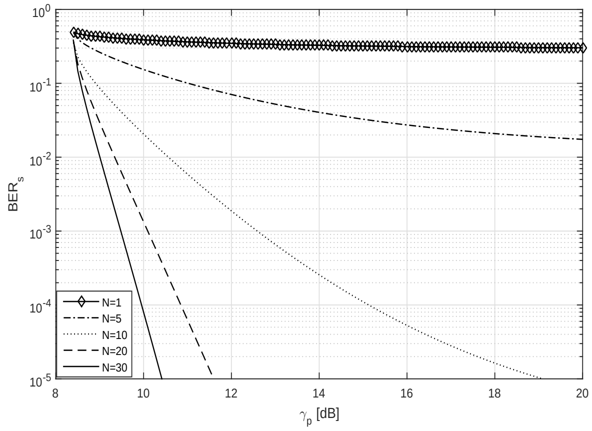

Figure 2. BER at SR $\mathtt{BER}_s$ vs. SNR at PR γ_p in dB for $\tau_p = 10^{-4}$ and $N = 1, 5, 10, 20, 30$.

A. SU Systems

First we consider the following parameters: $\tau_p = 10^{-4}$ and $N = 1, 5, 10, 20, 30$. In Figure 1, the interference-free SNR at the SR, γ_s, in dB vs. the interference-free SNR at the PR, γ_p, in dB is shown. It is shown that as N increases, i.e., the rate decreses, the allowed power from the secondary system increases as well. This is because the interference margin at PR is constant, while at the same time, increasing N decreases the actual interference from the ST. The corresponding BER at the SR, $\mathtt{BER}_s$, vs. the interference-free SNR at the PR, γ_p, in dB is shown in Figure 2, where we can see that, as N increases, the BER decreases for a given value of γ_p. This improvement is attributed to coding gain, where as N increases, each bit is repeated a larger number of times, while the SNR per coded bit, γ_s/N, is kept constant, because of the increased power allowed by the low coding rate, as it is shown in (5).

We now examine the case when both the primary and secondary systems have a QoS requirements, we consider the following parameters: $\tau_p = 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}$ and $\tau_s = 10^{-4}$. In Figure 3, the minimum number of repetitions per bit to satisfy the QoS of both systems $N_{\min}$ in dB vs. the interference-free SNR at the PR γ_p in dB is shown. We can observe two things here: first, as the QoS requirement at the PR becomes more stringent, the secondary system requires higher power from the PT, to create enough interference margin to start operating. Second, when γ_p is high enough for a given τ_p for the secondary system to start operating satisfactory, the coding rate required to satisfy both systems' QoS is very low, i.e., $N_{\min}$ is very large. This is because the interference margin is very low at the PR. However, $N_{\min}$ decays fast as γ_p gets larger than the minimum value required for the secondary system to operate, and then it becomes almost constant at yet higher γ_p. For example, if we want the secondary system to operate immediately at $\gamma_p \simeq 12$ dB for $\tau_p = 10^{-5}$, then we would need $N_{\min}$ as large as 1000. However, $N_{\min} \simeq 100$ at $\gamma_p \simeq 12.5$ dB, and $N_{\min} \simeq 25$ for $\gamma_p \geq 16$ dB. In Figure 4 the corresponding interference-free SNR at the SR normalized by $N_{\min}$, i.e., $\gamma_s/N_{\min}$ in dB is shown versus the interference-free SNR at the PR γ_p in dB, where it is apparent that ST can transmit at higher power for lower QoS requirements at the PR.

It is worth mentioning here that, using RC to spread the secondary system's power, decreases the secondary system bandwidth efficiency, because we transmit the same bit several times. This is the cost the secondary system has to pay, in exchange of accessing the channel, in the presence of a primary system, with QoS constraints on the secondary and/or primary systems. However, RC serves as a very simple coding scheme, where all we have to do, is just to repeat each data bit at the transmitter, and use the majority logic detection principle at the receiver, and thus, *very low* coding rates can be realized with reasonable complexity. More complex low coding rate codes require increased hardware and computational complexities for the encoding and decoding processes, although they may offer better performance.

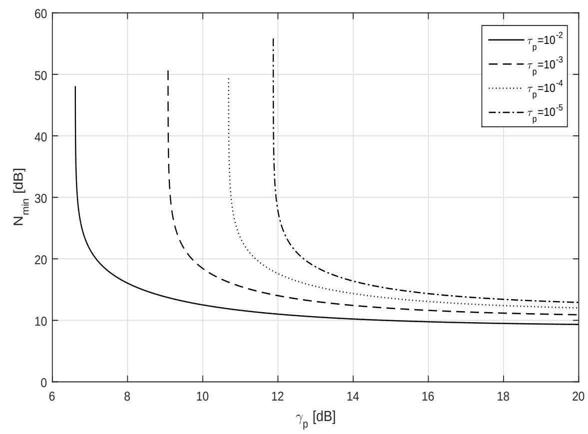

Figure 3. The value $N_{\min}$ in dB vs. SNR at PR γ_p in dB for $\tau_p = 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}$ and $\tau_s = 10^{-4}$.

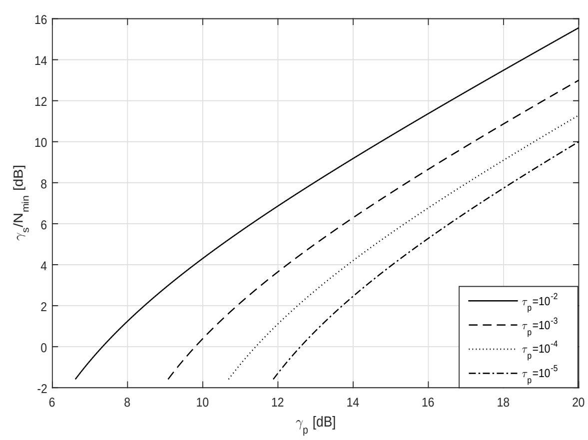

Figure 4. SNR at SR normalized by $N_{\min}$ $\gamma_s/N_{\min}$ in dB vs. SNR at PR γ_p in dB for $\tau_p = 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}$ and $\tau_s = 10^{-4}$.

B. MU Systems

In the MU case, we consider the following parameters for the numerical simulations: the total available bandwidth, normalized by the baseband bandwidth is $G_p = 2^{10} = 1024$, and the number of primary users is $N_p = 2^9 = 512$. The maximum allowable BER at each PR is set to be 10^{-4}.

In Figure 5, the interference-free SNR at each SR γ_s in dB vs. the interference-free SNR at each PR γ_p in dB, is shown for $M_s = 2^1 = 2$ repetitions per bit, and the number of secondary users (SUs) is $N_s = 2^{n_s}$ for $n_s = 4, 5, 6, 7, 9$. We can see that as the number of SUs increases, the allowed transmit power at each ST decreases for a given γ_p. This is natural, since as N_s increases, the interference at each PR increases, and thus to maintain the maximum allowed interference power at each PR, the transmit power at each ST must be decreased. In Figure 6, the coded SS BER $\mathtt{BER}_{s,\mathrm{RCSS}}$ vs. interference-free SNR at each PR in dB, is shown for $N_s = 64$ and $M_s = [1, 2, 4, 8, 16]$. For each value of M_s, a WH matrix of dimensions $Q_s \times Q_s$ is used for SS, where $Q_s = G_p/M_s$. Also shown the case when the whole available bandwidth is allocated to SS only (i.e., no coding is used), where a WH matrix of dimensions 1024×1024 is used. We can see that for $M_s = 2, 4$ coded SS outperforms uncoded SS, significantly so for $M_s = 2$. However, for $M_s = 8, 16$, coded SS has inferior performance compared to uncoded SS. This trend holds true for different values of N_s. The implication from this figure is that, dividing the total available bandwidth between coding and SS, is more beneficial in some cases compared to uncoded SS.

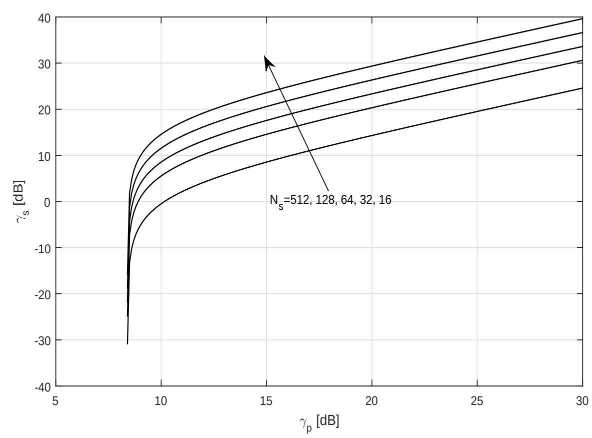

Figure 5. SNR at each SR γ_s in dB vs. SNR at each PR γ_p in dB for $G_p = 1024$, $N_p = 512$, $M_s = 2$, $N_s = [16, 32, 64, 128, 512]$, and maximum BER of $\tau_p = 10^{-4}$.

V. CONCLUSIONS AND FUTURE WORKS

In this paper, we investigated the use of repetition coding, as a means to spread the signal power, possibly in conjunction with other spreading techniques such as spread spectrum, in an underlay cognitive radio system. We considered single user and multiuser systems. In single user systems, we considered two cases: when the primary system only has a QoS requirement, and when both the primary and secondary systems have QoS requirements. In multiuser systems, we incorporated Walsh-Hadamard coding as an a means to distinguish the signals from each others, while deploying repetition coding at each secondary transmitter. Simulation results showed that, in single user systems, repetition codes with low enough coding rate, can decrease the interference level at the primary receiver effectively, only by repeating each data bit, instead of using more complex spreading techniques, while at the same time enhancing the bit error rate at the secondary receiver due to coding gain. In multiuser systems, it is shown that, in some cases, dividing the total bandwidth between coding and spread spectrum, is more beneficial, in terms of bit error rate performance at each secondary receiver, than allocating the total available bandwidth to spread spectrum only. As a future work, convolutional codes will be investigated and compared with RC in terms of performance, as well as complexity requirements.

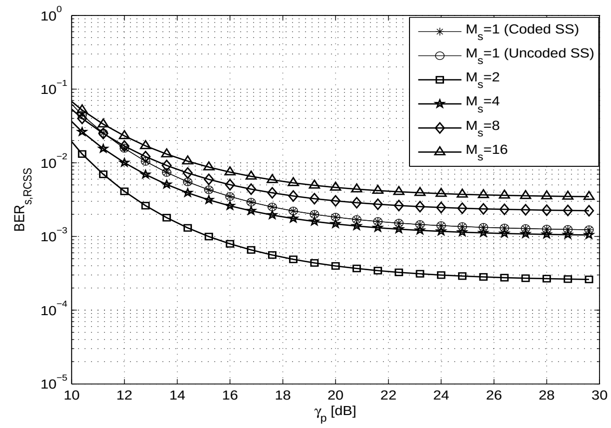

Figure 6. BER at each SR $\mathtt{BER}_{s,\mathrm{RCSS}}$ vs. SNR at each PR γ_p in dB for $G_p = 1024$, $N_p = 512$, $M_s = [1, 2, 4, 8, 16]$, $N_s = 64$, and maximum BER of $\tau_p = 10^{-4}$.

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