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Cognitive-Cooperative Multiple Access for Gigabit Wireless Networks (1/2)

英文摘要

The next generation wireless networks will integrate several application scenarios and provide a wide spectrum of services. To accommodate this and maintain seamless wireless access, the user devices will become smarter than ever and capable of sensing the surrounding environment and seizing available wireless resource whenever needed. In this project, we try to accomplish this goal by employing dynamic resource allocation and terminal cooperation to create a new gigabit wireless network. The former technology can maximize the sum rate of the network through interference avoidance, while the latter provides space diversity for performance improvement without the need of multiple antennas. In the first year of this project, autonomous multi-user dynamic resource allocation was investigated. Wavelet packet bases with autonomous signature waveform design were adopted to facilitate optimal spectral shaping, interference avoidance and power water filling. A reconfigurable basis selection algorithm was further developed to maximize the sum rate of the network in various network and channel conditions.

Keywords: Gigabit, wireless network, cognitive radio, resource allocation, MIMO, OFDM, wavelet.

中文摘要

下一代的無線網路勢必會整合多樣服務項目與應用方式。為適應此需求，以及維持完全覆蓋的無線上網，用戶的通訊裝置將會變得無比聰明，具有感測周遭環境，並且在需要的時候取得可用的無線網路資源。本計畫嘗試利用動態資源分配及用戶協同合作來達到此目標、並創造一個新的十億位元級的無線網路。動態資源分配利用避免用戶互相干擾的方式來將網路的總傳輸速率提昇至最大，用戶協同合作則是能在不需多天線裝備的情況下提供空間多重增益來改善傳輸品質。在計畫的第一年裡，我們探討了自主式多用戶動態資源分配。我們採用小波封包（Wavelet Packet）及自主式特徵波型設計來達到最佳的頻譜塑型、干擾規避、及功率分配。我們進一步提出可調式基礎波型選擇演算法在任何網路及通道狀況下均可達到最大的系統總傳輸率。

關鍵詞：十億位元、無線網路、感知無線電、資源分配、多輸入多輸出通道、正交分頻多工調變、小波。

Cognitive-Cooperative Multiple Access for Gigabit Wireless Networks (1/2)

Abstract

The next generation wireless networks will integrate several application scenarios and provide a wide spectrum of services. To accommodate this and maintain seamless wireless access, the user devices will become smarter than ever and capable of sensing the surrounding environment and seizing available wireless resource whenever needed. In this project, we try to accomplish this goal by employing dynamic resource allocation and terminal cooperation to create a new gigabit wireless network. The former technology can maximize the sum rate of the network through interference avoidance, while the latter provides space diversity for performance improvement without the need of multiple antennas. In the first year of this project, autonomous multi-user dynamic resource allocation was investigated. Wavelet packet bases with autonomous signature waveform design were adopted to facilitate optimal spectral shaping, interference avoidance and power water filling. A reconfigurable basis selection algorithm was further developed to maximize the sum rate of the network in various network and channel conditions.

Index Terms

Gigabit, wireless network, cognitive radio, resource allocation, MIMO, OFDM, wavelet.

I. INTRODUCTION

The next generation wireless networks will integrate several application scenarios and provide a wide spectrum of services. In order to support seamless wireless access for data-rate hungry applications such as multimedia and gaming, the communication bandwidth will be very wide, and the area spectral efficiency will have to be highly increased. To accommodate these needs, the computation of wireless networks will become more and more distributed, and moving from infrastructure toward terminals/devices. The end-user devices will become smarter than ever and capable of inspecting the surrounding environment and seizing enough wireless resource whenever needed. In addition, in order to be highly portable, the end-users devices will have to be small in size, with low power consumption, and utilizing most globally available spectra. Hassle free upgrade for the end-users is also an important feature. Thus, the new devices should be backward compatible to the existing popular wireless services (such as the wireless local area networks (WLAN)), and a new multiple access mechanism has to be defined for these new devices.

There are two recent developments in communication theory that might help to achieve the aforementioned new user device requirements. One is dynamic resource allocation based on Shannon's water-filling concept. This helps the user devices seize as much useful wireless resource (e.g., spectrum) as possible. In order to accomplish a good resource allocation, the devices first need to be environment-aware and able to accurately sense and understand the surrounding environment. This calls for an intelligent, or cognitive radio device [1]. The resource allocation mechanism will be network-wide, but possibly distributed to the individual devices (namely, autonomous) to achieve good spectrum pooling [2].

The other helpful concept is diversity which appears in many forms. It can help lower the power consumption for a given performance requirement. Frequency and time diversities in general can be obtained through good channel coding and modulation design, as well as good resource allocation. Space diversity needs the deployment of multiple antennas which the new small-size devices may not afford. Fortunately, as the new wireless networks will be packed densely in space to achieve high frequency reuse and low power consumption, the end-user devices will likely find many other user devices placed nearby. In this scenario, the user devices can help relay each other's data to obtain space diversity through cooperation [3] [4] [5]. The channel coding and modulation design for this scenario will be distributed as opposed to the conventional space-time coding for which the multiple coded data streams are generated and emitted from the same user on its different antennas.

In this project, we intend to combine dynamic resource allocation with user cooperation to form a new cognitive-cooperative multiple access (C^2MA) scheme. In the first year of this project, autonomous multi-user dynamic resource allocation was investigated. Wavelet packet bases with autonomous signature waveform design were adopted to facilitate optimal spectral shaping, interference avoidance and power water filling. A reconfigurable basis selection algorithm was further developed to maximize the sum rate of the network in various network and channel conditions.

II. Cognitive Radio and Dynamic Resource Allocation

The C^2MA will occupy a wide spectrum in the US U-NII bands to support over 1 Gbps transmission rate. In the targeted bands, several existing wireless systems (e.g., IEEE 802.11a) make a clean, sufficiently wide spectrum exclusive for C^2MA almost impossible. To overcome this practical limitation, the C^2MA system will be equipped with the cognition capability, which includes sensing and analyzing the environment, then opportunistically adapting the transmission waveforms, spectra and power to minimize the interference to/from the incumbent systems and maximize the spectral efficiency. Among the C^2MA users, a further dynamic resource allocation rule will be imposed such that their transmission waveforms will not severely interfere with each other and the overall network-wide throughput can be maximized.

The existing resource allocation schemes, including optimization of transmission waveforms, spectra and power, etc. to maximize the network-wide throughput, is mostly code division multiple access (CDMA) based. This is because CDMA is interference constrained instead of bandwidth constrained. There are several works on user signature waveform design for CDMA systems in both synchronous and asynchronous cases, and different design objectives and criteria have been considered. There are both explicit [6] [7] and iterative [8] methods for the signature waveform design. When each user has an average power constraint, and there is no fading in the system, [9] shows that when the number of users is less than or equal to the processing gain, the optimal strategy is to allocate orthogonal signature sequences to all users. And when the number of users is greater than the processing gain, with all users having the same average power constraints, the optimal strategy is to allocate Welch Bound Equality (WBE) [10] sequences. [7] generalizes the method in [9] to accommodate unequal average power constraints, and gives the optimal signature sequence allocation as a function of the power constraints of the users, by making use of some results from the theory of majorization in matrix analysis [11]. Specifically, for the case in which the number of users is greater than the processing gain, when a user has a relatively larger power constraint than the others, it is called *oversized*. The oversized users should be allocated orthogonal signature sequences; whereas the non-oversized users are allocated the so-called Generalized Welch-Bound-Equality (GWBE) sequences. [12] provides a matrix-theoretic perspective for the sequence design and points out that it is the *tight frame* design problem.

For C^2MA, as the legacy systems may not be CDMA, using the CDMA “chips” (i.e., time-separated pulses) as basis may not be the most satisfactory. We thus investigated the possibility of using more flexible waveform bases which are preferably reconfigurable to suit the environment and interference patter caused by legacy systems. One of the possible waveform bases is wavelet packet. Through multi-resolution analysis (MRA) [13], it can be found that given a signal space, a binary tree structure can be created to decompose the signal space into orthogonal subspaces. And the division is flexible, which allows the possibility of forming many different bases and signal multiplexing schemes with a simple adjustment of parameters. With such a flexible signal space decomposition, the wavelet packet division multiplexing (WPDM) [14] [15] subsumes the conventional multiplexing schemes such as time division multiplexing (TDM), whose basis functions are orthogonal time domain pulses, or frequency division multiplexing (FDM), whose basis functions are orthogonal frequency tones, as its special cases. By adjusting the wavelet parameters and the number of subband filterings, one can tile the frequency-time plane freely to find a proper waveform basis that suits the interference pattern of the environment [14]. This basis selection is well structured and can be easily implemented on a programmable radio platform.

Once the waveform basis is determined, multiple access signature waveform optimization algorithms can be used to obtain the best weights and combination of the basis functions to form the signature waveforms for individual users. The signature waveform design methods based on the minimum mean square error (MMSE) criterion [8] [16] were adopted in this project.

III. Adaptive Signature Waveform Design for Cognitive Radio Systems Based on Wavelet Packet Division Multiplexing

In this section, we use the wavelet packet division multiplexing (WPDM) scheme combined with the MMSE update algorithm applied in CDMA systems [8] [16] to design the signature waveforms of cognitive radio (CR) users. Utilizing the flexibility of WPDM in the frequency and time domains, we will focus on how to tile the Frequency-Time plane (F-T plane) according to the measured interferences to avoid interferences between the legacy users and the CR users, in order to obtain better performance.

In the following sections, we will discuss the properties of wavelet packet, and utilize them to design the signature waveforms of CR users. We consider the cases where the legacy and CR users employ orthogonal frequency division multiplexing (OFDM) or wavelet packet division multiplexing (WPDM), and compare different tiling methods of the F-T plane of CR systems. We then propose an algorithm to tile the F-T plane of CR systems according to the measured interference, and compare it with arbitrary tiling of the F-T plane.

A. Preliminary

In this section, some basic knowledge related to the proposed design is briefly reviewed. First, we discuss the concept of wavelet packet, and wavelet packet division multiplexing (WPDM) [14] [15]. Then some multiple access techniques are compared. We further introduce a signature update algorithm, which is applied in CDMA systems, and separate into two cases, synchronous [8] and asynchronous [16], respectively, to discuss the difference between them.

1) Wavelet Packet Division Multiplexing: WPDM is a multiple signal transmission technique in which the message signals are waveform coded onto wavelet packet basis functions for transmission. In this section, we will give a brief introduction to the concepts of wavelet packets, and discuss the properties of them. Then some multiple access techniques, including WPDM, frequency division multiplexing (FDM) and time division multiplexing (TDM), will be compared.

Wavelet Packet

A multiresolution analysis (MRA) [13] consists of a collection of embedded subspaces $\cdots \subset V_{21} \subset V_{11} \subset V_{01} \subset V_{-11} \subset \cdots$ in the space of finite energy signals $L_2(R)$ with some particular properties. Each subspace V_{d1} has a set of orthonormal bases $\{\phi_{d1}(t-nT_d)\}_{n\in Z}$, where T_d represents the time interval at integer multiples of which the bases are self and mutually orthogonal, and Z represents the set of integers. We can recursively decompose the spaces $V_{dm}, d \geq 0, 1 \leq m \leq 2^d$, by partitioning the corresponding orthonormal bases $\{\phi_{dm}(t-nT_d)\}_{n\in Z}$ in the following tree-structured manner [17]:

$$\phi_{d+1,2m-1}(t) = \sum_n h[n]\,\phi_{dm}(t-nT_d)$$
$$\phi_{d+1,2m}(t) = \sum_n g[n]\,\phi_{dm}(t-nT_d)$$

where $h[n]$ and $g[n]$ are finite impulse response (FIR) filters forming an orthonormal two-channel perfect reconstruction filter bank. The first subscript denotes the ”level” in the tree structure induced by the recursive decomposition of V_{01}, and the second subscript denotes the position of a node in a given level. We can grow or prune the tree in any desired fashion, and the functions $V_{dm}(t)$ at the ”leaves” or terminals of a given tree structure provide a set of ”wavelet packet basis functions” or simply a wavelet packet, as exemplified in Fig. 1 [15].

We now discuss some properties of wavelet packets. The wavelet packet bases at higher levels generated by the ones at lower levels will have durations twice as long as those of their parents, but with half bandwidth of them. These bases provide self orthogonality based on time translation and mutual orthogonality based on occupancy of different orthogonal subspaces. In WPDM systems, the binary messages

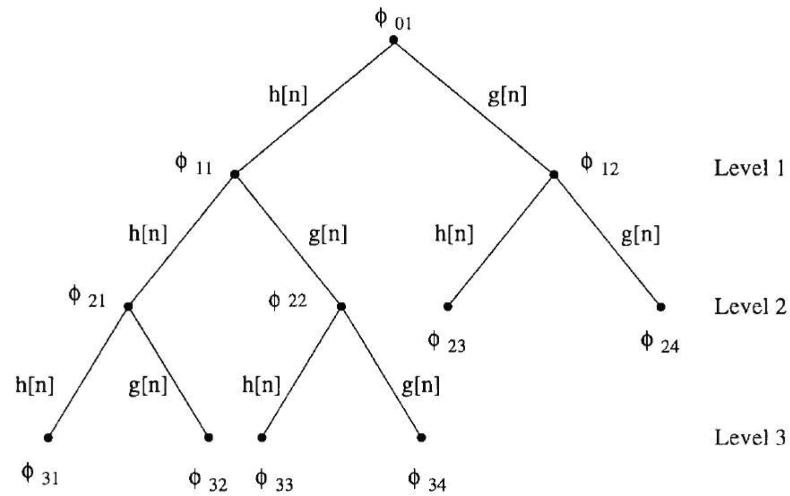

Fig. 1. Typical WPDM Tree Structure

are waveform coded by pulse amplitude modulation (PAM) or quadrature amplitude modulation (QAM) of $\phi_{dm}(t-nT_d)$ and are added together to form the composite signal $s(t)$.

Comparisons between Some Multiple Access Techniques

When transmitting a large number of independent messages over a common channel, two forms of orthogonality are commonly used: 1) orthogonality in frequency results in the method of frequency division multiplexing (FDM) in which bandlimited baseband digital signals are translated in frequency by modulating different sinusoidal carriers to occupy nonoverlapping bands, thereby partitioning the frequency bandwidth of the channel and allocating a different frequency band to each message signal; 2) orthogonality in time results in the method of time division multiplexing (TDM) in which the transmission of the message signals engages the channel periodically for different nonoverlapping time slots, thereby enabling the joint utilization of the channel by a plurality of message sources on a time-shared basis. FDM and TDM have been used to transmit multiuser communication signals for decades now and are the primary methods of multiplexing at present. However, waveform orthogonality is not limited to orthogonality in frequency or orthogonality in time only. It can be easily conceived that a set of waveforms that provides self-orthogonality based on translation in time and mutual orthogonality based on occupancy of different orthogonal subspaces can be utilized to code and multiplex the digital signals of a multiuser communication system. Wavelet and wavelet packet decompositions are convenient techniques by which waveforms providing such orthogonality can be obtained. In fact, the concepts of FDM and TDM schemes are the special cases of wavelet packet decomposition. Fig. 2 shows the relations between FDM, TDM, and WPDM. When all users code their message signals onto the scaling function of wavelet packet, it will become a TDM scheme; when all users transmit their signals by the wavelet packet bases of the same level, it will become an FDM technique.

There is another scheme called orthogonal CDMA. When it uses Walsh-Hadamard codes as spreading codes, it can be seen as a WPDM scheme with Haar wavelet, also a special case of wavelet packet decomposition.

2) MMSE Update Algorithm: In [8] [16], Ulukus and Yates proposed a signature update algorithm applied to CDMA systems. In this algorithm, users update their transmission signature sequences sequentially, in a distributed fashion, by using available receiver measurements. They showed that each update decreases the total squared correlation (TSC) of the set, and produces better signature sequence

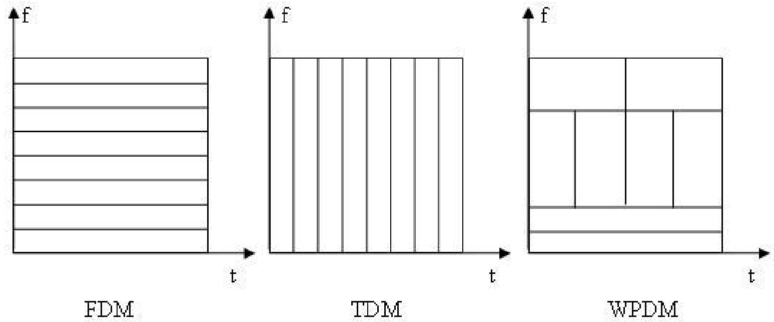

Fig. 2. Comparison of Different Multiple Access Techniques

sets progressively. They proved that the algorithm converges to a set of orthogonal signature sequences when the number K of users is less than or equal to the processing gain N. They observed and conjectured that the algorithm converges to a set of Welch bound equality (WBE) sequences when the number K of users is greater than the processing gain N. At each step, the algorithm replaces one signature sequence from the set with the normalized MMSE filter corresponding to that signature sequence. In the following, we will discuss this algorithm applied in two cases: synchronous systems and asynchronous systems.

Synchronous Systems

In this section, the downlink of a single cell synchronous CDMA system with K users and processing gain N is considered. In the presence of additive white Gaussian noise (AWGN), $n(t)$, with zero mean and power spectral density σ^2, the received signal in one symbol interval is

$$r(t) = \sum_{i=1}^{K} \sqrt{p_i} b_i s_i(t) + n(t) \tag{1}$$

where, for user i, p_i is the received power, b_i is the information symbol with zero mean and variance $E\left[b_i^2\right] = 1$, and $s_i(t)$ is the signature waveform. The signature waveforms of the users, which are zero outside the symbol interval, have unit energies, and can be represented by N orthonormal basis waveforms $\left\{\phi_j(t)\right\}_{j=1}^{N}$ such that

$$s_i(t) = \sum_{j=1}^{N} s_{ij} \phi_j(t) \tag{2}$$

where $s_{ij} = \left\langle s_i(t), \phi_j(t) \right\rangle$. In standard CDMA notation, $\left\{\phi_j(t)\right\}_{j=1}^{N}$ can be chosen as the shifted versions of the basic chip waveform by multiples of the chip duration. Projecting the received signal onto these basis waveforms yields a set of sufficient statistics $\left\{r_j\right\}_{j=1}^{N}$ where $r_j = \left\langle r(t), \phi_j(t) \right\rangle$. By defining the signature sequence of user i as $\mathbf{s}_i = [s_{i1}, \ldots, s_{iN}]^T$ and the received signal vector $\mathbf{r} = [r_1, \ldots, r_N]^T$, we can write (1) in the equivalent vector notation

$$\mathbf{r} = \sum_{i=1}^{K} \sqrt{p_i} b_i \mathbf{s}_i + \mathbf{n}. \tag{3}$$

Note that $\mathbf{n}$ is a zero mean Gaussian random vector with $E\left[\mathbf{n}\mathbf{n}^T\right] = \sigma^2 I_N$, where I_N denotes the $N \times N$ identity matrix.

Given a set of signatures represented by the columns of the matrix $S=[\mathbf{s}_1,\ldots,\mathbf{s}_K]$, in each iteration of the update algorithm we replace the signatures sequence of user k with the unit energy vector

$$\mathbf{c}_k = Z_k^{-1}\mathbf{s}_k \Big/ \left(\mathbf{s}_k^{\mathrm{T}} Z_k^{-2}\mathbf{s}_k\right)^{1/2}$$

where

$$Z_k = \sum_{j\neq k} \mathbf{s}_i\mathbf{s}_j^T + \sigma^2 I_N.$$

This maps the set of signature sequences S to a new set of signatures

$$\bar{S} = [\mathbf{s}_1,\ldots,\mathbf{s}_{k-1},\mathbf{c}_k,\mathbf{s}_{k+1},\ldots,\mathbf{s}_K]$$

In [8], it was shown that this algorithm yields a set of optimal signature sequences minimizing the TSC. When $K<N$, the minimum value TSC $=K$ is achieved by K orthonormal vectors. On the other hand, when $K>N$, the minimum value TSC $= K^2/N$ is achieved by the K vectors, which form the Welch bound equality sequences.

Asynchronous Systems

In this section, we consider a single-cell symbol-asynchronous (but chip-synchronous) CDMA system with K users and processing gain N. The received signal in the nth symbol interval of user k is given as [16] (see Fig. 3)

$$\mathbf{r}_k(n) = \sqrt{p_k}b_k(n)\mathbf{s}_k + \sum_{l\neq k}\sqrt{p_l}\left(b_l(n)T_L^{d_{kl}}\mathbf{s}_l + b_l(n+1)T_R^{d_{kl}}\mathbf{s}_l\right) + \mathbf{n}_k$$

where p_k, $b_k(n)$, and $\mathbf{s}_k$ are the received power, the nth transmitted symbol, and the signature sequence of user k, respectively, and $\mathbf{n}_k$ is a zero-mean Gaussian random vector with $E\left[\mathbf{n}\mathbf{n}^T\right]=\sigma^2 I_N$. The signature sequences of all users are of unit energy, i.e., $\mathbf{s}_k^T\mathbf{s}_k=1$, for all k. For users k and l, d_{kl} represents the relative time delay of user l with respect to the time delay of user k, that is, $d_{kl}=d_l-d_k$, where d_k and d_l are the time delay of users k and l, respectively. T_R^d and T_L^d denote the operations of shifting, to right and left, respectively, of a vector by d and $N-d$ chips. For both operators, the vacated positions in the vector are filled with zeros. That is, for a vector $\mathbf{x}=[x_1,\ldots,x_N]^T$ and integer $d\geq 0$, we define

$$T_L^d\mathbf{x} = \left[x_{N-d+1},\ldots,x_N,0^{N-d}\right]^T$$

and

$$T_R^d\mathbf{x} = \left[0^d,x_1,\ldots,x_{N-d}\right]^T$$

where 0^d denotes d consecutive zeros. Given a set of signatures represented by the columns of the matrix $S=[\mathbf{s}_1,\ldots,\mathbf{s}_K]$ and delay profile $\mathbf{d}=[d_1,\ldots,d_K]^T$ in which d_i represents the time delay of the ith user, in each iteration of the update algorithm we replace the signatures sequence of user k with the unit energy vector

$$\mathbf{c}_k = B_k^{-1}\mathbf{s}_k \Big/ \left(\mathbf{s}_k^{\mathrm{T}} B_k^{-2}\mathbf{s}_k\right)^{1/2}$$

where

$$B_k = \sum_{j\neq k}\left[T_L^{d_{kl}}\mathbf{s}_l\left(T_L^{d_{kl}}\mathbf{s}_l\right)^T + T_R^{d_{kl}}\mathbf{s}_l\left(T_R^{d_{kl}}\mathbf{s}_l\right)^T\right] + \sigma^2 I_N.$$

This maps the set of signature sequences S to a new set of signatures

$$\bar{S} = [\mathbf{s}_1,\ldots,\mathbf{s}_{k-1},\mathbf{c}_k,\mathbf{s}_{k+1},\ldots,\mathbf{s}_K].$$

In asynchronous systems, the algorithm steps are almost the same as in synchronous systems, except the computation of covariance matrix B_k. Ulukus and Yates [16] showed that the lower bound for the total squared asynchronous correlation (TSAC) is independent of the users' delays, and if the signature set achieves this TSAC lower bound, then the user capacity of the asynchronous CDMA system using matched filters becomes the same as that of a single-cell synchronous CDMA system. In this case, there is no loss in user capacity due to asynchronism. The TSAC lower bound will be the same as TSC.

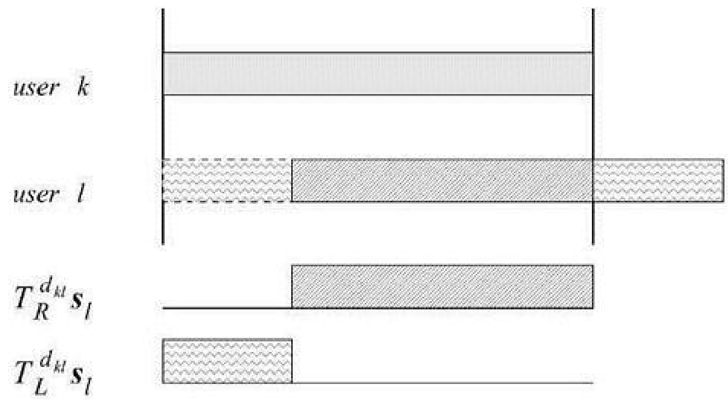

Fig. 3. Asynchronous Interference Calculation

B. Joint WPDM and MMSE Update Algorithm

In this section, we first introduce the approach which combines the two aforementioned topics. Then, the system model and some assumptions are described. In our system model, we discuss two cases: downlink channel (i.e., synchronous) and uplink channel (i.e., asynchronous), respectively. Numerical results and discussion are also given.

1) Introduction of the Joint Approach: In standard CDMA notation, $\{\phi_l(t)\}_{l=1}^N$ could be chosen as the shifted versions of the basic chip waveform by multiples of the chip duration, as shown in (2). Here, we will choose the bases $\{\phi_l(t)\}_{l=1}^N$ as the wavelet packets, so the signature sequence $\mathbf{s}_i = [s_{i1}, \ldots, s_{iN}]^T$ will represent the weights of projecting the signature waveform onto these bases. Then the signature sequences of CR users will be iteratively updated by applying the MMSE update algorithm to minimize the TSC or TSAC.

2) System Model and Assumptions: In this project, we set the CR system to be a WPDM system whose bandwidth is located between 5.15 GHz and 5.35 GHz, while we simulate the base-band signals. In our simulations, the wavelet packet bases are generated by the Daubechies wavelet whose filter length is 14. The maximum level of wavelet packet tree is 3, as in Fig. 6. We use indices 1 - 15 (the numbers parenthesized beside each node in Fig. 6) to represent the fifteen wavelet packet bases. Fig. 7 is the frequency responses of the total fifteen wavelet packet bases. In the beginning, the CR user measure the interference caused by legacy users. Then the CR base-station updates CR users' transmission signature sequences sequentially by utilizing the measured interference. When finishing the update steps, the base-station will feed the signature waveforms back to each user, and each user will transmit signals with the new signature waveform. We assume that in the uplink channel, the base-station knows the delay profile of all users to update their signature waveforms. The channel we consider is AGWN channel.

3) Downlink Channel: The CR base-station transmits signal to every user simultaneously, so all users are synchronous with respect to others. In the sequel, we will show some synchronous cases. In cases I and II, there are two WPDM legacy users using the 12th and 14th wavelet packet bases, respectively, and

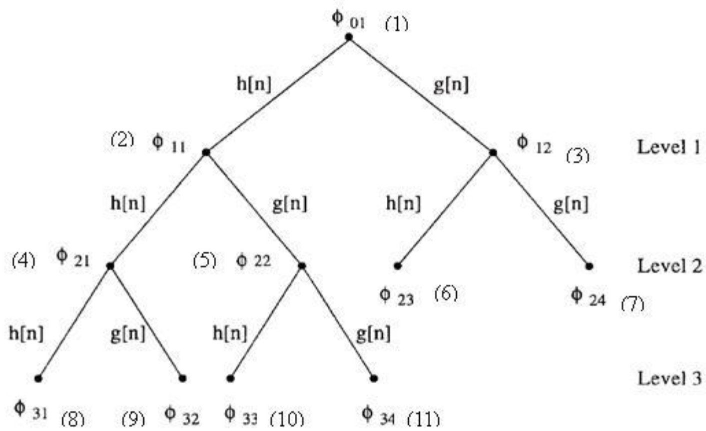

Fig. 4. Tree Structure of Wavelet Packet Bases

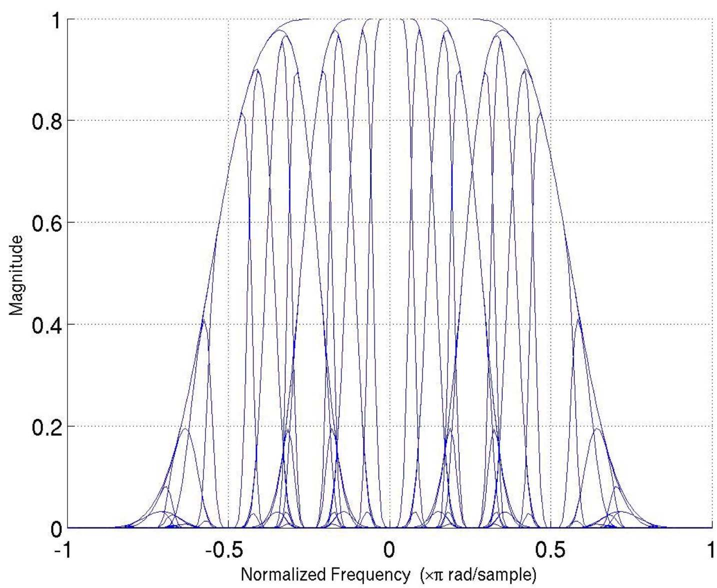

Fig. 5. Frequency Responses of Wavelet Packet Bases

six CR users using MMSE update algorithm to update their signature waveforms. Each case tiles the F-T plane with different permutations. In case III, the number of users is more than the processing gain N. In the case IV, we let the legacy user be an OFDM system user, and discuss the results.

Numerical Results and Discussion

Case I: Number of CR users: 6, number of legacy users: 2, WP bases used by legacy users: [12 14].

Case II: Number of CR users: 6, number of legacy users: 2, WP bases used by legacy users: [12 14].

From cases I and II, we can find that the values of TSC in both cases are achieved by eight orthonormal bases. So in synchronous systems, how to tile the spectrum to avoid interference dose not influence the performances of CR users and legacy users.

Case III: Number of CR users: 9, number of legacy users: 0.

In case III, the number K of users is great than the processing gain N. So, unlike cases I and II, the

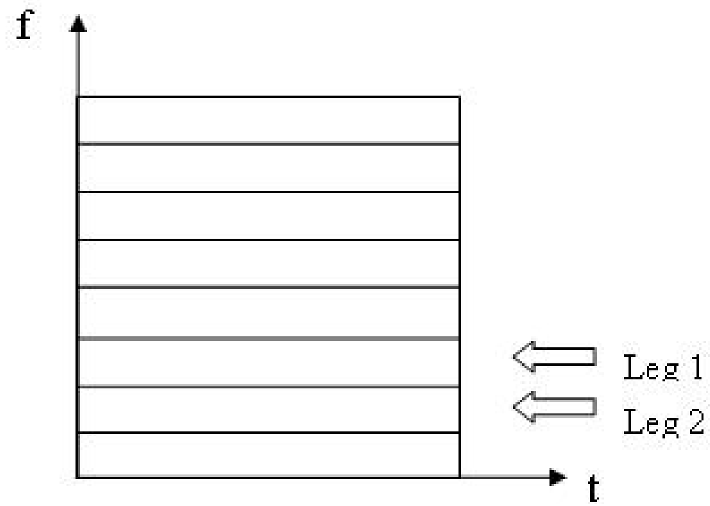

Fig. 6. Tiling of F-T Plane (Synchronous, Case I)

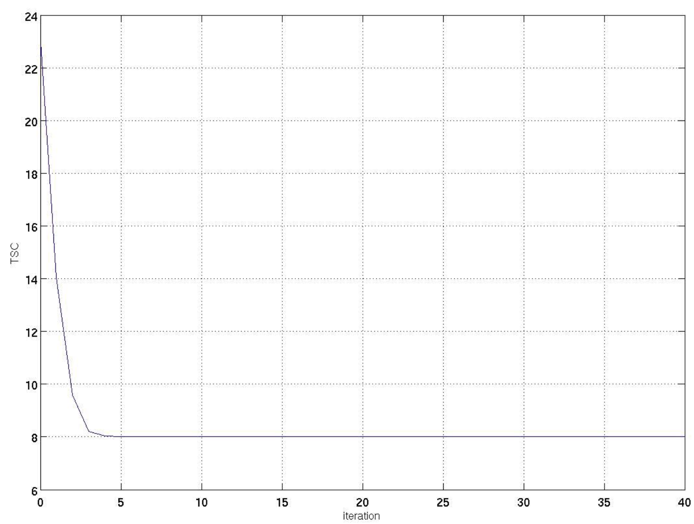

Fig. 7. TSC of All Users after Each Iteration Update (Synchronous, case I)

algorithm results in the Welch bound equality sequences which minimize the TSC value when K is great than N. From Fig. 15, we find that the TSC of WBE sequences converges to 11.3, which is great than the value K^2/N discussed previously. This is because in WPDM systems, the transmitter transmits a data symbol in every time interval T_d, which is shorter than their signature waveforms. So if the sequences are not orthogonal to one another, the users of WPDM systems will suffer from more interference than that of CDMA systems.

Case IV: Number of CR users: 5, number of legacy users: 1, subcarriers used by legacy users: 1 - 64.

In case IV, we let the legacy user be an OFDM user. We assume that each OFDM user has 64 subcarriers and a bandwidth of 20 MHz. So in the band the scaling function engages (i.e., 5.15 GHz - 5.35 GHz),

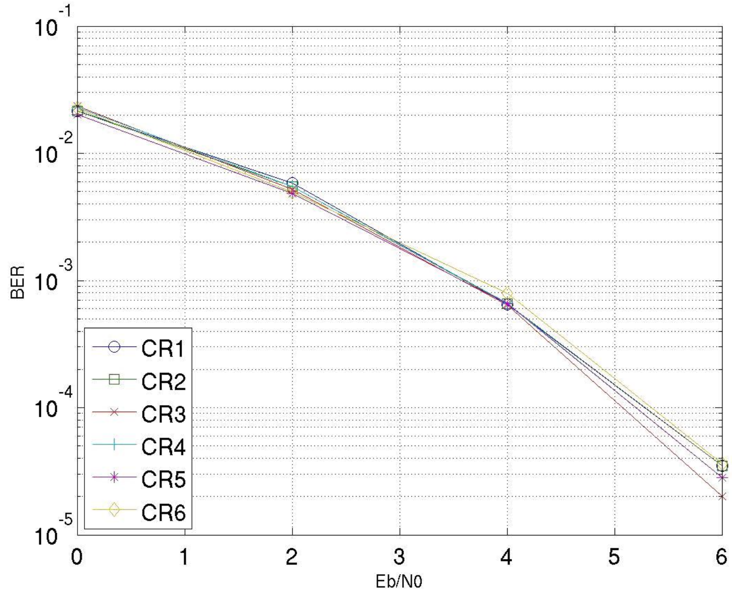

Fig. 8. BER Performances of CR Users (Synchronous, Case I)

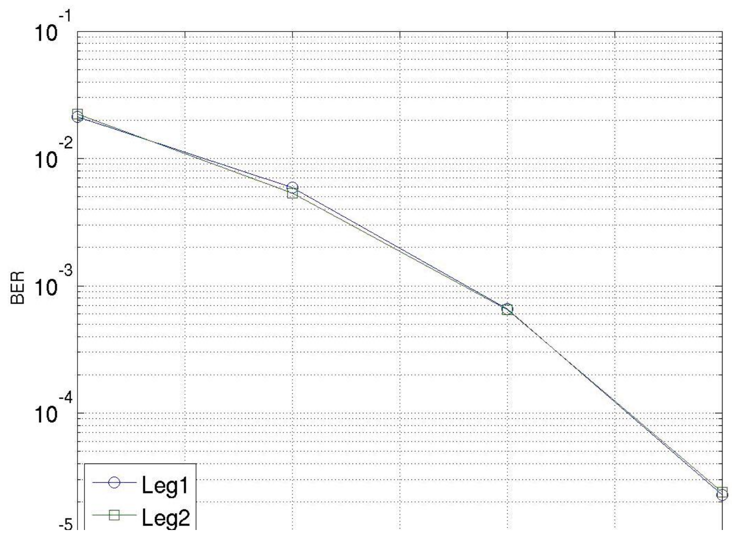

Fig. 9. BER Performances of Legacy Users (Synchronous, Case I)

10 OFDM users could be allocated. Here, we assume the legacy OFDM user uses 5.25 - 5.27 GHz (corresponding to the normalized frequency 0 - 0.2π). In Fig. 18, TSC converges to the value about 7.1. The weights by which the legacy interference project onto the bases are

$$[0.1809\ 0.2282\ 0.1698\ 0.1775\ 0.6786\ 0.3440\ 0.8716\ 0.6677],$$

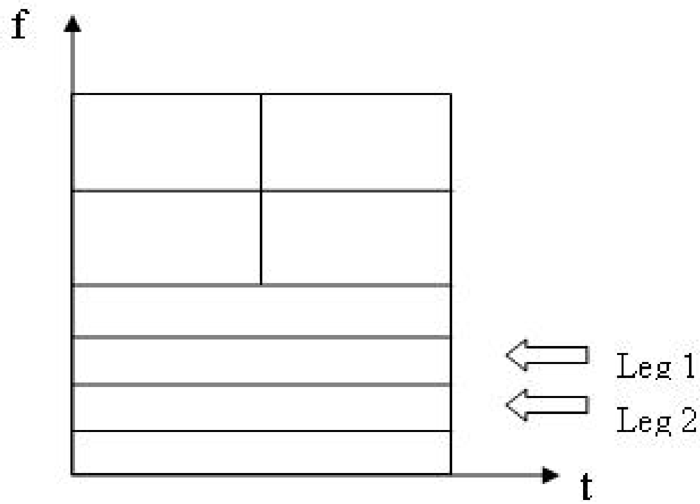

Fig. 10. Tiling of F-T Plane (Synchronous, Case II)

and the signature sequences of CR users after updating are,

$$\begin{bmatrix} 0.2346 & 0.4563 & 0.1170 & 0.7163 & -0.0000 & -0.4582 & -0.0000 & -0.0000 \\ 0.4750 & 0.4793 & 0.4572 & -0.5772 & -0.0000 & -0.0504 & -0.0000 & -0.0000 \\ -0.5801 & -0.0429 & 0.1600 & -0.3182 & -0.0000 & -0.7312 & -0.0000 & -0.0000 \\ -0.2114 & 0.6422 & -0.7085 & -0.1947 & 0.0000 & 0.0545 & 0.0000 & 0.0000 \\ 0.6023 & -0.3735 & -0.5139 & -0.1835 & -0.0000 & -0.4471 & -0.0000 & -0.0000 \end{bmatrix}.$$

We can see that after updating, the signature sequences of CR users obviously avoid the bases interfered heavily by legacy users. The worse performance of the third CR user is due to large portion of his weights is on the basis interfered more heavily than other uninterfered bases.

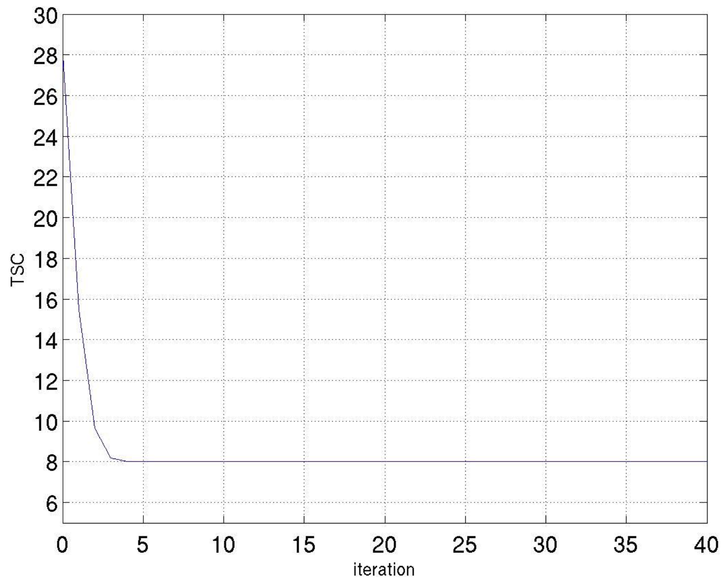

Fig. 11. TSC of All Users after Each Iteration Update (Synchronous, case II)

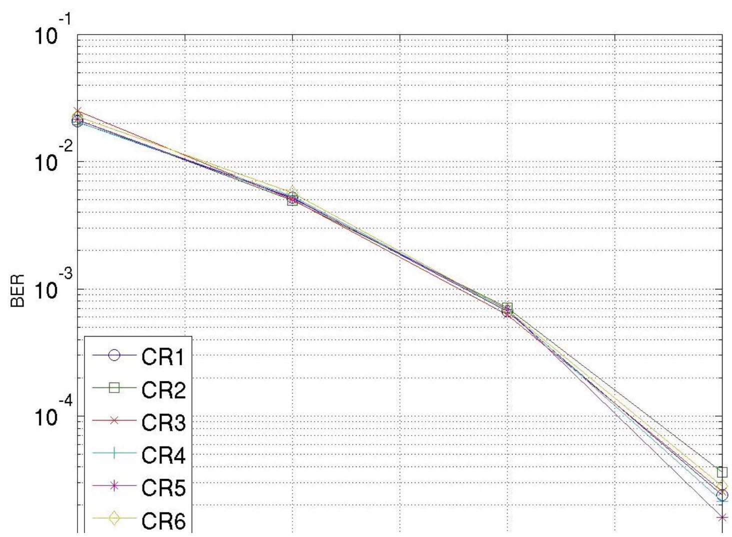

Fig. 12. BER Performances of CR Users (Synchronous, Case II)

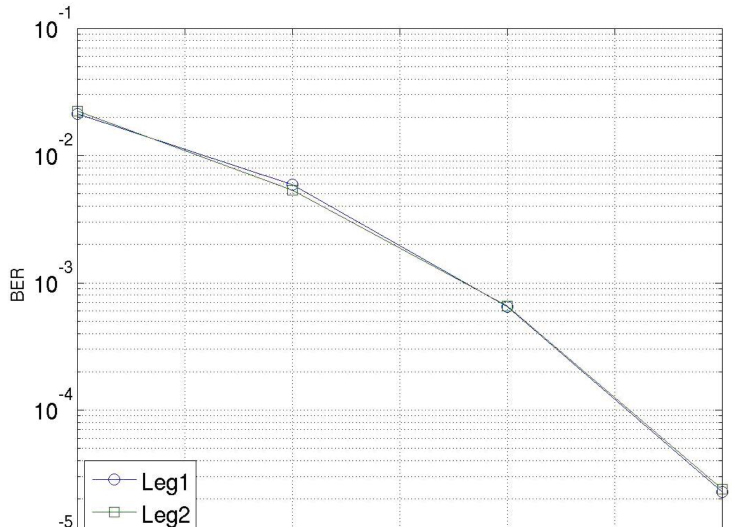

Fig. 13. BER Performances of Legacy Users (Synchronous, Case II)

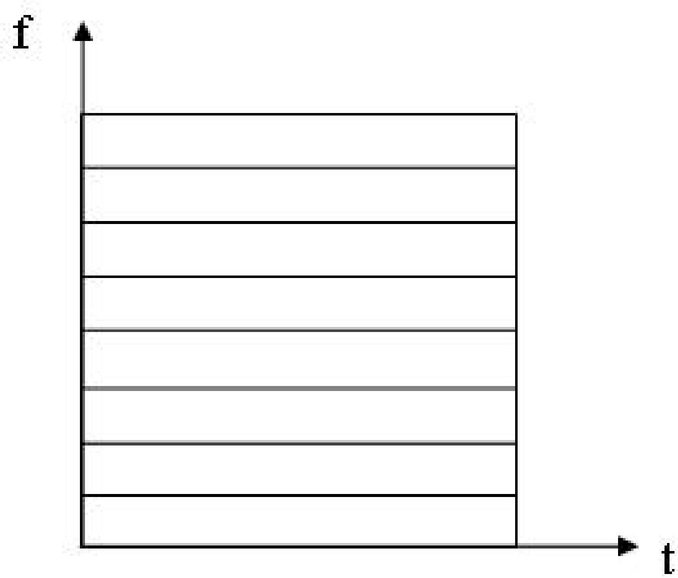

Fig. 14. Tiling of F-T Plane (Synchronous, Case III)

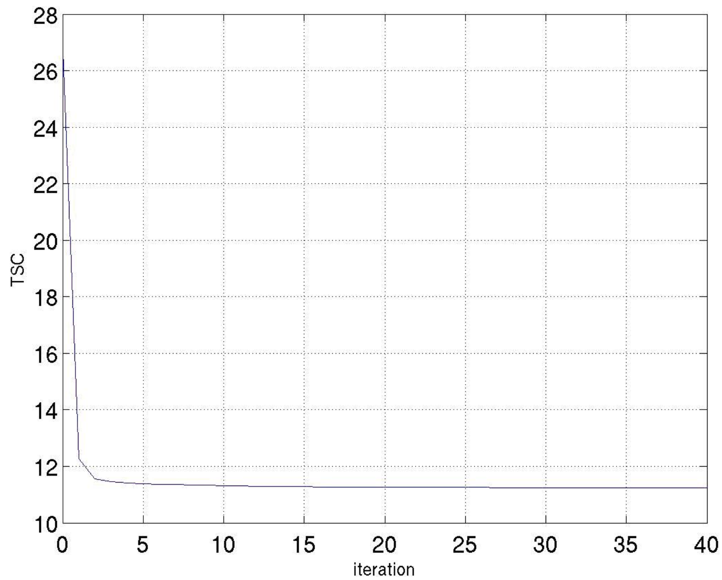

Fig. 15. TSC of All Users after Each Iteration Update (Synchronous, case III)

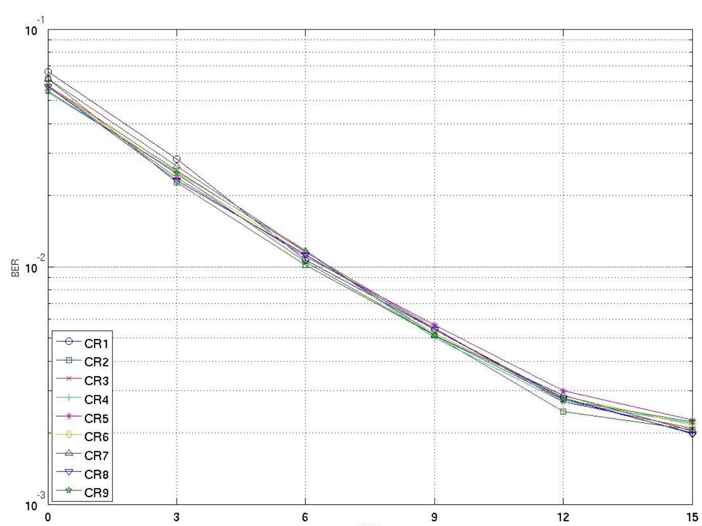

Fig. 16. BER Performances of CR Users (Synchronous, Case III)

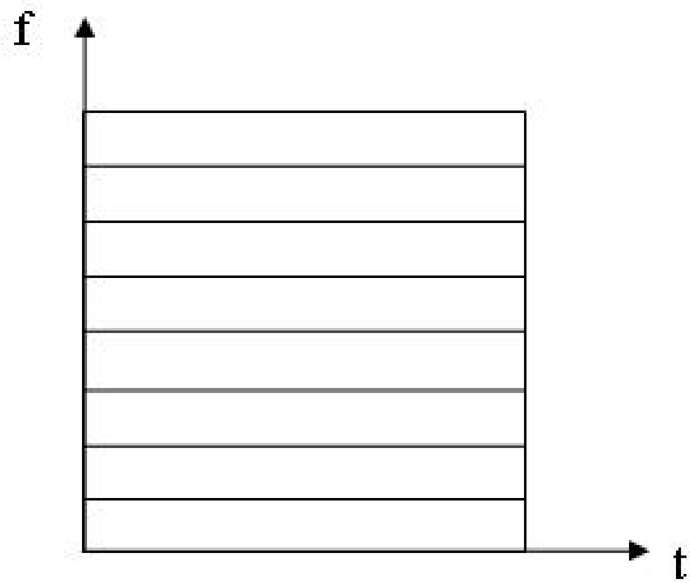

Fig. 17. Tiling of F-T Plane (Synchronous, Case IV)

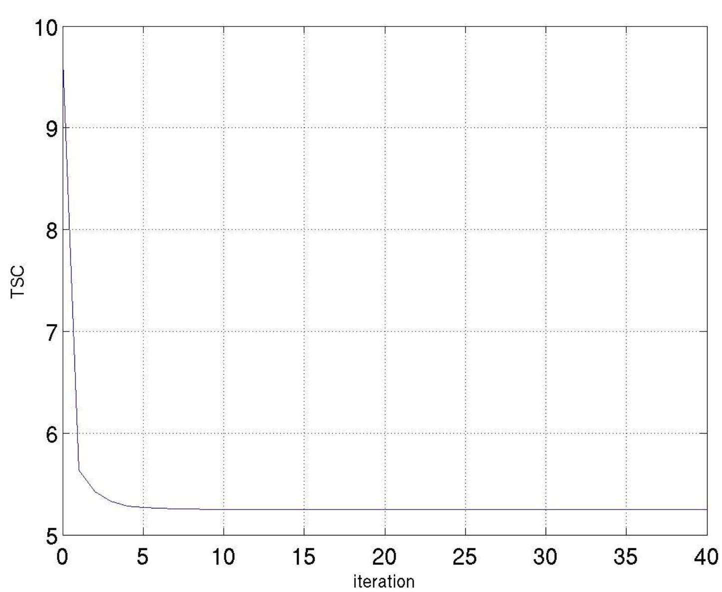

Fig. 18. TSC of All Users after Each Iteration Update (Synchronous, case IV)

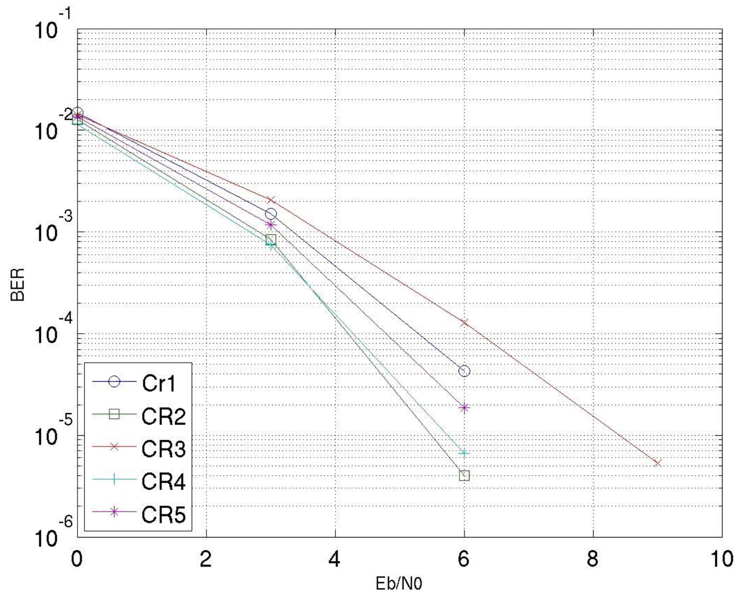

Fig. 19. BER Performances of CR Users (Synchronous, Case IV)

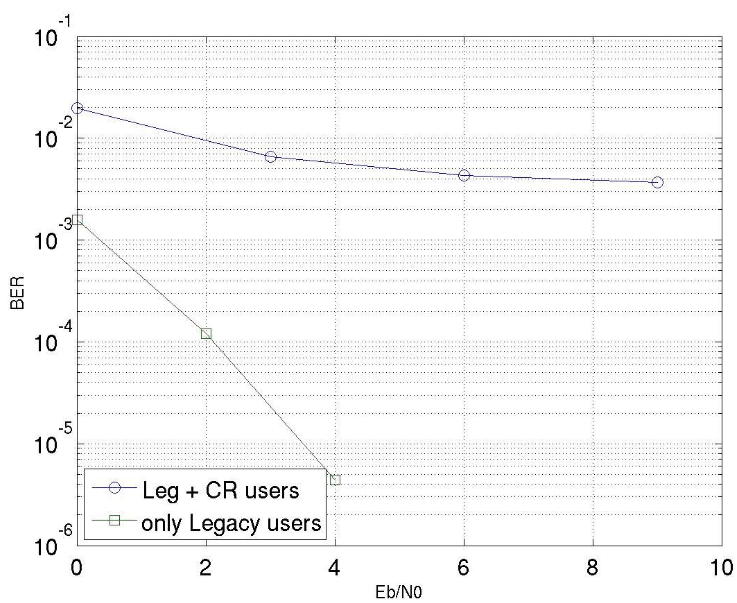

Fig. 20. BER Performances of Legacy Users (Synchronous, Case IV)

4) Uplink Channel: In the uplink channel, users transmit signals to the base-station, so each one is asynchronous with respect to others, unlike in the downlink channel. In the following, we show some asynchronous cases. In cases I - III, there are two WPDM legacy users using the 12th and 14th wavelet packet bases, respectively, and five CR users using MMSE update algorithm to update their signature waveforms. The users are asynchronous and the time delays are relative delays respect to the first user. Each case tiles the F-T plane with different permutations. We also show a case in which the legacy user is an OFDM user.

Numerical Results and Discussion

Case I: Number of CR users: 5, delay profile of CR users: [0 0 2 2 4], number of legacy users: 2, delay profile of legacy users: [0 0], WP bases used by legacy users: [12 14].

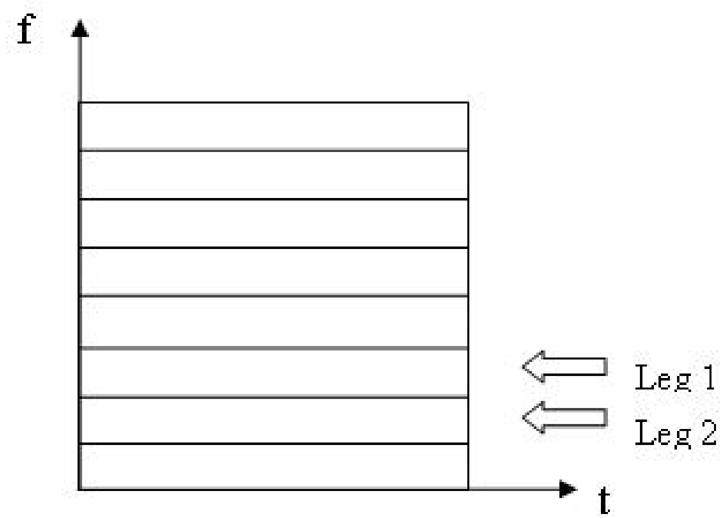

Fig. 21. Tiling of F-T Plane (Asynchronous, Case I)

Case II: Number of CR users: 5, delay profile of CR users: [0 0 2 2 4], number of legacy users: 2, delay profile of legacy users: [0 0], WP bases used by legacy users: [12 14].

Case III: Number of CR users: 5, delay profile of CR users: [0 0 2 2 4], number of leg users: 2, delay profile of leg users: [0 0], WP bases used by legacy users: [12 14].

From the above cases, we can find that in the asynchronous systems, the wavelet packet bases at the lower levels (i.e., the bases closer to the scaling function) will have more immunity against the asynchronism. That is because the lower levels at which wavelet packet bases are, the shorter time interval at integer multiples of which the bases are self and mutually orthogonal. In the next section, we will discuss this property and utilize it to choose the wavelet packet bases, and propose an algorithm to adaptively tile the F-T plane according to the measured interference.

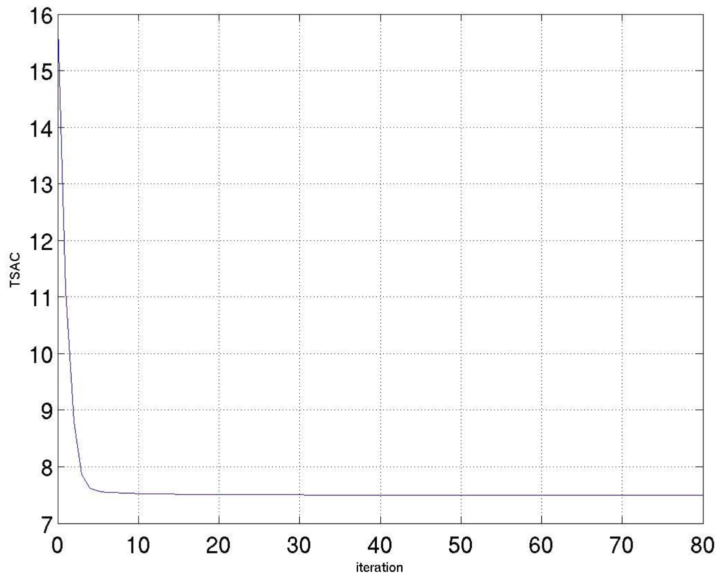

Fig. 22. TSC of All Users after Each Iteration Update (Asynchronous, Case I)

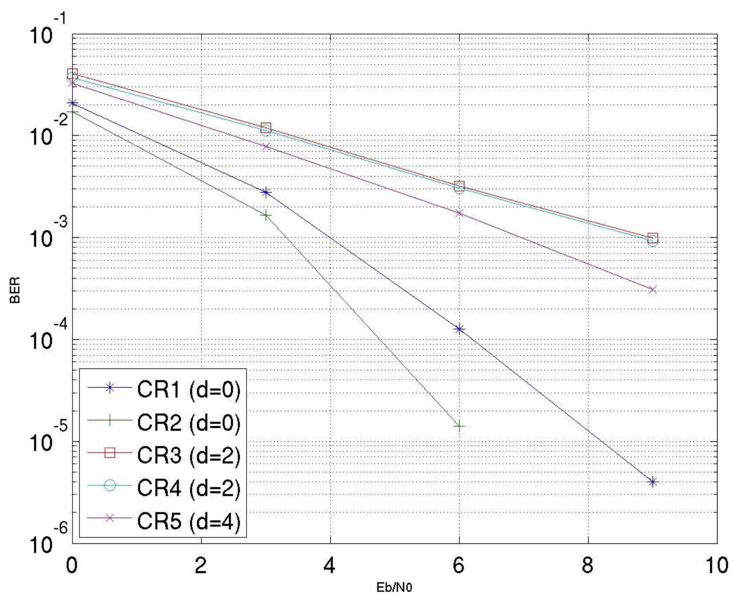

Fig. 23. BER Performances of CR Users (Asynchronous, Case I)

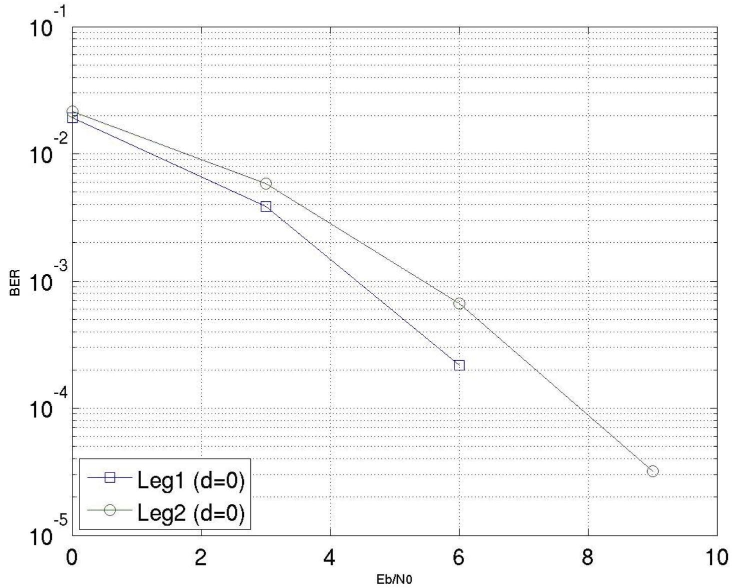

Fig. 24. BER Performances of Legacy Users (Asynchronous, Case I)

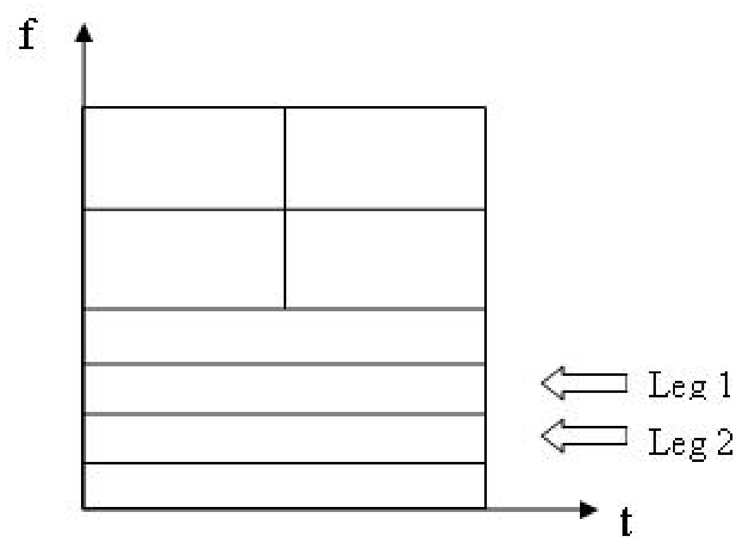

Fig. 25. Tiling of F-T Plane (Asynchronous, Case II)

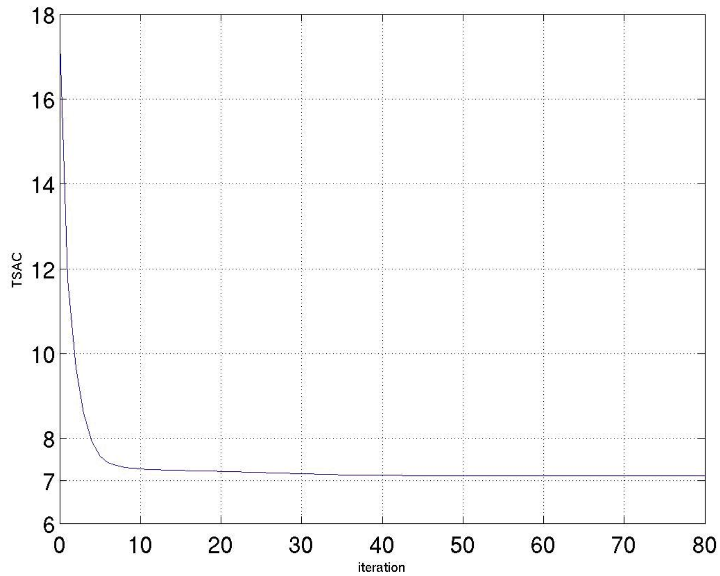

Fig. 26. TSC of All Users after Each Iteration Update (Asynchronous, case II)

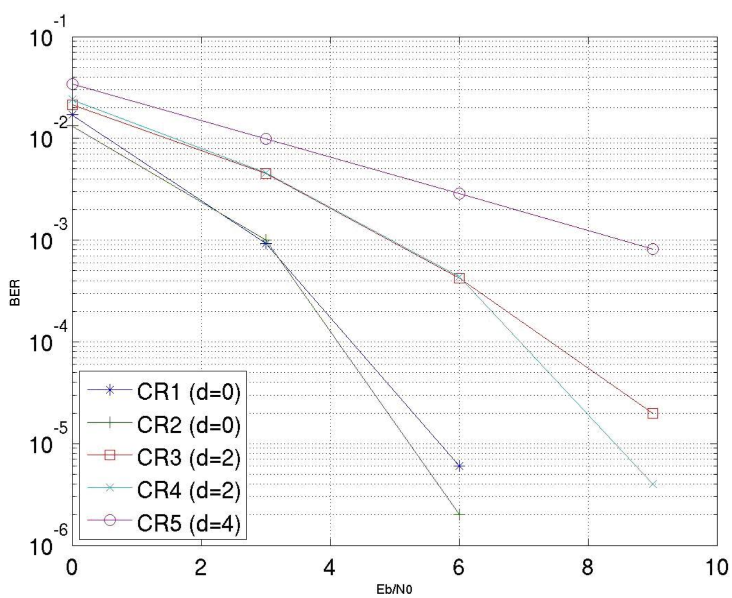

Fig. 27. BER Performances of CR Users (Asynchronous, Case II)

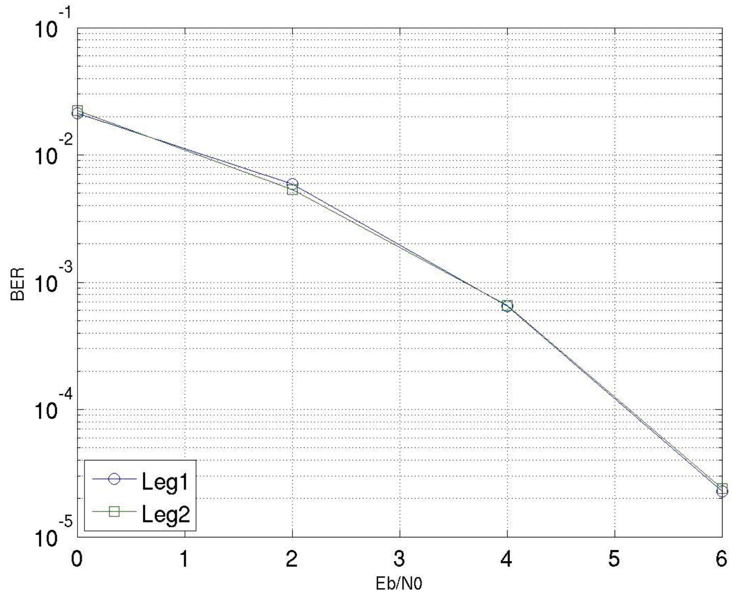

Fig. 28. BER Performances of Legacy Users (Asynchronous, Case II)

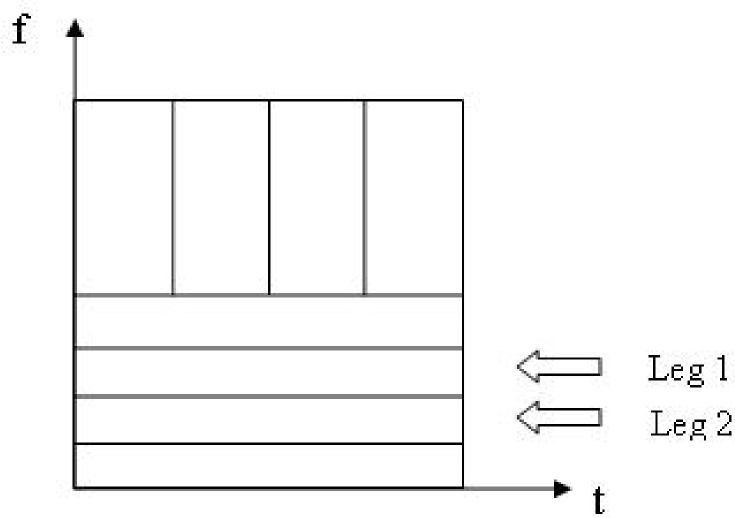

Fig. 29. Tiling of F-T Plane (Asynchronous, Case III)

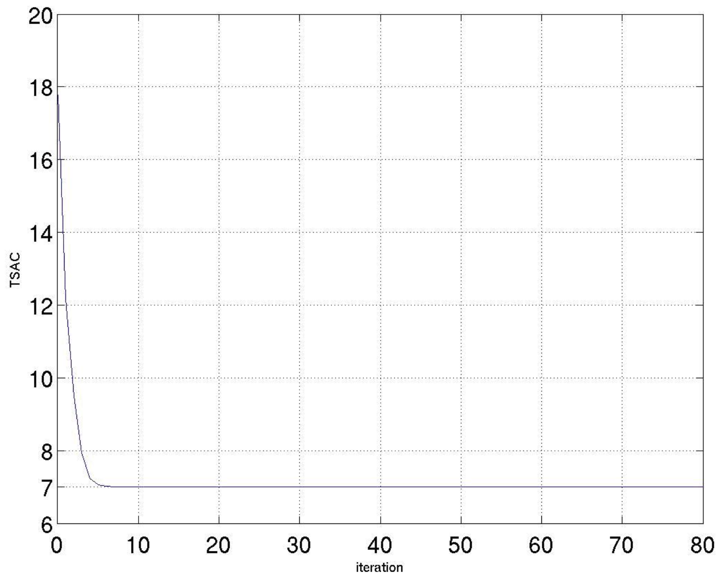

Fig. 30. TSC of All Users after Each Iteration Update (Asynchronous, case III)

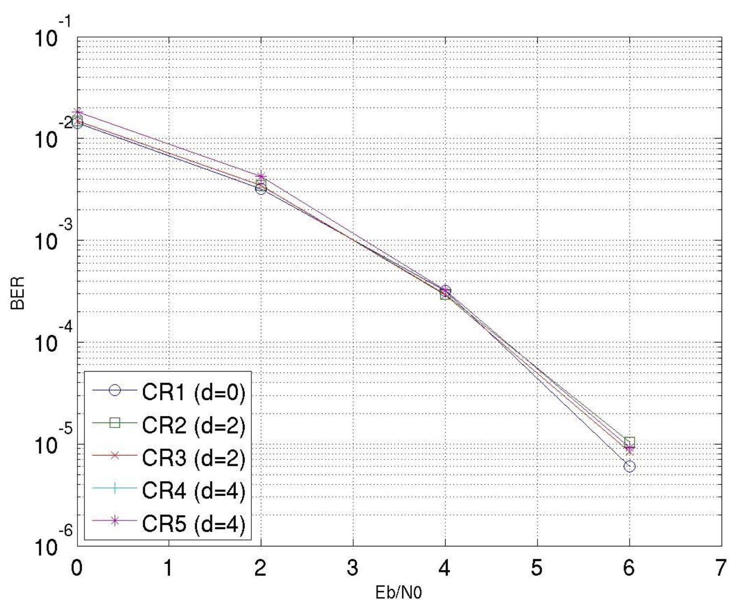

Fig. 31. BER Performances of CR Users (Asynchronous, Case III)

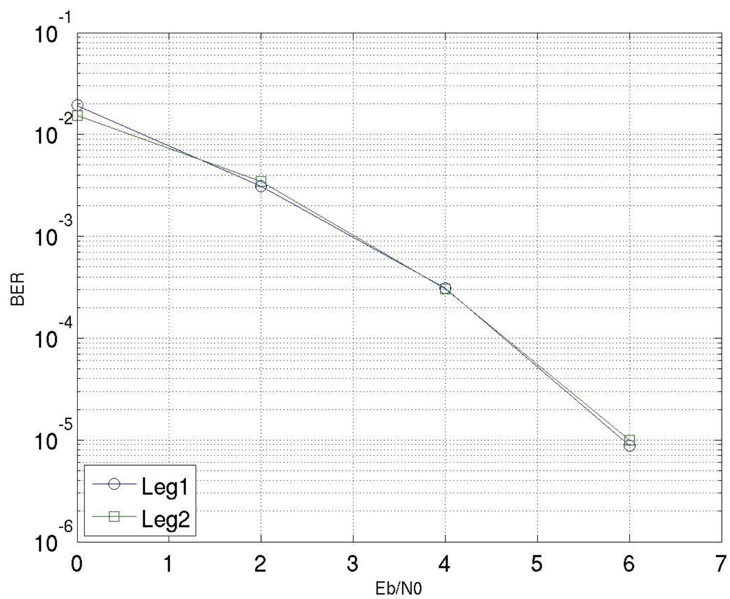

Fig. 32. BER Performances of Legacy Users (Asynchronous, Case III)

C. Algorithm for the Tiling Method of F-T Plane

In the previous section, it has been shown that different tiling methods of F-T plane could result in different performances. In this section, we first discuss the properties of wavelet packet. Then we propose an algorithm to tile the F-T plane according to the measured interference from the view points of frequency domain and time domain, respectively.

1) Further Properties of Wavelet Packets: Wavelet packet decomposition is a method utilizing both frequency domain and time domain, unlike FDM, in which frequency domain is considered, or TDM, in which time domain is considered. The scaling function $\phi_{01}(t)$ is a basis which has a widest bandwidth, but a shortest duration, $(L-1)T_0$, where L represents the length of filters $h[n]$ and $g[n]$, and T_0 represents the time interval at integer multiples of which the scaling function is self and mutually orthogonal. The children bases $\phi_{11}(t)$ and $\phi_{12}(t)$ yielded by $\phi_{01}(t)$ have a half bandwidth, but a double duration of $\phi_{01}(t)$. Every time the level grows, the resulted bases have a half bandwidth, but a double duration of their parents. So bandwidth of the bases at level three is one-eighth of $\phi_{01}(t)$, but they have eight times the duration of the scaling function. This is the property we will utilize to design the signature waveform of CR users.

2) Tiling Methods of F-T Plane: In cognitive radio systems, dynamic spectrum management is one of the major concepts. The primary purpose of spectrum management is to develop an adaptive strategy for the efficient and effective utilization of the RF spectrum. In WPDM scheme, this task is achieved by tiling of F-T plane. In this section we propose an algorithm to tile the F-T plane. In our method, the CR users first sense the environment and observe the interference levels at the outputs of eight match filters each matching to one of the eight wavelet packet bases at level three (i.e., the bases indexed as 8 - 15 in Fig. 6). The eight outputs of match filters represent the weights by which the interference projects on the corresponding bases. After getting the weights, we partition the eight bases into two groups, interfered ones and un-interfered ones, distinguished by the threshold value 0.4. The threshold value is set to be 0.4 because the weights on the un-interfered bases (with only noise) are usually around 0.1 - 0.35 when we set SNR of legacy users to be 3 dB. If there are brother bases (i.e., the ones having the same parents) in the same groups, we will combine them and replace them with their parent bases. Recursively combining and replacing until there are no brother bases in the same groups, we finish the tiling of F-T plane and get the bases for MMSE update algorithm. The tiling algorithm is summarized in Algorithm 1, and an example is given

Algorithm 1: Tiling of F-T plane

Assumption: The threshold value: 0.4

Initialization: The weights by which interference signal projects on the level 3 bases (i.e., indexed as 8 - 15): $\{a_1, a_2, \ldots, a_8\}$

1) Scan and combine the level 3 bases.
   Group the eight weights into two groups using the threshold value. If there are any bases in the same group having the same parents, combine them and replace them with their parents.
2) Scan and combine the level 2 bases.
   If the number of level 2 bases is zero, then stop the algorithm. Group the weights of level 2 bases into two groups using the threshold value. If there are any bases in the same group having the same parents, combine them and replace them with their parents.
3) Scan and combine the level 1 bases.
   If the number of level 1 bases is zero, then stop the algorithm. Group the weights of level 1 bases into two groups using the threshold value. If there are any bases in the same group having the same parents, combine them and replace them with their parents.

3) Numerical Results and Discussion:

Case I: Number of CR users: 5, delay profile of CR users: [0 0 2 2 4], number of legacy users: 3, delay profile of legacy users: [0 0 0], WP bases used by legacy users: [2 13 7].

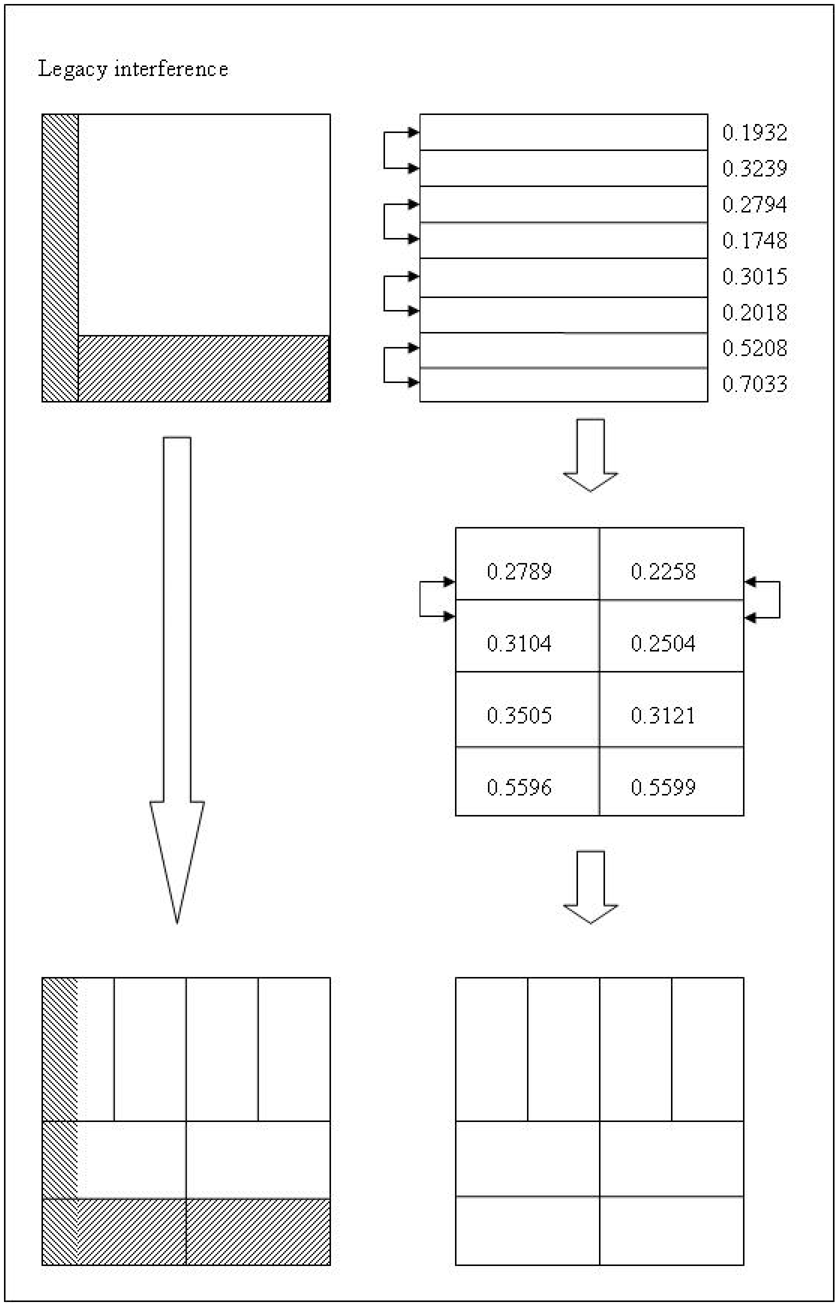

Fig. 33. Example for tiling of F-T plane

Case II: Number of CR users: 5, delay profile of CR users: [0 0 2 2 4], number of legacy users: 3, delay profile of legacy users: [0 0 0], WP bases used by legacy users: [2 13 7].

In case I, the CR system uses the eight bases at level three to tile the F-T plane, while in case II, it tiles the F-T plane using Algorithm 1. From the simulation results, it is clear that tiling F-T plane with Algorithm 1 has better performance than arbitrary tiling.

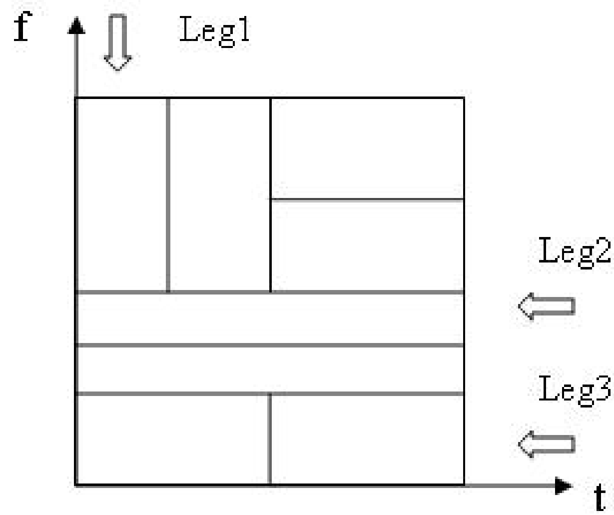

Fig. 34. Tiling of Legacy Users' F-T Plane (Case I).

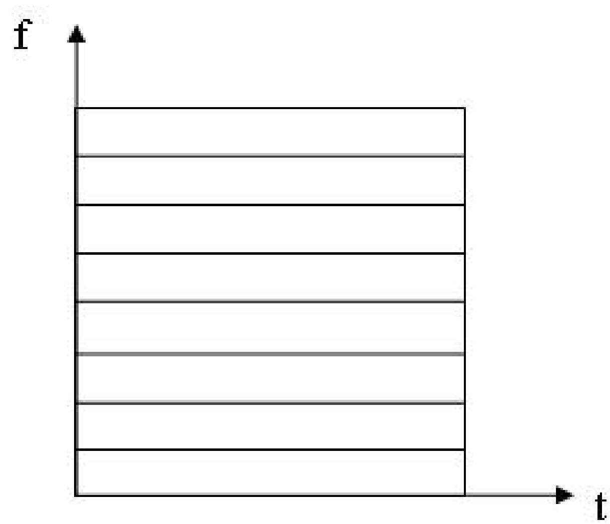

Fig. 35. Tiling of CR Users' F-T Plane (Case I).

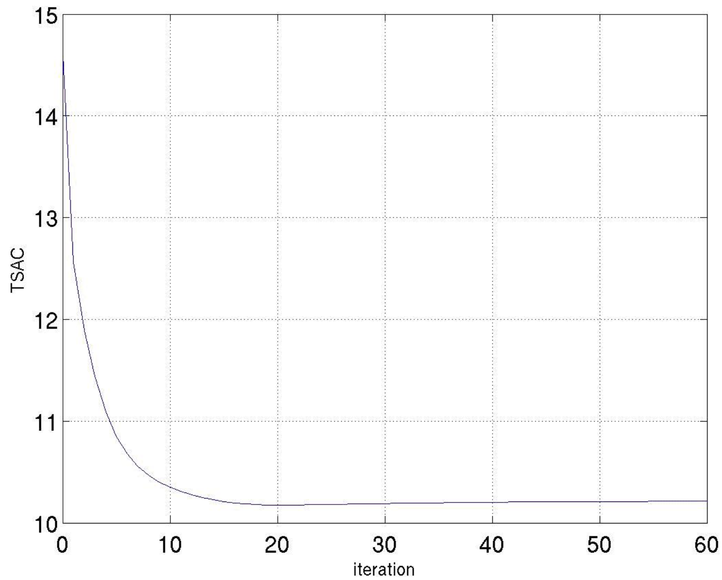

Fig. 36. TSC of All Users after Each Iteration Update (Case I)

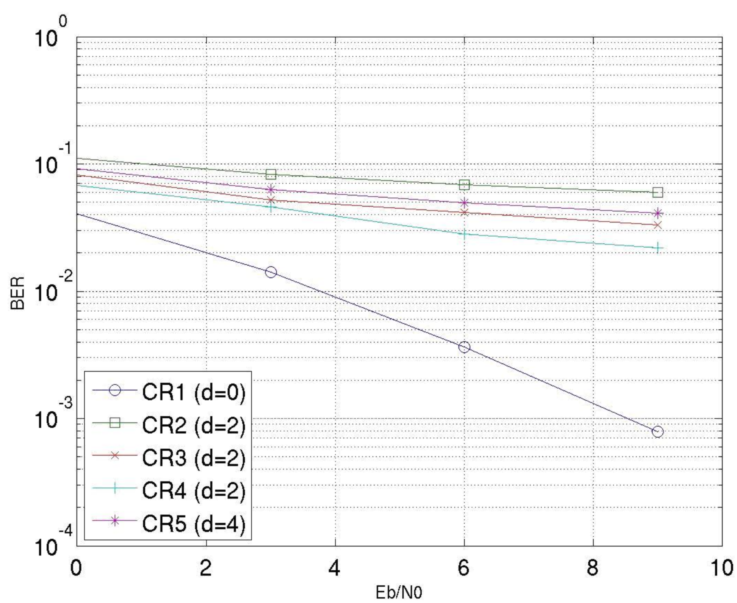

Fig. 37. BER Performances of CR Users (Case I)

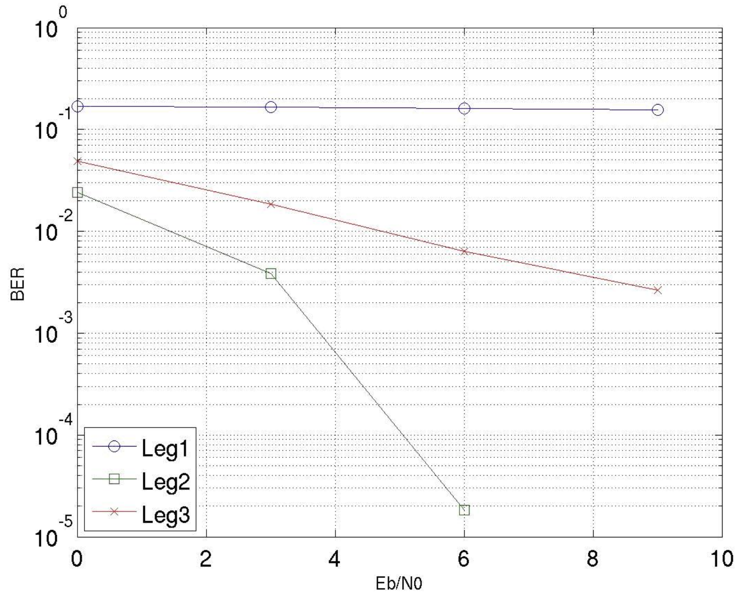

Fig. 38. BER Performances of Legacy Users (Case I)

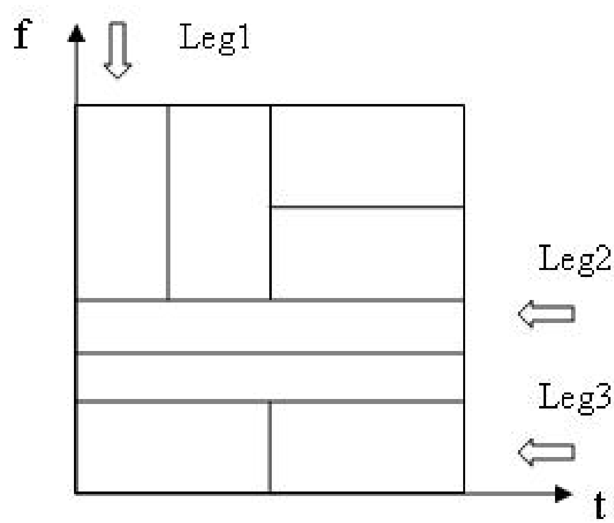

Fig. 39. Tiling of Legacy Users' F-T Plane (Case II).

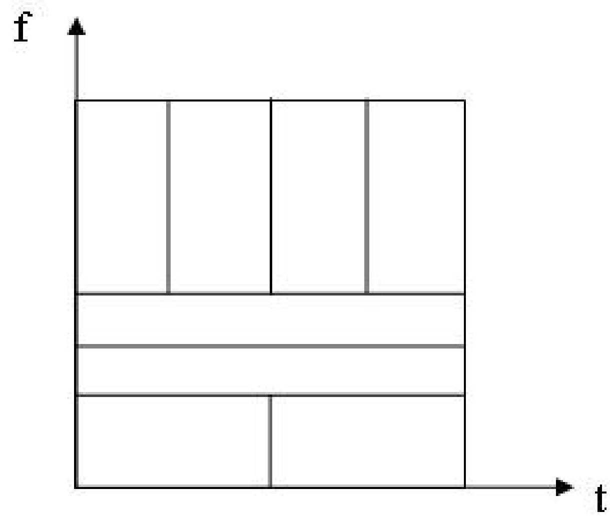

Fig. 40. Tiling of CR Users' F-T Plane (Case II).

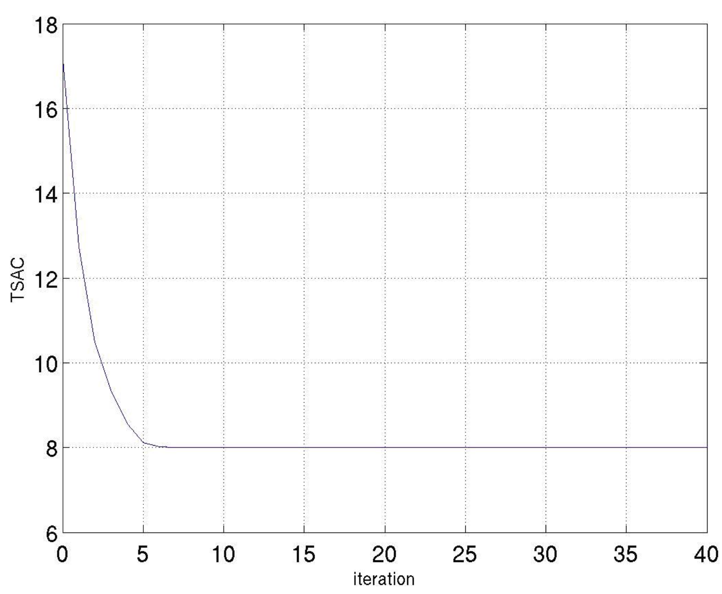

Fig. 41. TSC of All Users after Each Iteration Update (Case II)

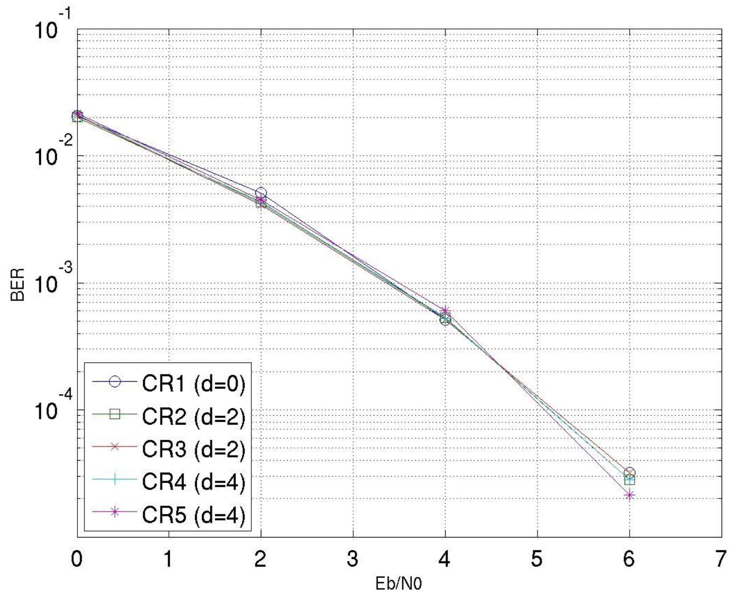

Fig. 42. BER Performances of CR Users (Case II)

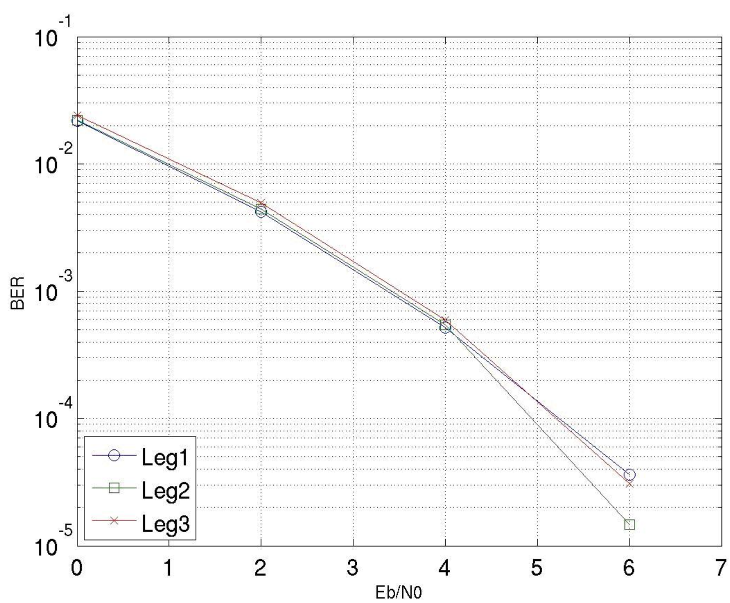

Fig. 43. BER Performances of Legacy Users (Case II)

Case III: Number of CR users: 3, delay profile of CR users: [0 2 4], number of legacy users: 1, subcarriers used by legacy users: 1-64, 129 - 192.

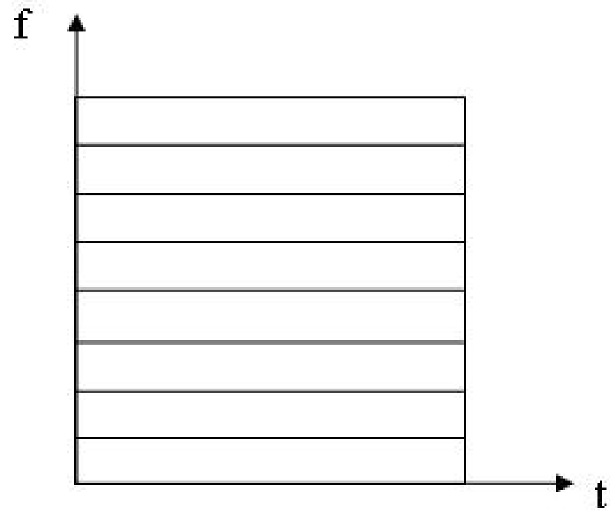

Fig. 44. Tiling of CR Users' F-T Plane (Case III).

Case IV: Number of CR users: 3, delay profile of CR users: [0 2 4], number of legacy users: 1, subcarriers used by legacy users: 1-64, 129 - 192.

In cases III and IV, we assume that the legacy user uses OFDM and engages normalized bandwidth between $0-0.2\pi$ and $0.4\pi-0.6\pi$. The weights the legacy interference projects onto the bases at level three (i.e., bases indexed 8 - 15) are

$$[0.3613\ 0.2434\ 0.6475\ 0.6284\ 0.5413\ 0.3503\ 0.6357\ 0.5313].$$

The tiling method for case IV is Algorithm 1, while case III uses arbitrary tiling. TSAC (total squared asynchronous correlation between CR users plus cross-correlation between legacy users and CR users) in case IV, which is around 3.25, is lower than that in case III, which is around 3.5. Both CR users and legacy users in case IV outperform those in case III. This is because in asynchronous systems, the bases with shorter durations have better immunity against the asynchronism. From the TSAC of both cases, however, we can find that CR users and legacy users are not orthogonal perfectly. This is also reflected Fig. 47 and Fig. 51. This is because we use the eight wavelet packet bases to represent the OFDM waveforms which are not orthogonal to the wavelet packets. We now discuss some possible methods to reduce interference to legacy users. 1) set the maximum level of wavelet packet tree to be larger, i.e. use more wavelet bases whose bandwidth are thinner to represent the waveforms of legacy users. This will reduce the error due to projecting the waveforms of legacy users onto the wavelet packet space. 2) Increase the weights of legacy users in the TSC or TSAC. This will emphasize the legacy interference and let the CR users avoid the legacy signals more effectively. 3) Change the wavelet packet bases to OFDM waveforms. When base station of CR systems senses the environment and finds that the legacy users are OFDM users, the base-station might choose OFDM waveforms to be bases. In other words, the base station has the capability to choose the bases suited to the legacy users to reduce the interference to them.

Case V: Number of CR users: 6, number of legacy users: 1.

Case VI: Number of CR users: 6, number of legacy users: 1.

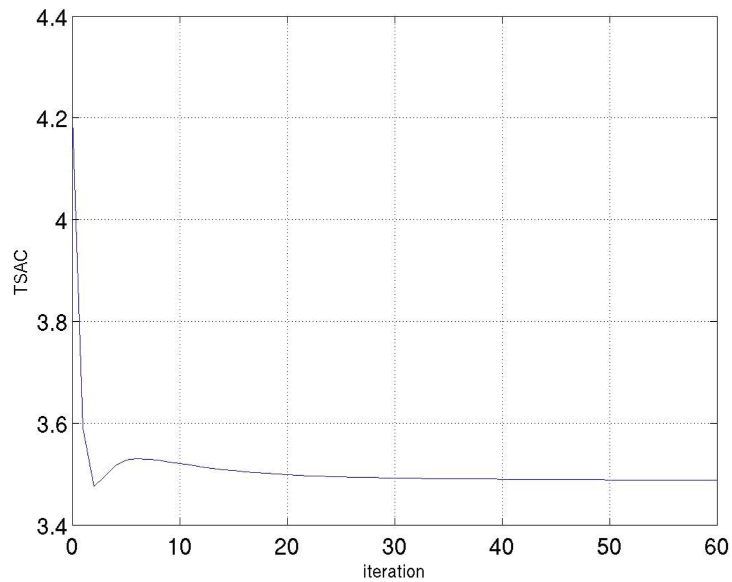

Fig. 45. TSC of All Users after Each Iteration Update (Case III).

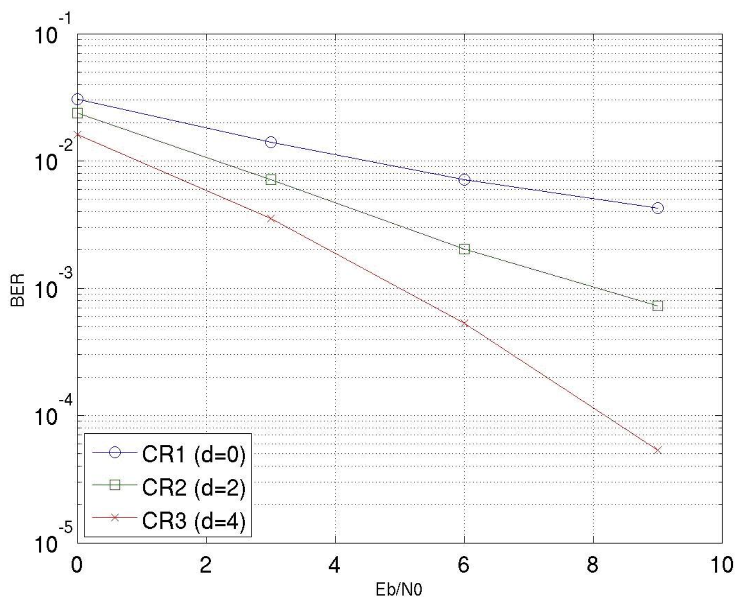

Fig. 46. BER Performances of CR Users (Case III)

In cases V and VI, the legacy interference is set to be a rectangular waveform in the time interval $0-13T_0$ with a period of $104T_0$. We can find that when the legacy interference is a TDM signal, transmitting signals by wavelet bases with a shorter duration, as in case V, can effectively avoid the interference in time domain, while transmitting signals by wavelet bases with a longer duration, as in case VI, results in worse performance.

Case VII: Number of CR users: 5, delay profile of CR users: [0 0 2 4 4], number of legacy users: 1.

Case VIII: Number of CR users: 5, delay profile of CR users: [0 0 2 4 4], number of legacy users: 1.

In cases VII and VIII, we let the legacy interference be a mixed signal of two extreme cases, FDM and TDM. Both cases are asynchronous systems. In case VII, Algorithm 1 is used for tiling, while case

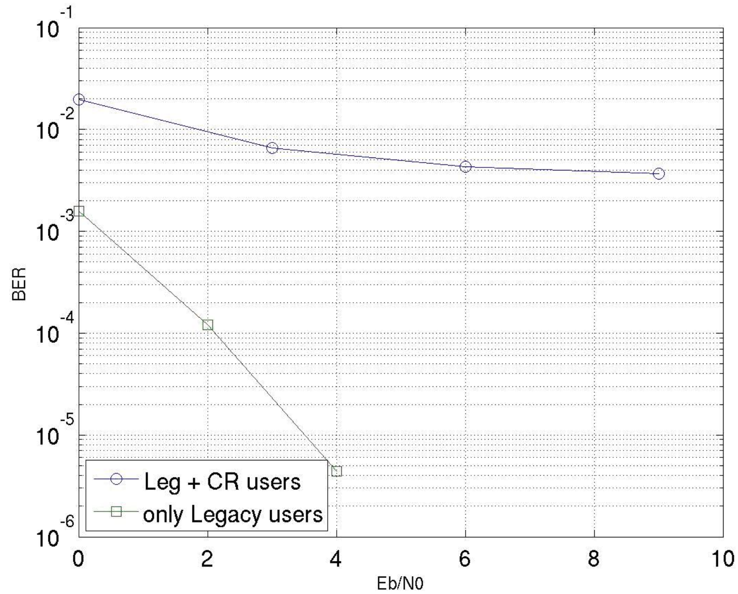

Fig. 47. BER Performances of Legacy Users (Case III)

VIII uses arbitrary tiling. Because of tiling according to the measured interference in case VII, the bases we choose will be cleaner (i.e., less interfered) than those in case VIII. So the performances of CR users in case VII are better than those in case VIII using arbitrary tiling.

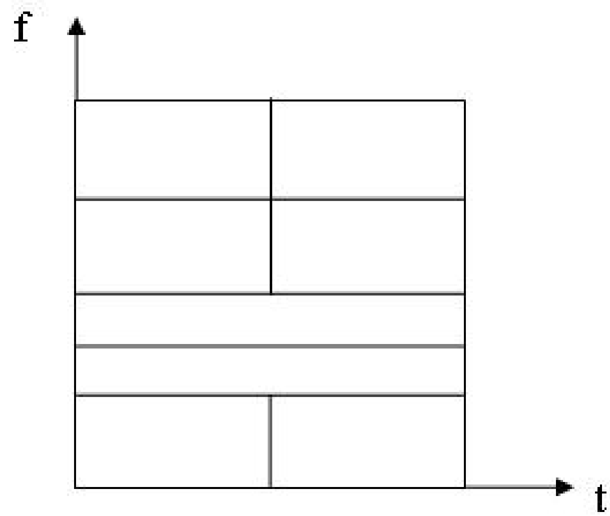

Fig. 48. Tiling of CR Users’ F-T Plane (Case IV).

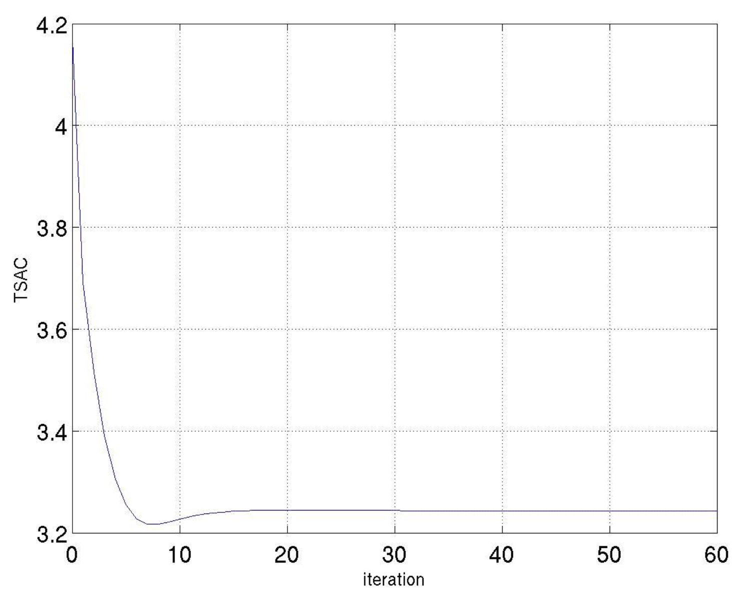

Fig. 49. TSC of All Users after Each Iteration Update (Case IV).

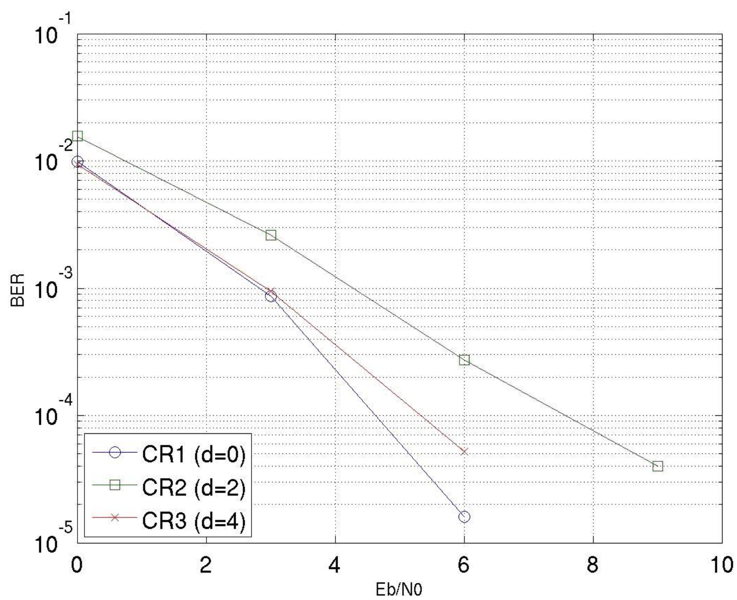

Fig. 50. BER Performances of CR Users (Case IV)

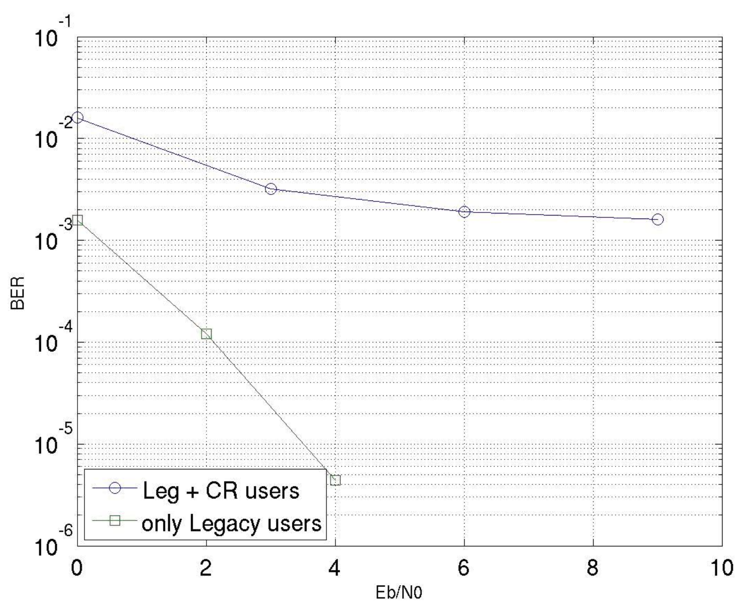

Fig. 51. BER Performances of Legacy Users (Case IV)

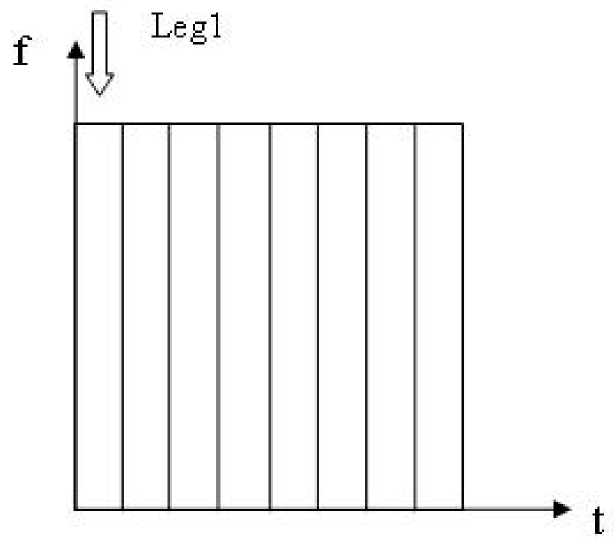

Fig. 52. Tiling of CR Users' F-T Plane (Case V).

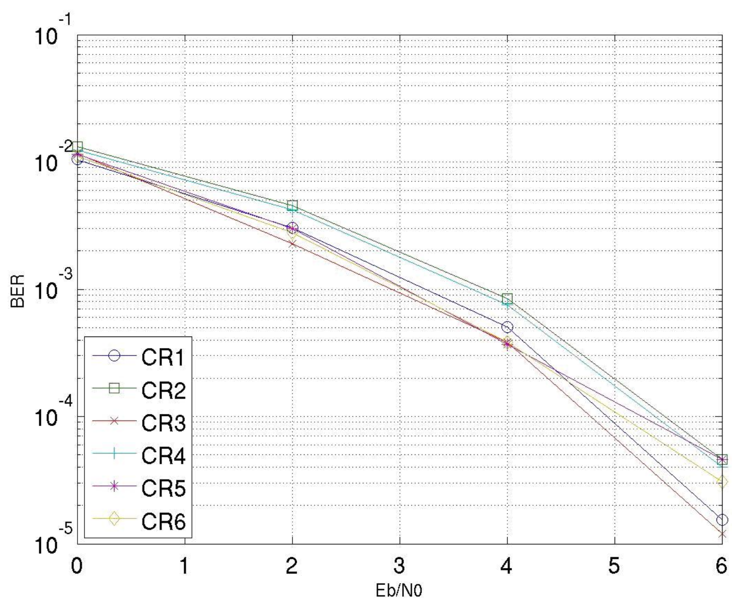

Fig. 53. BER Performances of CR Users (Case V).

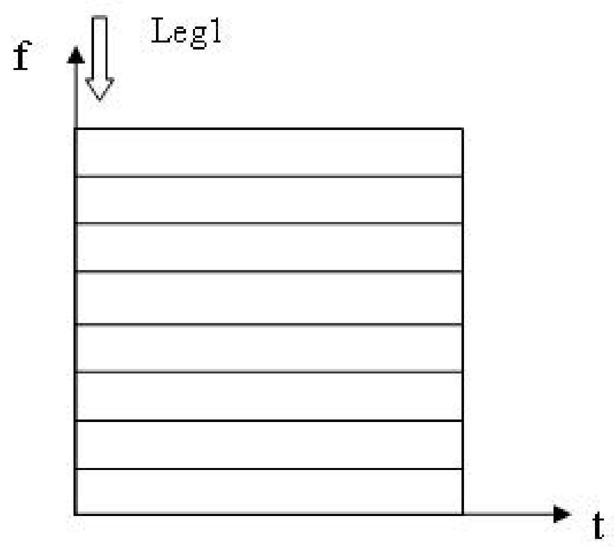

Fig. 54. Tiling of CR Users' F-T Plane (Case VI).

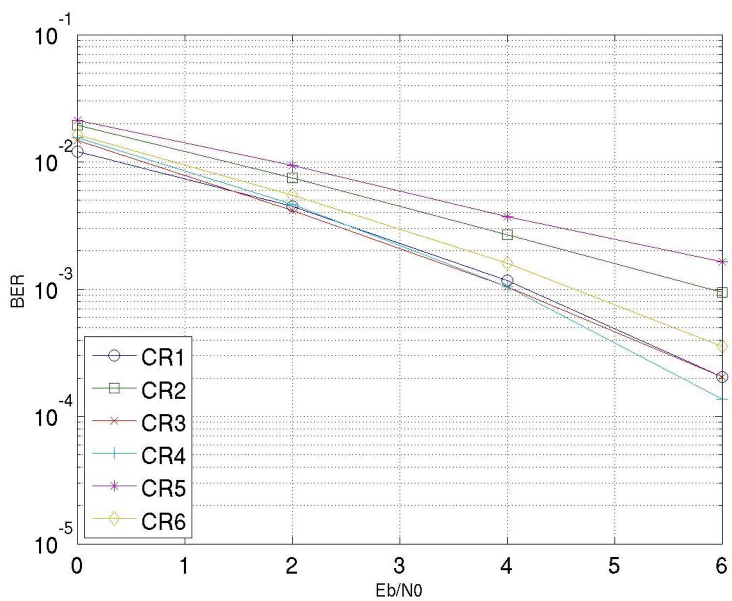

Fig. 55. BER Performances of CR Users (Case VI).

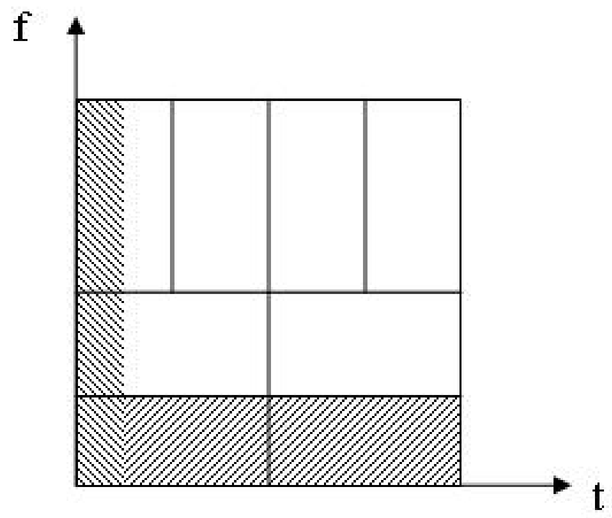

Fig. 56. Tiling of CR Users' F-T Plane (Case VII).

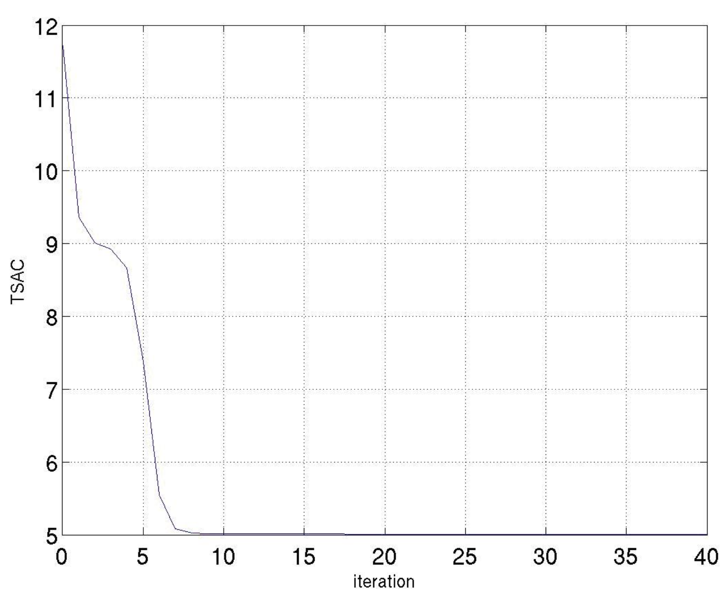

Fig. 57. TSC of CR Users after Each Iteration Update (Case VII).

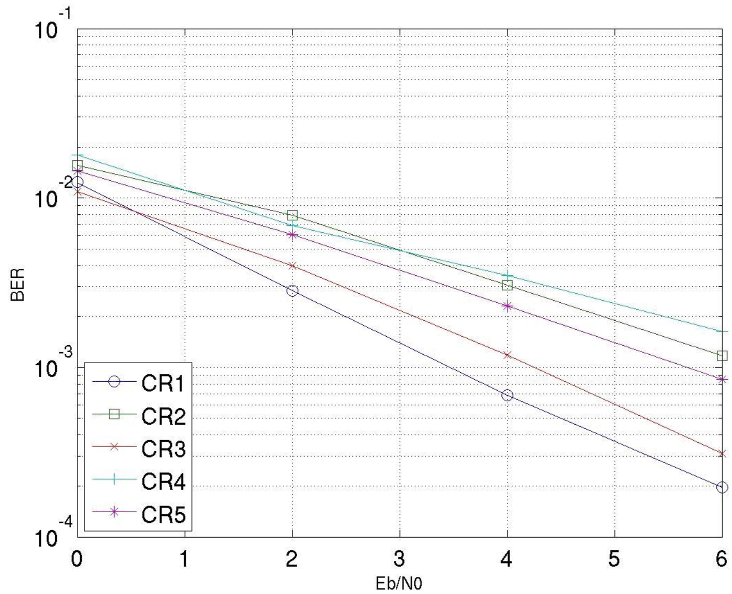

Fig. 58. BER Performances of CR Users (Case VII).

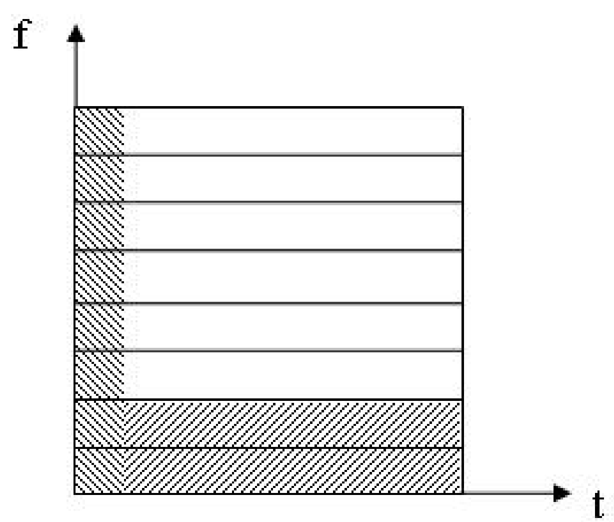

Fig. 59. Tiling of CR Users' F-T Plane (Case VIII).

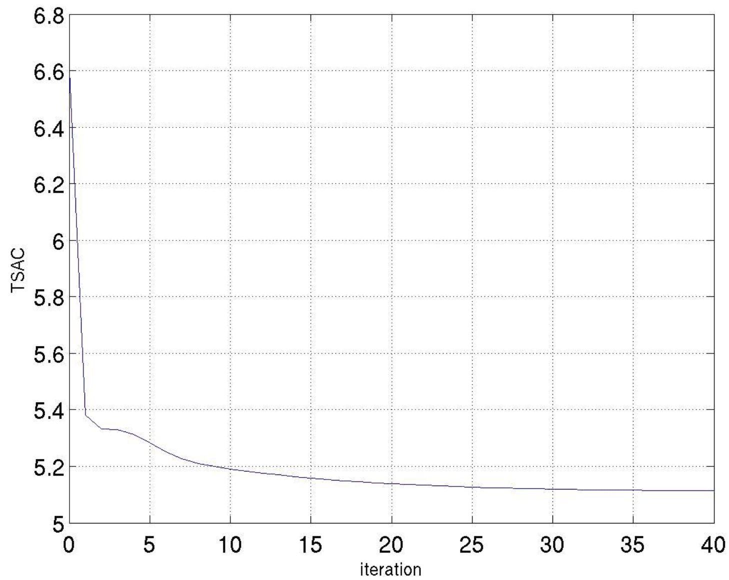

Fig. 60. TSC of CR Users after Each Iteration Update (Case VIII).

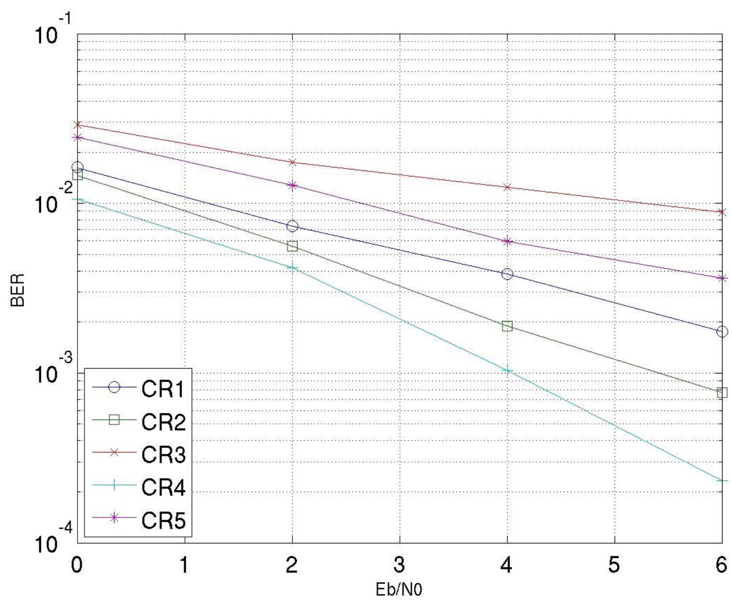

Fig. 61. BER Performances of CR Users (Case VIII).

IV. CONCLUSION

In the first year of this project, autonomous multi-user dynamic resource allocation was investigated. Wavelet packet bases with autonomous signature waveform design were adopted to facilitate optimal spectral shaping, interference avoidance and power water filling. Simulation results showed that the autonomous signature waveform design algorithm indeed minimizes the TSC and TSAC and results in low error probability. In addition, the wavelet packet bases helps in achieving good spectral shaping and compact bandwidth. A reconfigurable basis selection algorithm was further developed to maximize the sum rate of the network in various network and channel conditions.

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