Wireless Pers Commun (2014) 74:559–567
DOI 10.1007/s11277-013-1306-6

A Novel Underlay Cognitive Radio Based on Direct Sequence Complementary Coded CDMA

Refik Caglar Kizilirmak

Published online: 30 June 2013

Abstract In this study, we propose a spectrum sharing scheme where secondary-users (SUs) can co-exist at the same frequency band with the primary-users simultaneously. Both primary (PN) and secondary networks (SN) are considered as CDMA based networks with the same set of orthogonal complementary codes. An orthogonal complementary code set possesses both ideal auto-correlation function (ACF) of any code and ideal cross-correlation function for any two codes in the same set. In the proposed scheme, a delay is applied to the transmission of the SN which exploits ideal ACF properties of complementary codes and will not interfere the transmission of the primary user. Numerical results show that the proposed scheme enables SUs to efficiently utilize the PN's licensed spectrum without any harmful interference.

Keywords Complementary codes · Cognitive radio · CDMA

1 Introduction

Cognitive radio technology is to share the spectrum with the licensed primary network without any harmful interference. In literature, there are a number of spectrum sharing schemes to achieve this challenging goal and these schemes can be grouped into three categories; *overlay*, *underlay* and *interweave* schemes [1,2]. In the overlay approach, SUs assist the communication of the PUs and use their spectrum in return. The implementation of this approach is costly and needs the knowledge of PN's structure. In the underlay approach, SUs use spread spectrum techniques to communicate each other such that the interference to the PN is below the noise level. In the interweave approach, SUs seek the spectrum holes and try to transmit the data over these holes. The capacity of interweave cognitive radios heavily depends on the traffic in the PN and successful detection of the holes. In this study an underlay approach is considered.

R. C. Kizilirmak (✉)
Department of Electrical and Electronics Engineering,
KTO Karatay University, Konya, Turkey
e-mail: caglar.kizilirmak@gmail.com; refik.kizilirmak@karatay.edu.tr

Code Division Multiple Access (CDMA) has been in use in 2G and 3G networks since 90's. The most important characteristics of CDMA is that it allows users to send their data over the same spectrum at the same time with different codes per each user. These codes should have ideal correlation and spreading properties. Ideal correlation properties include; auto-correlation of any code is a single peak for successful detection and cross-correlation of any two codes is zero for any time shift. A code should also spread the information over the transmission bandwidth while keeping its correlation properties. Most of the current CDMA networks such as IS-95, cdma2000, W-CDMA and TDS-CDMA are based on Gold codes, Kasami codes, m-sequences and Walsh-Hadamard sequences. Although these codes are orthogonal in synchronous transmission, their correlation properties are far from ideal in asynchronous channels (especially in the uplink) which cause very well-known interference limitation problem for the capacity of CDMA.

Authors in [3] discusses a new set of codes, Complementary Codes (CC), which provides better correlation properties. It was reported in [3] that for an orthogonal complementary code, the auto-correlation function (ACF) is zero for any shift, and the cross-correlation function (CCF) for any pair of orthogonal complementary codes is zero for any shift. This reduces the multiple-access interference (MAI) and multipath interference (MI) and increases the system performance. Several advantages of Complementary Coded CDMA (CC-CDMA) systems are addressed in [3,4] and considered as a next generation CDMA technology.

One advantage of CC-CDMA systems is that it has strong resistance to the near-far problem due to its perfect ACF and CCF properties. Therefore, heavy power control processes in traditional CDMA networks are not needed for CC-CDMA. Moreover, in CC-CDMA inter-path delays do not cause MI and rake receiver can also be replaced by simple correlator receiver. A major disadvantage of CC-CDMA systems is that the number of available codes is limited and less than the other traditional codes. The work in [5] proposes code hopping scheme for CC-CDMA systems to increase the number of users in the network.

In addition to several benefits of CCs already pointed in literature, in this work we aim to introduce a novel cognitive radio architecture based on orthogonal CCs and their perfect AFC and CCF properties. We consider both PN and SN are DS/CC-CDMA based networks and use the same set of complementary codes. Analysis is carried out for asynchronous channel. A delay of one chip duration with respect to the primary base station (PBS) is applied to the secondary base station (SBS). The co-existence is achieved by the strong ACF properties of the complementary codes such that the pair of PU and SU using the same complementary code will not interfere each other.

The remaining of the paper is organized as follows: Sect. 2 gives preliminaries on DS/CC-CDMA systems. Then Sect. 3 describes the proposed system. In Sect. 4, numerical results are presented and Sect. 5 concludes the paper.

2 Preliminaries on DS/CC-CDMA

A complementary code consists of a number of element codes. Consider M number of complementary codes each having N number of element codes. The number of users in the network is K where $K \leq M$. Figure 1 illustrates the transmitter and receiver blocks of DS/CC-CDMA system for the user k. The information is encoded with different element codes $[\mathrm{c}_{k1}\, \mathrm{c}_{k2}\, \mathrm{c}_{k3} \cdots \mathrm{c}_{kN}]$ of the same complementary code $\mathbf{C}_k$ assigned. Then, each spread streams are modulated and sent over N different subcarriers $f_1, f_2, \ldots, f_N$. At the receiver side, different subcarriers are first demodulated and then correlated with the element codes tuned to user k. The decoded streams are then summed and fed to the decision device. Here,

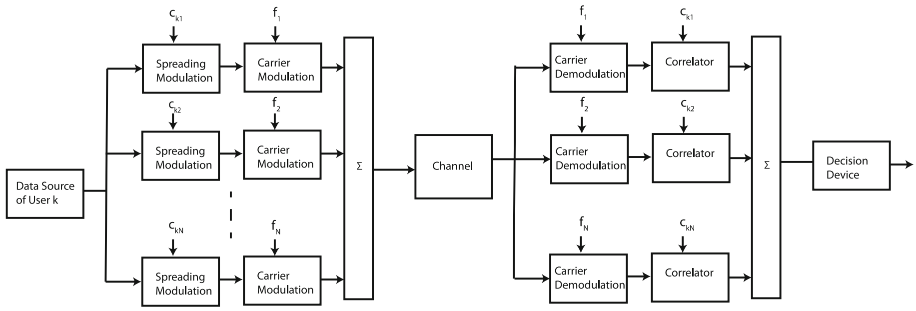


Fig. 1 Primary network based on complementary coded CDMA

multi-carrier transmission is to avoid the interference among the element codes which is different from the multi-carrier CDMA where different information is carried over different subcarriers.

The multi-carrier transmission provides strong ACF and CCF behaviors. Although, the individual ACFs of the element codes $R(c_{kj};\tau)$ has many side lobes, the ACF of their sum over different channels

$$R(\mathbf{C}_k;\tau) = \sum_{j=1}^{N} \int_{-\infty}^{+\infty} c_{kj}(t)c_{kj}(t-\tau)dt \tag{1}$$

is zero for any time shift τ except zero shift. Similarly, although the individual CCFs of the elements codes for different users of the same subcarrier, $\rho(c_{kj}, c_{k'j};\tau)$, is not ideal, the CCF of the sum

$$\rho(\mathbf{C}_k, \mathbf{C}_{k'};\tau) = \sum_{j=1}^{N} \int_{-\infty}^{+\infty} c_{kj}(t)c_{k'j}(t-\tau)dt \tag{2}$$

is zero for all possible time shifts.

Assume, the two complementary codes $\mathbf{C}_1 = [c_{11}; c_{12}]$ and $\mathrm{C}_2 = [c_{21}; c_{22}]$ where c_{11} and c_{12} are the elements codes of the code C_1 and similarly c_{21} and c_{22} are the elements codes of the code $\mathbf{C}_2$, and hence $N = 2$. $c_{11} = [+1+1+1-1]$, $c_{12} = [+1-1+1+1]$, $c_{21} = [+1+1-1+1]$ and $c_{22} = [+1-1-1-1]$. Figures 2 and 3 illustrate the ACF and CCF properties of the complementary codes.

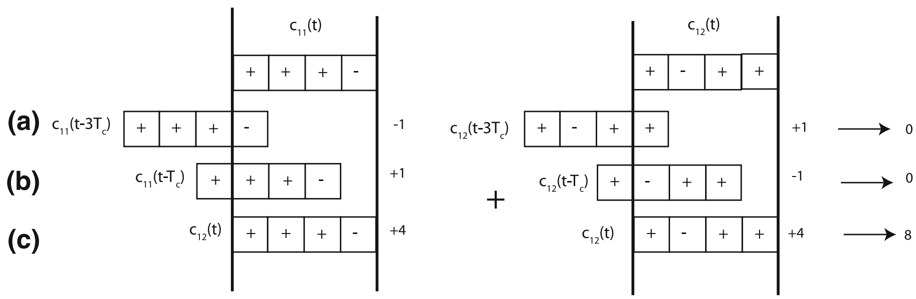


Fig. 2 Illustration of perfect ACF of complementary codes for different τ. **a** $\tau = 3T_c$ **b** $\tau = T_c$ **c** $\tau = 0$

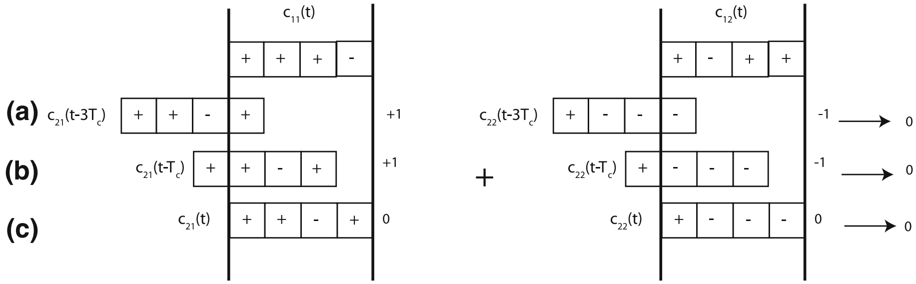
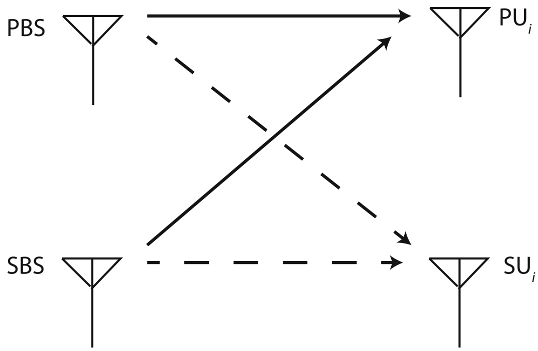


Fig. 3 Illustration of perfect CCF of complementary codes for different τ. **a** $\tau = 3T_c$ **b** $\tau = T_c$ **c** $\tau = 0$

Fig. 4 Interference channel model



In Fig. 2, the auto-correlation property of complementary codes is mentioned for different values of τ in terms of chip duration T_c. In Fig. 2a, when $\tau = 3T_c$ the ACF of element code c_{11} is $\int c_{11}(t)c_{11}(t-3T_c) = -1$, however when the ACFs of c_{11} and c_{12} is summed, the result is zero: $\int c_{11}(t)c_{11}(t-3T_c) + \int c_{12}(t)c_{12}(t-3T_c) = 0$. This holds for any time shift $\tau \neq 0$. Figure 2b illustrates the case $\tau = T_c$. In Fig. 2c, it is shown that when there is no time shift the auto-correlation of a complementary code $\mathbf{C}_1$ is 8, which is the processing gain for this example. This yields perfect auto-correlation property for the complementary codes.

Figure 3 illustrates the prefect cross-correlation property for the complementary codes. The cross-correlation between the elements codes corresponding to the same band is not perfect. In Fig. 3a, for $\tau = 3T_c$, it is shown that $\int c_{11}(t)c_{21}(t-3T_c) = -1$. Together with $\int c_{12}(t)c_{22}(t-3T_c) = +1$, the summation becomes zero. This holds for any time shift τ and provides perfect cross-correlation property for the complementary codes.

3 Cognitive DS/CC-CDMA Network

Assume that the same set of complementary codes for the PN is available for the SN and the numbers of users in both PN and SN are the same. Let the users i of PN and SN use the same complementary code $\mathbf{C}_i$. Assume that SN has a dedicated uplink channel and needs cognition only in downlink. Figure 4 shows the interference channel model for the primary user i in the downlink. In a traditional CDMA networks based on conventional codes (such as Walsh-Hadamard codes) PU_i will be interfered by the the other primary users and the secondary users in the channel. On the other hand, when the complementary codes are used, the ideal CCF properties of the complementary codes will cancel the interference from all the users k of PN and SN, $k \neq i$. The only interference source left is the user i of SN which uses the same complementary code $\mathbf{C}_i$. Applying a delay to the transmission of the secondary user i will exploit the benefit of ideal ACF property and suppresses the interference from the SU_i.

The received signal by a primary user i at subcarrier j over a multipath channel is

$$r_{ij}(t) = \left[\sum_{k=1}^{K} p_k(t) c_{kj}(t) \right] + SU_j(t) + n_{ij}(t) \tag{3}$$

where $p_k(t)$ is the transmitted data of the primary BS for the user k, $c_{kj}(t)$ is the element code of user k for the jth subcarrier, $n_{ij}(t)$ is the noise term for the jth subcarrier and $SU_j(t)$ is the total interference from the secondary network users at the jth subcarrier. The transmitted waveform $p_k(t)$ can be written as

$$p_k(t) = \sum_{n=0}^{\infty} p_k[n] P_u(t - nT) \tag{4}$$

where T is the bit duration, $p_k[n]$ is binary information ∓ 1 and P_u is the rectangular pulse shaping filter.

$SU_j(t)$ can be written as

$$SU_j = \sum_{k=1}^{K} s_k(t - \tau_{Sk}) c_{kj} \tag{5}$$

where $t - \tau_{Sk}$ is the delay added to the SBS for the user k, s_k is the transmitted data of the secondary BS for the user k. The transmitted waveform from the secondary user $s_k(t)$ can be written as $s_k(t) = \sum_{n=0}^{\infty} s_k[n] P_u(t - nT)$.

Primary user i then correlates the different received signals $r_{ij}(t)$ from different subcarriers $j = 1, 2, .., N$ with the corresponding elementary code $c_{ij}(t)$ and obtains the decision variable $\hat{d}_i$ as

$$\hat{d}_i = \sum_{j=1}^{N} \int_0^T r_{ij}(t) c_{ij}(t) dt \tag{6}$$

where T is the duration of the element code. $\hat{d}_i$ can be further written as

$$\hat{d}_i = \sum_{j=1}^{N} \int_0^T \left[\sum_{k=1}^{K} (p_k(t) + s_k(t - \tau_S)) c_{kj}(t) + n_{ij} \right] c_{ij}(t) dt. \tag{7}$$

An illustrative example is given in Fig. 5. Assume that there are $K = 2$ number of users in PN and SN that are based on DS/CC-CDMA technology. The number of complementary codes M is 2 and each having $N = 2$ element codes with 4 chips. $c_{11} = [+1+1+1-1]$, $c_{12} = [+1-1+1+1]$, $c_{21} = [+1+1-1+1]$ and $c_{22} = [+1-1-1-1]$. Consider signals are sent in packets consisting of three bits. It is assumed that the packet $(+1-1+1)$ is transmitted. The processing gain of such system is $M \times N$ which is 8. All the delays are given in multiples of chip duration for illustrative purposes however it is shown in [3] that the correlation properties of CC is still perfect for the fractional chip durations.

The example in Fig. 5 can be derived as follows. The complementary code $\mathbf{C}_1 = [c_{11}; c_{12}]$ is assigned to PU_1 and $\mathbf{C}_2 = [c_{21}; c_{22}]$ is assigned to PU_2. The transmitted signal from the PBS to PU_1 is

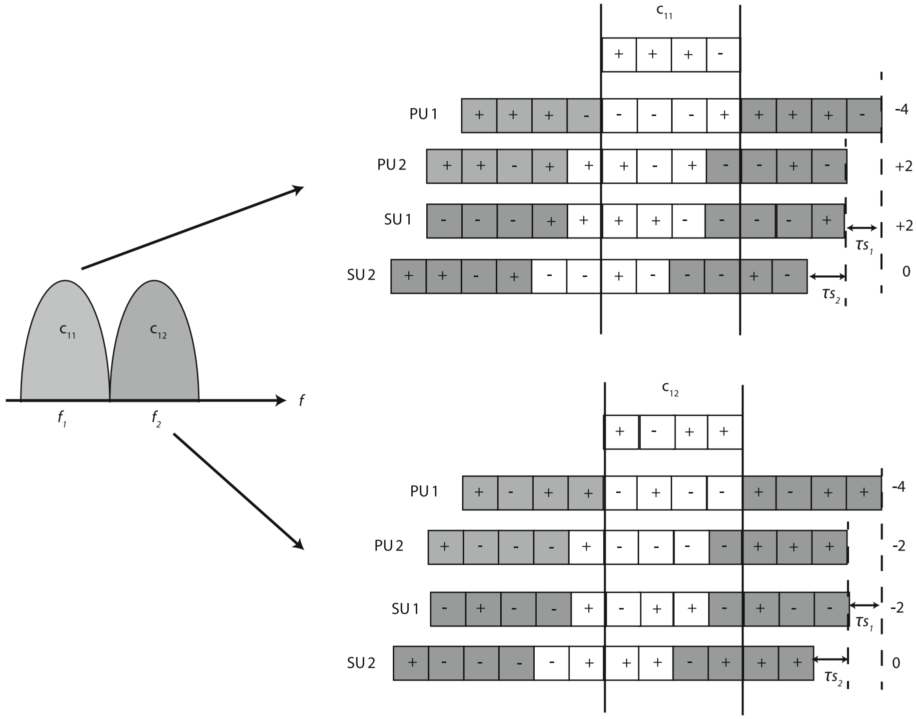


Fig. 5 Illustration of the detection of the second bit of PU_1 in a noise-free channel. $\hat{d}_1 = -4+2+2-4-2-2 = -8$

$$s_{PU1}(t) = p_1(t)[c_{11}(t)cos(2\pi f_1 t) + c_{12}(t)cos(2\pi f_2 t)] \tag{8}$$

where c_{11} and c_{12} are the two element codes of $\mathbf{C}_1$. If no secondary network exists in the environment, the PU_1 receives the signal transmitted for itself and for the second user in the network. The received signal at the jth subcarrier by PU_1 is

$$r_{1,j}(t) = p_1(t)[c_{1j}(t)cos(2\pi f_j t)] + p_2(t-\tau)[c_{2j}(t-\tau)cos(2\pi f_j t)]. \tag{9}$$

PU_1 can easily obtain the p_1 by correlating Eq. (9) with $c_{11}(t)$ and $c_{12}(t)$ at the corresponding bands f_1 and f_2. The decision will be based on the sum of the correlator outputs at the frequency bands f_1 and f_2:

$$\begin{aligned}\hat{d}_1 &= p_1(t)[c_{11}(t)c_{11}(t) + c_{12}(t)c_{12}(t)] \\ &\quad + p_2(t-\tau)[c_{11}(t)c_{21}(t-\tau) + c_{12}(t)c_{22}(t-\tau)].\end{aligned} \tag{10}$$

In Eq. (10), although the CCF of the individual element codes are not ideal, i.e $[c_{11}(t)c_{21}(t-\tau) \neq 0$, the sum of $[c_{11}(t)c_{21}(t-\tau) + c_{12}(t)c_{22}(t-\tau)]$ is always 0 for any τ including $\tau = 0$. Therefore, the decision variable after the correlator reduces to

$$\begin{aligned}\hat{d}_1 &= p_1(t)[c_{11}(t)c_{11}(t) + c_{12}(t)c_{12}(t)] \\ &= p_1(t)\text{PG}\end{aligned} \tag{11}$$

where PG is the processing gain which is 8 in this case.

Now, consider secondary network appears in the environment with the same code set $\mathbf{C}_1$ and $\mathbf{C}_2$. The SBS starts transmission at an arbitrary time. The received signal at the jth subcarrier by PU_1 is

$$\begin{aligned} r_{1,j}(t) = {} & p_1(t)[c_{1j}(t)cos(2\pi f_j t)] + p_2(t-\tau)[c_{2j}(t-\tau)cos(2\pi f_j t)] \\ & + s_1(t-\tau_{S1})[c_{1j}(t-\tau_{S1})cos(2\pi f_j t)] + s_2(t-\tau_{S2})[c_{2j}(t-\tau_{S2})cos(2\pi f_j t)]. \end{aligned} \tag{12}$$

When this signal is correlated with c_{11} and c_{12} and the correlator outputs are summed, PU_1 would decide based on

$$\begin{aligned} \hat{d}_1(t) = {} & p_1(t)[c_{11}(t)c_{11}(t) + c_{12}(t)c_{12}(t)] \\ & + p_2(t-\tau)[c_{11}(t)c_{21}(t-\tau) + c_{12}(t)c_{22}(t-\tau)] \\ & + s_1(t-\tau_{S_1})[c_{11}(t)c_{11}(t-\tau_{S_1}) + c_{12}(t)c_{12}(t-\tau_{S_1})] \\ & + s_2(t-\tau_{S_2})[c_{11}(t)c_{21}(t-\tau_{S_2}) + c_{12}(t)c_{22}(t-\tau_{S_2})]. \end{aligned} \tag{13}$$

The perfect ACF and CCF properties of the complementary codes help to suppress the signal from the SN to PU_1. Although the ACF of individual elements codes are not ideal, i.e $c_{11}(t)c_{11}(t-\tau_{S_1}) \neq 0$, the sum $c_{11}(t)c_{11}(t-\tau_{S_1}) + c_{12}(t)c_{12}(t-\tau_{S_1})$ is zero for any τ_{S_1}. Similarly, with the aid of CCF property of the complementary codes $c_{11}(t)c_{21}(t-\tau_{S_2}) + c_{12}(t)c_{22}(t-\tau_{S_2})$ is zero for any τ_{S_2}. Even with the secondary network, Eq. (13) reduces to Eq. (11). Note that, the performance of the system will be the same for $\tau_{S_1} = \tau_{S_2}$ case as well.

4 Numerical Results

The BER performance of the proposed cognitive radio is evaluated through computer simulations. BPSK modulation scheme is selected and the channel is assumed as AWGN channel. Figure 6 shows the BER performance of the proposed scheme. E_b/N_0 is defined as the noise power per transmitted bit energy. The numbers of users in PN and SN are taken as 2. The same set of complementary codes are used as given in the previous section for the PN and SN. Table 1 summarizes the simulation parameters. As seen in Fig. 6, when the complementary codes are used, the SN does not introduce interference to PN and the performance of PN is still limited only by the noise. However, when traditional Walsh codes are used, the SN disrupts the PN signals and the BER performance of PN is heavily degraded.

5 Discussions and Future Work

This work proposes a novel cognitive radio architecture based on complementary codes. The results have revealed that networks based on DS/CC-CDMA technology can accommodate secondary underlay another DS/CC-CDMA without interference due to perfect correlation properties of complementary codes. The only requirement for the cognitive radio is that the transmissions with the same complementary codes at PN and SN should be asynchronous. In this work, we applied a delay of one chip duration to the secondary network. However, any delay including fractional chip durations will also work. The analysis has been kept limited to AWGN channels and the extension to multipath fading channels is left as a future work. It is known that complementary codes keep their properties in fading channels with an adaptive recursive multipath signal reception filter [6].

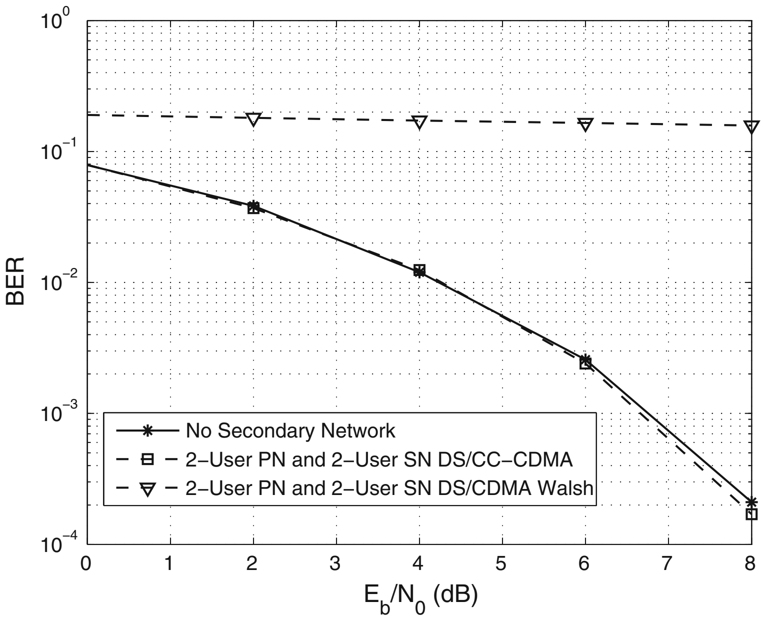


Fig. 6 BER performance of the single user in PN

Table 1 Simulation conditions

Modulation scheme	BPSK
Channel	AWGN
Number of users in PN	2
Number of users in SN	2
Complementary codes	$\mathbf{C}_1 = [+1+1+1-1; +1-1+1+1]$ $\mathbf{C}_2 = [+1+1-1+1; +1-1-1-1]$
Hadamard codes	$\mathbf{C}_1 = [+1+1+1+1+1+1+1+1]$ $\mathbf{C}_2 = [+1-1+1-1+1-1+1-1]$
Processing gain	8
Delay profile	$[\tau,\ \tau_{S_1},\ \tau_{S_2}] = [T_c,\ T_c, 2T_c]$

In practice, base station transmits packets for every user at the same time in the downlink channel. The received packets by any user in the network are bit by bit aligned. Hence, the downlink channel is synchronous. On the other hand, in the uplink since every user is located at a different place, the transmitted signals from each user arrive base station at different times. Therefore, the uplink transmission is asynchronous. In this work, we have considered asynchronous case to indicate that the results can also be applied to the uplink channel.

References

1. Goldsmith, A., Jafar, S. A., Maric, I., & Srinivasa, S. (2009). Breaking spectrum gridlock with cognitive radios: An information theoretic perspective. *Proceedings of the IEEE*, *97*(5), 894–914.
2. Zhang, X., & Su, H. (2011). Opportunistic spectrum sharing schemes for CDMA-based uplink MAC in cognitive radio networks. *IEEE Journal on Selected Areas in Communications, 29*(4), 716–730.
3. Chen, H. H. (2007). *The next generation CDMA technologies*. London: Wiley.
4. Guizani, M. (2004). *Wireless communications systems and networks*. Dordrecht: Kluwer.
5. Chen, H. H., Zhang, H. M., & Huang, Z. K. (2011). Code-hopping multiple access based on orthogonal complementary codes. *IEEE Transactions on Vehicular Technology*, *61*(3), 1074–1083.
6. Chen, H. H., Yeh, J. F., Suehiro, N. (2001). A multicarrier CDMA architecture based on orthogonal complementary codes for new generations of wideband wireless communications. *IEEE Communications Magazine*, *39*(10), 126–235.

Author Biography

Refik Caglar Kizilirmak was born in Izmir Turkey in 1981. He received B.Sc. and M.Sc. degrees in electrical and electronics engineering from Bilkent University in 2004 and 2006, respectively. He worked as a research engineer in Communications and Spectrum Management Research Center, Turkey between 2004 and 2006. He got his Ph.D. degree in electrical and electronics engineering from Keio University, Yokohama, Japan in 2010. He has been involved in projects related to defense and security as a technical leader in Turkey. Since 2011, he is with KTO Karatay University where he serves as the chair of the Electrical and Electronics Engineering department. His research interests are in the field of communication theory and signal processing. He is the recipient of IEEE VTC Young Researcher's Encouragement Award (2008) and IEICE Student Paper Award (2007). Dr. Kizilirmak is a member of IEEE, IEICE and NYAS.