

Robust Cognitive-Radio-Based OFDM Architecture with Adaptive Traffic Allocation in Time and Frequency

Nak-Myeong Kim, Mee-Ran Kim, Eun-Ju Kim, Su-Jung Shin, Hye-In Yu, and Sang-Boh Yun

Cognitive radio (CR) has been proposed as an effective technology for flexible use of the radio spectrum. The interference between primary users and CR users, however, becomes a critical problem when they are using adjacent frequency channels with different transmission power levels. In this paper, a robust CR orthogonal frequency division multiplexing (OFDM) architecture, which can effectively suppress interference to nearby primary users and overcome adjacent channel interference (ACI) to the CR user, is proposed. This new approach is characterized by adaptive data repetition for subcarriers under heavy ACI, and adaptive time spreading for subcarriers near the borders of the CR user's spectrum. The data repetition scheme provides extra power gain against the ACI coming from primary users. Time spreading guarantees an acceptable interference level to nearby primary users. By computer simulation, we demonstrate that, under a CR environment, the proposed CR OFDM architecture outperforms conventional OFDM systems in terms of throughput and BER performance.

Keywords: Cognitive radio, data repetition over frequency, time spreading, orthogonal frequency division multiplexing (OFDM).

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I. Introduction

In future wireless communication systems, more spectral resources will be needed to provide ubiquitous multimedia services. Considering the limited frequency resources, innovative technologies for efficient spectrum utilization are required. The Federal Communications Commission (FCC)'s *Spectrum Policy Task Force Report* [1] identified that most spectrum resources are under-utilized most of time. Sometimes, spectrum scarcity results from unsuitable spectrum management rather than from a fundamental lack of spectrum. Cognitive radio (CR) technology offers a possible solution based on spectrum sharing or leases, in terms of time, frequency, or space diversity. The CR system is defined as a communication system that has the ability to dynamically detect unused spectrum and to adjust its power, frequency, modulation, coding, and other parameters to efficiently utilize the vacant spectrum [2].

Recently, there have been several studies on interference analysis in relation to CR systems. In [3], orthogonal frequency division multiplexing (OFDM) was considered as a promising candidate for the CR system because it is possible to provide a flexible spectral shape that fills the spectral gaps. Here, the concept of adaptive guard bands has been proposed for the mitigation of mutual interference between the CR system and the primary system. However, decrease in bandwidth efficiency and throughput is inevitable because of an additional deactivation of the subcarriers near the borders of the OFDM spectrum of the CR terminal. In [4], power scaling to the CR system was proposed to maintain guaranteed quality for

primary users. Also, Zhou and others [5] proposed an interference avoidance scheme to effectively protect primary transmission from intercarrier interference for OFDM systems. These schemes, however, only focus on the mitigation of interference of the CR system to the primary system.

For reliable operation of the CR system, it is necessary to mitigate the interference in both directions between the primary system and the CR system. When a CR user uses a frequency channel in the vicinity of active primary users' transmission channels, the OFDM subcarriers nearer to the border of the bandwidth get more severe adjacent channel interference (ACI) from the primary users. On the other hand, the CR user creates more interference for the primary users. In this paper, we propose a CR-based bandwidth sharing architecture for OFDM systems, which includes adaptive data repetition over frequency subcarriers (ADRF), and adaptive time spreading (ATS) with power control capabilities against ACI between primary users and CR users. The ADRF scheme provides CR users with extra power gain against ACI, and the ATS scheme guarantees a tolerable interference level to primary users.

The remainder of the paper is organized as follows. In section II, the CR system environment is briefly introduced, and in section III, the principles of ADRF and ATS are described. We then discuss the proposed CR OFDM architecture in section IV and describe the simulation results in section V. We conclude in section VI.

II. Cognitive Radio System Environment

In a CR environment, there are two types of terminals: primary (or licensed) terminals, which have the right to access the spectral resources any time, including GPRS, UMTS, emergency services, broadcast TV; and secondary (or CR) terminals, which seek transmission opportunities by exploiting the idle periods or unused spectrum of the primary system. Primary users take up most of the spectrum, and CR users can use their unused spectrum opportunistically [6]. The CR terminals are assumed to be able to detect any unoccupied frequencies and to estimate the strength of the received signal of nearby primary users by spectrum sensing so that they can infer the signal to noise ratio (SNR) of the primary users. The CR terminals are assumed to be equipped with extra RF circuits only for sensing, so they can communicate using a carrier frequency and sense adjacent frequencies at the same time. The CR user is assumed to be able to sense the reappearance of a primary user in the frequency in use by monitoring the degradation of his SNR in the downlink.

Once a CR user detects free frequency spectrum within the licensed frequency range, he may negotiate with the primary system, or begin data transmission without extra permission,

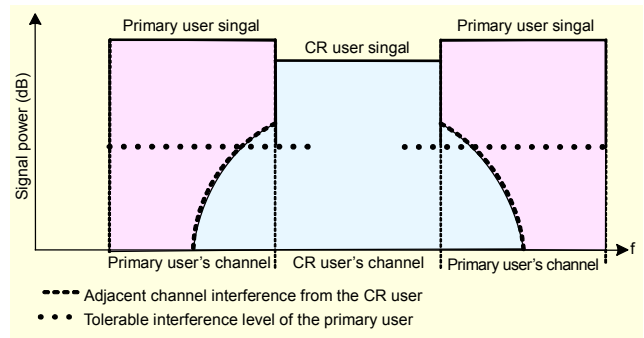


Fig. 1. ACI from CR user to primary users in the CR environment.

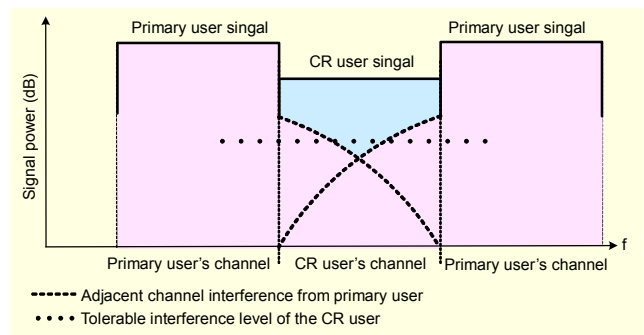


Fig. 2. ACI from primary users to CR user in the CR environment.

depending on the CR system structure. If any primary users become active in the same frequency band later on, the CR user has to clear this band as soon as possible, giving priority to the primary users. Also, CR users should quit their communication if the estimated SNR levels of the primary users are below an acceptable level.

When a CR user operates in a channel adjacent to any active primary users' spectrums, ACI occurs between the two parties. However, the performance of the primary system should be maintained, whether spectrum sharing is allowed or not. We assume that a minimum SNR requirement is predefined for the primary system so that the maximum allowable ACI at each location can be evaluated by the CR user. The CR user can then determine whether he may use the frequency band or not. At the same time, the CR user needs to avoid the influence of interference from primary users in order to maximize its own data throughput.

Figure 1 shows a model of ACI from a CR user to the primary users. In this case, since the ACI from the CR user is higher than the tolerable interference level of the primary users, the performance of the primary users is degraded. Therefore, the CR system should control the transmission power somehow to mitigate the interference to the primary system. On the other hand, as shown in Fig. 2, the CR user operating close to the transmitter of the primary system receives a

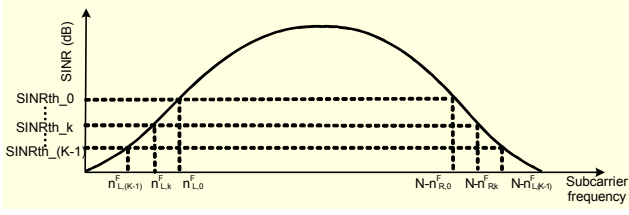


Fig. 3. Model of the SINR measured at the CR terminal in the transmission band.

considerable amount of ACI unless the frequency spectra are far enough from each other.

With OFDM modulation, it is possible to provide a flexible spectral shape, which fills the spectral gaps. Therefore, applying OFDM modulation to the CR system has an advantage of flexibly moderating the ACI between the two systems [3]. The OFDM-based CR architecture may feed certain subcarriers with zeros, resulting in no emission of radio power in those subcarriers that cause severe ACI to primary users. Another way to limit ACI could be to disable frequency channels adjacent to the spectra in use by primary users. Both methods, however, cause a reduction of available bandwidth for the CR system.

III. Principles of ADRF and ATS schemes

1. Data Repetition Scheme over Frequency Subcarriers

The ADRF scheme is proposed to overcome the interference from primary users to the CR user. When a primary user is operating at either end of the spectrum through which a CR user is communicating, the signal to interference and noise ratio (SINR) of the subcarriers nearer to the boundary of the spectrum is much degraded. The SINR of such subcarriers in the CR terminal may easily decrease below the target SINR threshold, denoted as $SINR_{th_0}$.

To adaptively improve the performance of such subcarriers, we propose repeating the transmission data along adjacent subcarriers, considering relative separation from the primary user's spectrum. The number of repetitions depends on the current ACI level and the target SINR threshold of CR user. Without loss of generality, it is assumed that the primary users are at both ends of the CR user's frequency band. If any side of the frequency band is not in use, the proposed algorithm can only be applied to the side getting severe interference.

Figure 3 describes a model of the SINR of each subcarrier measured in a CR terminal. Here, we define several SINR threshold values $SINR_{th_k}$ as

$$SINR_{th_k} = SINR_{th_0} - 3 \cdot k \text{ (dB)}, \quad (1)$$

to be used as metrics to categorize subcarriers according to

how much their SINR levels are degraded below $SINR_{th_0}$, where k denotes the depth of ADRF. Let $n_{L,k}^F$ be the number of subcarriers which satisfy

$$\gamma_i < SINR_{th_k}, \text{ for } i \leq \frac{N}{2}, \quad (2)$$

and let $n_{R,k}^F$ be the number of subcarriers which satisfy

$$\gamma_i < SINR_{th_k}, \text{ for } i > \frac{N}{2}, \quad (3)$$

where γ_i is the SINR of the i -th subcarrier. We then repeat the transmission data by 2^k times and assign it to the subcarriers whose SINR is between $SINR_{th_k}$ and $SINR_{th_{(k-1)}}$. Because the ADRF processes for the left and right sides of the spectrum are identical except the reciprocity of indices, we can use the description of the left side process without loss of generality. To accommodate the case in which the interval is not a multiple of 2, we recursively define $b_{L,k}^F$, the number of data symbols which have to be repeated 2^k times, as

$$b_{L,k}^F = \left\lceil \frac{n_{L,k-1}^F - \sum_{j=0}^{K-k} (b_{L,(K-j+1)}^F \cdot 2^{(K-j+1)})}{2^k} \right\rceil, \quad (4)$$

for $k=K, K-1, \dots, 1$, where K denotes the maximum depth of frequency repetition. Here, $b_{L,k}^F$ for $k > K$ is assumed to be zero. The map for ADRF for the CR OFDM system is defined by

$$\mathbf{R}^F = \{(2^k, b_k^F) \mid_{k=1,2,\dots,K}, n_{L,K}^F, n_{R,K}^F\}, \quad (5)$$

which controls the adaptive assignment of data traffic to each OFDM symbol. The repeated data symbols are further multiplied by a pseudo-random binary code $\mathbf{C}_k^F$ in order to randomize nearby data sequences, where

$$\mathbf{C}_k^F = [c_k^F[0], c_k^F[1], \dots, c_k^F[2^k - 1]], \quad k = 1, 2, \dots, K. \quad (6)$$

In the proposed scheme, the ADRF indicator for the i -th subcarrier, $n_{L,K}^F \leq i \leq N - n_{R,K}^F$, can be calculated iteratively as follows.

Procedure 1. Calculation of ADRF indicator

Given i and $\mathbf{R}^F$;

$k_i = 0$;

If $i \leq N/2$

for $p = 1 : K$, do

$$\text{if } n_{L,K}^F + \sum_{j=0}^{K-p-1} 2^{K-j} \cdot b_{L,K-j}^F \leq i < n_{L,K}^F + \sum_{j=0}^{K-p} 2^{K-j} \cdot b_{L,K-j}^F,$$

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    { $k_i = p$ , break;}
  end if
end for
else
  for  $p = 1 : K$ , do
    if  $N - n_{R,K}^F - \sum_{j=0}^{K-p} 2^{K-j} \cdot b_{R,K-j}^F \leq i < N - n_{R,K}^F - \sum_{j=0}^{K-p-1} 2^{K-j} \cdot b_{R,K-j}^F$ ,
      { $k_i = p$ , break;}
    end if
  end for
end if

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Then, the index u of the data symbol assigned to the i -th subcarrier for $i \leq N/2$ is expressed as

$$u_L = \sum_{k=k^*+1}^K b_{L,k}^F - \left\lfloor \frac{i - n_{L,K}^F - \sum_{k=k^*+1}^K 2^k \cdot b_{L,k}^F}{2^{k^*-1}} \right\rfloor. \quad (7)$$

The index of the data symbol assigned to the i -th subcarrier for $i > N/2$ can be similarly obtained.

2. Adaptive Time Spreading

In the CR environment, primary users may receive lots of interference from CR users, unless an appropriate protection mechanism is provided. More interference is caused by the power of the subcarriers that are nearer to the boundary of the CR users' spectrum. To mitigate such interference, we propose tapering the transmission power of those subcarriers. The tapered portion of data from the CR user is protected by an adaptive time spreading structure. That is, the data in the tapered portion is repeated in the subsequent symbols so that the total equivalent power can be maintained.

Figure 4 describes the proposed time spreading and stepwise power reduction structure, which is described in three aspects: power, time, and frequency. An OFDM symbol is constructed such that the power of subcarriers near the spectrum edges is gradually reduced, while the power of the central subcarriers is unchanged. The set of subcarriers to which the gradual power reduction is applied is controlled adaptively according to the channel status evaluation of nearby primary users. That is, the CR terminal first estimates the SNR of primary users. If the estimated SNR value does not allow enough margin for external interference above the minimally required SNR threshold of primary users, the CR terminal decides the ATS and stepwise power reduction. That is, when the communication channels of the primary users are

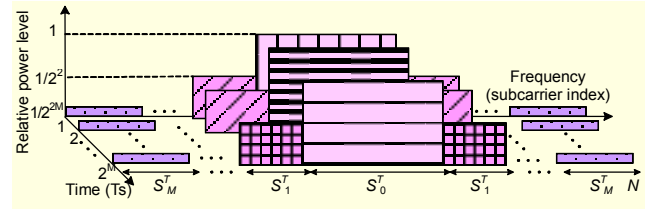


Fig. 4. Adaptive time spreading structure and stepwise power reduction.

in a worse condition, the depth of tapering becomes deeper.

To make up for the reduced power for such subcarriers, the transmission data assigned to them is repeated as many times as the inverse of the square root of the power reduction ratio. Supposing that the communication channel is quasi-stationary, the spread data in time would be summed up to recover equivalent total signal power at the receiver of the CR system. Some demodulation delay for spread data combining is inevitable. After the ATS procedure, a pseudo-random binary code is multiplied with each sequence generated from the same transmission data in order to further randomize in time.

The stepwise power reduction scheme is designed as follows. Let the minimum required SNR threshold of the primary receivers be given. In the ATS process, the data is spread in the subsequent 2^m OFDM symbols, each with amplitude reduced by $1/2^m$, where m denotes the depth of ATS. Since the maximum spreading time cannot exceed the coherence time of the channel observed at the output of channel equalizer, the maximum spreading depth M is determined by the channel coherence time τ_c of the CR user as

$$M = \left\lfloor \log_2 \frac{\tau_c}{T} \right\rfloor, \quad (8)$$

where T denotes the OFDM symbol duration.

Let $s_{L,m}^T$ and $s_{R,m}^T$ be the number of subcarriers having amplitude reduced by $1/2^m$ for $m = 0, 1, 2, \dots, M, \infty$, for the left and right side ATS processes. The overall implementation of ATS can be summarized as

$$\mathbf{S} = \{s_{L,\infty}^T, s_{L,M}^T, \dots, s_{L,1}^T, s_0^T, s_{R,1}^T, \dots, s_{R,M}^T, s_{R,\infty}^T\}. \quad (9)$$

To obtain the optimal subcarrier power allocation map for the current OFDM symbol, we set up the following optimization equation.

Given $n_{L,K}^F$ and $n_{R,K}^F$, solve for

$$\mathbf{S}^* = \arg \max_{\mathbf{S}} \{C_{proposed}\}, \quad (10)$$

such that

$$\frac{S_{P,estimate}}{(I_0 + N_0)/T} \geq \frac{S_{P,threshold}}{N_0/T}, \quad (11)$$

where

$$I_0 = \sqrt{T} \cdot \sum_{i=n_{L,K}^F}^{N-n_{R,K}^F-1} x_i \text{sinc} \left(T \left(f - \frac{i}{T} \right) \right) \Big|_{f=\frac{N}{T}}, \quad (12)$$

and $C_{proposed}$ is the throughput of an OFDM symbol derived in appendix in detail; $S_{P,estimate}$ and $S_{P,threshold}$ denote the estimate of received signal strength and the minimum required power threshold of the primary user, respectively; I_0 represents the interference power spectral density from the CR OFDM system to the primary user, measured at the edge of the primary user's spectrum; and x_i denotes the amplitude of the data assigned to the i -th subcarrier.

Now, the following procedure determines the corresponding power reduction indicator m_i for a given i .

Procedure 2. Calculation of ATS indicator

Given i and $\mathcal{S}^* = \{s_{L,\infty}^T, s_{L,M}^T, \dots, s_{L,1}^T, s_0^T, s_{R,1}^T, \dots, s_{R,M}^T, s_{R,\infty}^T\}$,

$m_i = \infty$;

if $i \leq N/2$

for $q = 0 : M$, do

if $s_{L,\infty}^T + \sum_{j=0}^{M-q-1} s_{L,M-j}^T \leq i < s_{L,\infty}^T + \sum_{j=0}^{M-q} s_{L,M-j}^T$,

$\{m_i = q, \text{ break};\}$

end if

end for

else

for $q = 0 : M$, do

if $N - s_{R,\infty}^T - \sum_{j=0}^{M-q} s_{R,M-j}^T \leq i < N - s_{R,\infty}^T - \sum_{j=0}^{M-q-1} s_{R,M-j}^T$,

$\{m_i = q, \text{ break};\}$

end if

end for

end if

Figure 5 shows the power spectral density when the stepwise power reduction scheme is applied to the CR OFDM system. The power of the subcarriers at both edges of the usage spectrum is decreased gradually at each step of power reduction. When the maximum power reduction is 18 dB, the total accumulative reduction of the ACI toward the primary user is about 15 dB.

A pseudo-random binary code $c_m^T[t]$ is then multiplied to the sequence of repeated data symbols to get a randomization

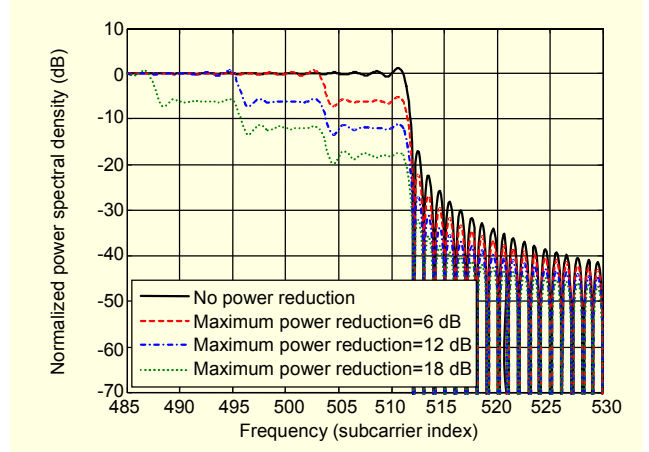


Fig. 5. Power spectral density of the CR OFDM system with stepwise power reduction.

effect. Since the sequence of data symbols can be combined in the receiver at the end of the 2^m -th OFDM symbols, the original power of the reduced data symbol can be recovered if the communication channel is quasi-stationary.

IV. Robust CR OFDM Architecture

We now propose a new CR OFDM architecture based on the ADRF and ATS schemes. Here, we assume that the CR MS has the capability to sense the activity of nearby primary stations and then roughly estimate the SNR of primary receivers.

1. Transmitter of the Proposed CR OFDM Architecture

The transmitter of the proposed CR OFDM system is shown in Fig. 6. The output of data modulator enters the adaptive serial-to-parallel (S/P) data converter, which adaptively links the data symbols to the CR OFDM modulator. The ADRF and ATS operations with stepwise power control are carried out by the spreading controller.

At the output of the adaptive S/P data converter, each data symbol d_u is adaptively spread in the frequency domain using R_F . A pseudo-random binary code C_k^F is multiplied by each group of repeated data symbol from the same source data.

After the ADRF process, the CR OFDM system performs the ATS process. The spreading controller first determines the range of subcarriers to apply the time spreading. The data symbols assigned to the subcarriers in need of time spreading are multiplied by a pseudo-random binary code $c_m^T[t]$ and the resultant data symbols are loaded in 2^m consecutive OFDM symbols.

Then, the i -th subcarrier before the inverse fast Fourier

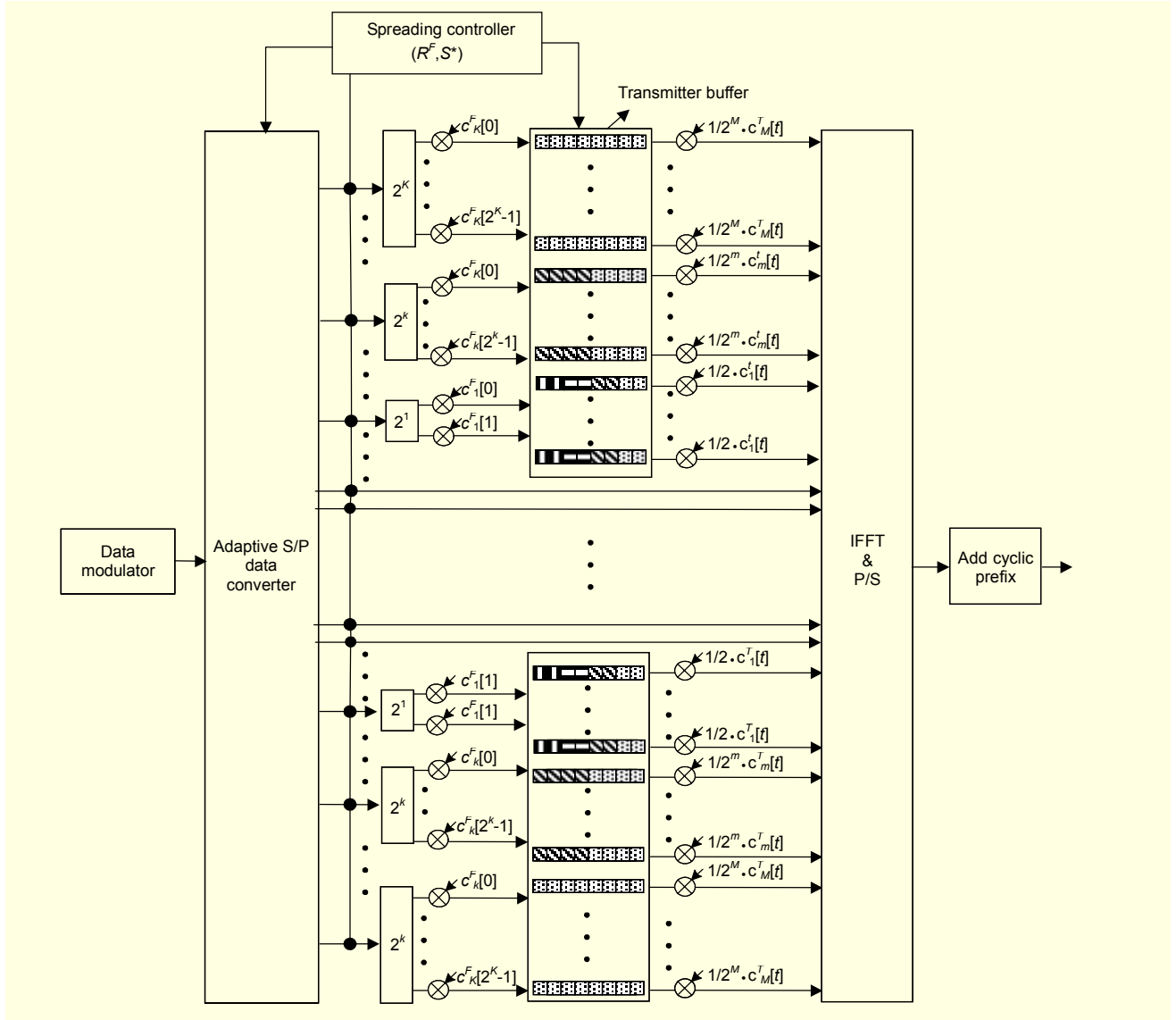


Fig. 6. Transmitter of the proposed CR OFDM system.

transform (IFFT) is described as

$$X_i = \begin{cases} d_u(i), & \text{if } SINR(i) > SINR_{th_0}, \\ d_u(i) \cdot c_k^F(i), & \text{if ADRF only,} \\ \frac{1}{2^m} \cdot d_u(i) \cdot c_k^F(i) \cdot c_m^T(i), & \text{if ADRF and ATS,} \end{cases} \quad (13)$$

for $i = 0, 1, \dots, N-1$,

where $SINR(i)$ is the SINR of the i -th subcarrier for the CR user, and N is the FFT length. Here, k is the ADRF indicator, and m is the ATS indicator for the i -th subcarrier, respectively.

The IFFT output samples are obtained by

$$x(n) = \frac{1}{N} \sum_{i=0}^{N-1} X_i \cdot e^{j2\pi(in/N)}, \quad n = 0, 1, \dots, N-1, \quad (14)$$

and the cyclic prefix (CP) is added; then, the n -th sample of the

transmitted signal is given by

$$s(n) = \frac{1}{N} \sum_{i=0}^{N-1} X_i \cdot e^{j2\pi(in/N)}, \quad n = -N_g, \dots, N-1, \quad (15)$$

where N_g denotes the length of CP.

2. Receiver of the Proposed CR OFDM Architecture

Figure 7 demonstrates the receiver of the proposed CR OFDM system. At the receiver, the source data is recovered in the reverse order of the transmitter process. After the removal of the CP, the n -th sample of the received signal is described as

$$y(n) = x(n) * h(n) + \ell(n) + w(n), \quad (16)$$

where $h(n)$ is the channel impulse response, $\ell(n)$ is the

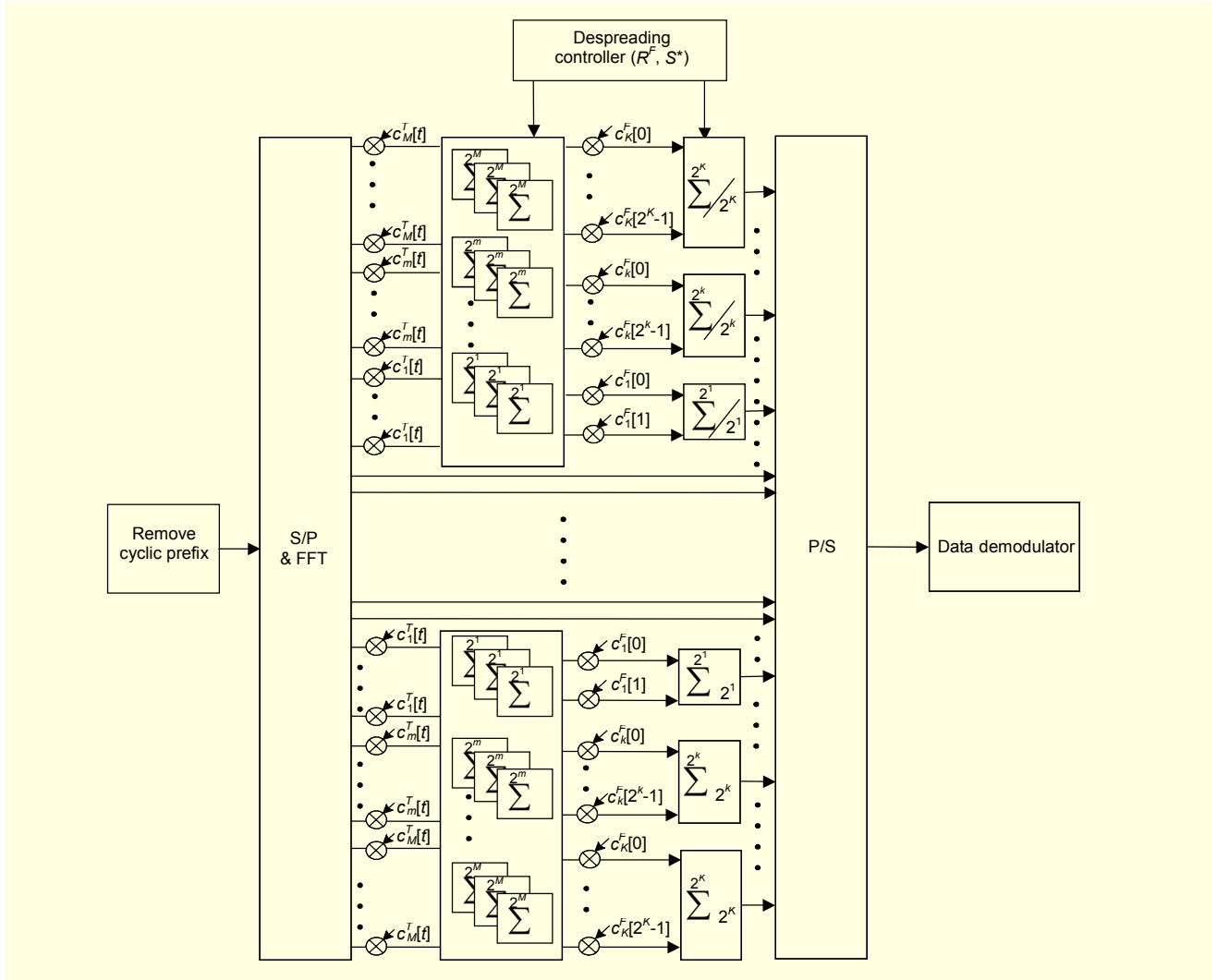


Fig. 7. Receiver of the proposed CR OFDM system.

interference signal from the primary users, and $w(n)$ is the additive white Gaussian noise. We assume that a quasi-stationary channel is provided in the CR system and that the synchronization is guaranteed so that the inter-symbol interference is negligible. The output of FFT for the i -th subcarrier is given by

$$Y_i = X_i \cdot H_i + I_i + W_i, \quad (17)$$

where X_i , H_i , I_i , and W_i are the corresponding frequency domain expressions of $x(n)$, $h(n)$, $\ell(n)$, and $w(n)$, respectively.

Now, the CR OFDM receiver performs the despreading process controlled by a despreading controller. First, for the time despreading, a pseudo-random binary code $c_m^T[t]$ is multiplied by each data symbol spread in time. The data symbols in each subcarrier are added up as many times as the length of time spreading, so that all the data corresponding to the current OFDM symbol can be combined at the end of 2^M

OFDM symbol periods. Figure 8 shows an example of data symbols being adaptively combined. Each color in the background represents a set of subcarriers combined within a specified time spreading interval. In the given example, the subcarriers ranging from n_3 to n_4 are the subcarriers transmitted without spreading. They can be demodulated at every symbol period at the receiver, while the subcarriers spread two times, from n_2 to n_3 and from n_4 to n_5 , should be combined by the end of two symbol periods for demodulation. Considering the data's arrival time at the transmitter, the combined data symbol needs to be demodulated at the beginning of the spreading period. Likewise, the subcarriers spread four times are combined at the end of four time periods, and demodulated at the beginning of the spreading period.

After completing the time despreading process, the data combining over frequency subcarriers is performed. For the data combining, a pseudo-random binary code C_k^F is first

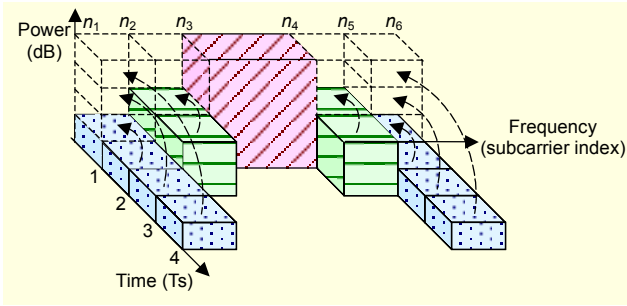


Fig. 8. Example of the data combining for the adaptive time despreading ($M=2$).

multiplied by the data symbols which are assigned to the repeated frequency subcarriers. Each data symbol is added up according to the corresponding spreading length, 2^k , and is also normalized by 2^k .

Then, the recovered data symbol for the i -th subcarrier after the time despreading process and the data combining process is obtained as

$$\hat{d}_u(i) = \begin{cases} Y_i, & \text{if } \text{SINR}(i) > \text{SINR}_{th_0}, \\ \frac{\sum_{k=1}^{2^K} Y_i \cdot c_k^F(i)}{2^k}, & \text{with ADRF only,} \\ \frac{\sum_{k=1}^{2^K} \sum_{m=1}^{2^M} \{Y_i \cdot c_m^T(i) \cdot c_k^F(i)\}}{2^k}, & \text{with ADRF and ATS,} \end{cases}$$

for $i = 0, 1, \dots, N-1$.

(18)

V. Performance Evaluation

In this section, we evaluate the performance of the proposed CR OFDM system in the presence of ACI from the primary system. For the primary system in the simulation, we use the digital television (DTV) stations operating in both of the neighboring channels of the spectrum of an active CR user. The ACI from the DTV is modeled by the adjacent channel emission mask defined in the FCC [7].

The simulation parameters for the CR OFDM system are summarized in Table 1. To evaluate the system performance, we compared the performance of the conventional CR OFDM system with guard bands to that of our proposed architecture. The length of the guard band on each side of the OFDM spectrum is assumed to be the number of subcarriers which have SINRs lower than the required SINR threshold. To evaluate the maximum throughput of each system, we assumed an adaptive modulation using M-quadrature amplitude modulation (QAM) according to [8].

In Fig. 9, the average bit error rate (BER) of the proposed

Table 1. Simulation parameters.

Parameter	Value
Center frequency	500 MHz
Bandwidth	6 MHz
Number of subcarriers	512
Subcarrier spacing	11.72 kHz
Modulation	64QAM, 16QAM, QPSK
Channel	AWGN
Maximum ADRF indicator	3
Maximum ATS indicator	3

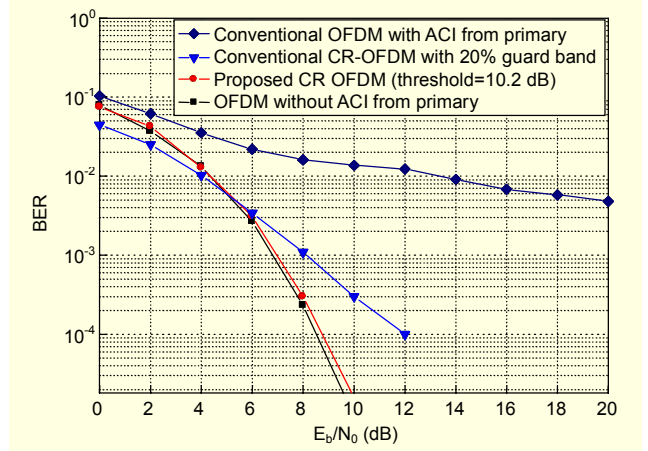


Fig. 9. Comparison of BER performance for the CR OFDM systems in the presence of ACI from primary users (ACI level at the boundary: -67 dBm).

CR OFDM architecture is compared with that of the conventional CR OFDM system. The performance curve of the OFDM system assuming no ACI is also included for reference. Note that when the conventional OFDM system operates without any protection in the vicinity of the primary transmitters, the BER performance is significantly degraded because of the ACI from the primary system. In the proposed CR OFDM system, the BER performance is much better and gets even closer to the case of the OFDM system without ACI, because of the signal gain in the receiver due to the ADRF and ATS. The conventional CR OFDM system with guard bands also has fairly good performance, but at the sacrifice of the throughput. At a very low E_b/N_0 , the BER performance becomes even better than that of OFDM without ACI, since the CR OFDM system with guard bands drops off those subcarriers having poor channel gain. At the BER of 10^{-4} , the proposed CR OFDM system achieves a gain of more than 3 dB in comparison with the conventional CR OFDM system.

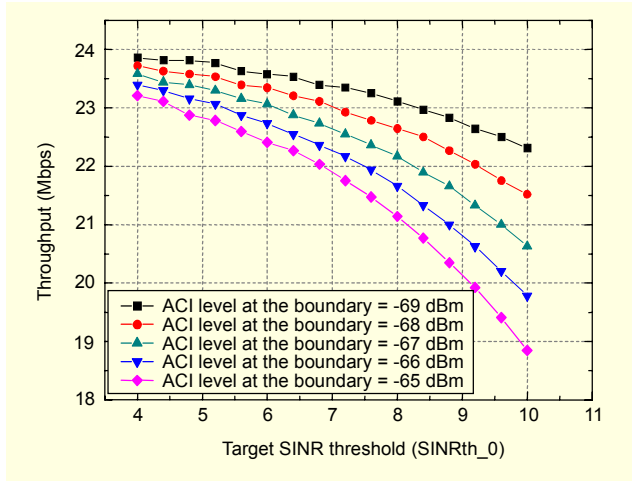


Fig. 10. Throughput of the proposed CR OFDM architecture under different levels of ACI from the primary system (CR received signal power: -60 dBm).

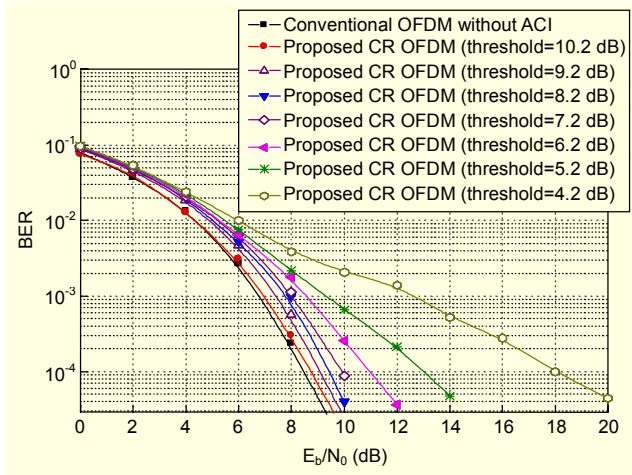


Fig. 11. BER performance according to different SINR threshold levels in the proposed CR OFDM architecture.

Figure 10 shows the average throughput of the proposed CR OFDM system with various target SINR thresholds and ACI levels at the boundary, which is defined as the interference power from the primary system measured at the subcarrier nearest to the spectrum of the primary systems. When the target SINR threshold is about 9 dB, the throughput of the proposed architecture becomes higher than 20 Mbps, which is about 3.3 bps/Hz, at all ACI levels. As the target SINR threshold increases, the average throughput decreases, while the BER performance is improved.

To evaluate the relationship between throughput and BER performance, Fig. 11 shows the BER performance of the proposed CR OFDM system under various target SINR thresholds. The BER performance worsens with the decrease of the target SINR thresholds. However, when the target SINR

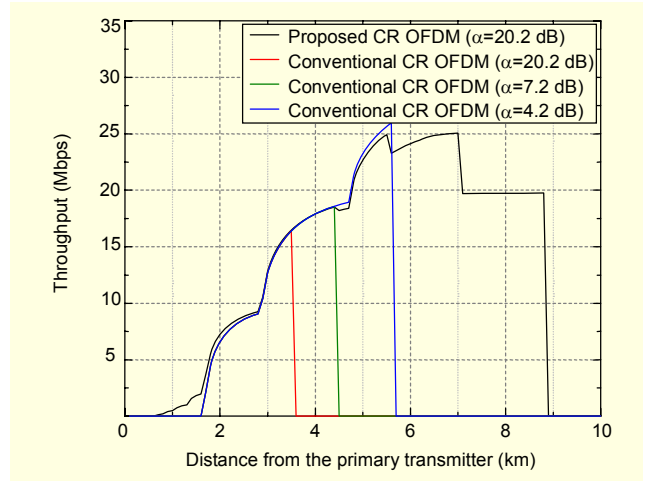


Fig. 12. Throughput of the CR OFDM systems according to the distance from the primary transmitter (α : the minimum SINR threshold of primary user).

threshold is decreased up to 7.2 dB from the normal operating condition of 10.2 dB for QPSK, the BER performance is degraded only by about 1 dB from the performance of the OFDM without ACI at the BER of 10^{-3} . On the other hand, the increase in the throughput shown in Fig. 10 is about 1.3 Mbps. However, further reduction of the threshold, for example, to 6 dB, is not acceptable since the BER performance is degraded by about 6 dB. Thus, the proposed CR OFDM system can be adaptively configured considering performance in terms of BER and throughput.

In Fig. 12, the average throughput of the proposed CR OFDM system is compared with that of a conventional CR OFDM system at various minimum SINR thresholds of primary users, denoted as α . The throughput performance has been measured according to the separation distance from the primary system transmitter. In both architectures, it is impossible to communicate in the proximity of the primary transmitter. The throughput begins to increase when it is located at a certain distance from the transmitter. The throughput then increases to a maximum as the distance increases, and later, either abruptly stops communication, as in the conventional CR OFDM system, or decreases in order to minimize interference to the nearby primary users, as in the proposed CR OFDM architecture.

As Fig. 12 shows, even under more severe interference from the primary transmitter, the proposed CR OFDM architecture can start communication at a shorter distance than the conventional CR OFDM system. This is mainly achieved by the ADRF process. As the distance increases, the depth of the data repetition is reduced while the ATS starts to be applied. As the CR users get even further from the primary transmitter (more than 8 km), the ATS process mainly operates, so the

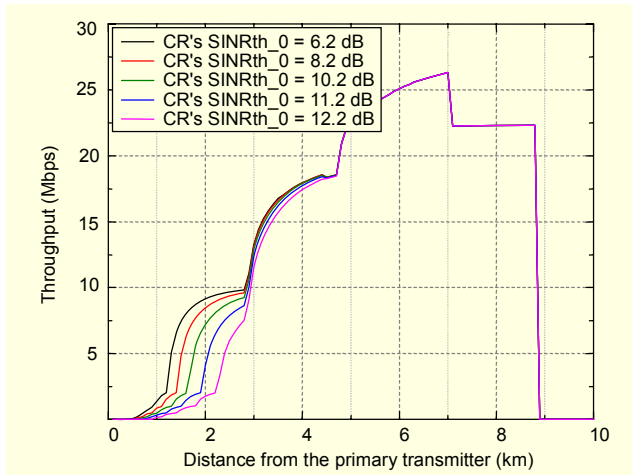


Fig. 13. Throughput of the proposed CR OFDM architecture according to different SINR threshold values of CR users at the minimum SINR threshold value of 20.2 dB for primary users.

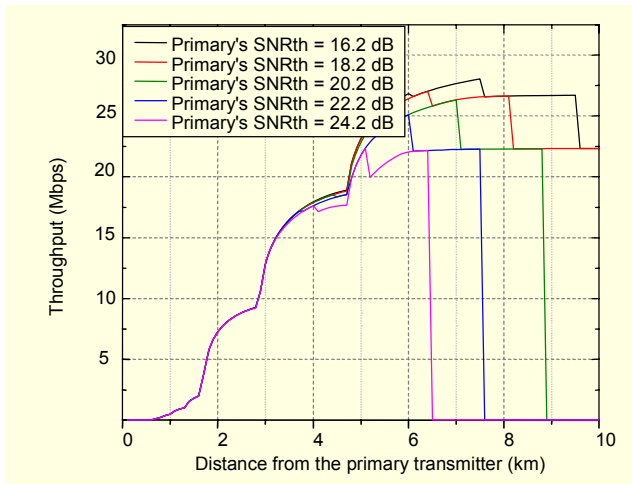


Fig. 14. Throughput of the proposed CR OFDM architecture according to different minimum SINR threshold values of primary users at the target SINR threshold value of 10.2 dB for CR users.

throughput decreases as a result of the stepwise power reduction. However, the proposed CR OFDM architecture can operate at much greater distances than the conventional CR OFDM system, where the received signal of the primary system becomes very weak, because the proposed architecture can still protect the primary receivers by means of the ATS scheme. The maximal throughput is achieved at some location in the middle, because the numbers of subcarriers applied to the ADRF and ATS are balanced.

Figure 13 shows the average throughput of the proposed CR OFDM architecture according to the relative location of the CR users under various target SINR thresholds of the CR terminal, at the minimum SNR threshold value of 20.2 dB for

primary users. As shown in the figure, the throughput of the proposed CR OFDM system decreases as the target SINR threshold of CR users increases, when the CR users are fairly close to the primary transmitter. However, all the performance curves converge to the same line as the CR users get further from the primary transmitter, because the criteria for the ATS process do not depend on the target SINR threshold of CR users.

Figure 14 shows the average throughput of the proposed CR OFDM system according to the relative location of the CR users under different minimum required SNR thresholds of primary users, at the target SINR threshold value of 10.2 dB for the CR users. As in Fig. 12, as the distance from the primary base station (BS) increases, the throughput curves tend to decrease due to the ATS process for the protection of nearby primary users. The decrease starts nearer to the primary BS, when the minimum SINR threshold of primary users is defined higher. In this figure, the average throughput decreases as the SNR threshold of primary users increases, when the CR users are located further from the primary transmitter. All the performance curves converge to the same line as the CR users gets closer to the primary transmitter, since the criterion for ADRF process does not depend on the target SINR threshold of the primary system.

The proposed CR OFDM architecture would become more robust, at the risk of some capacity loss, by applying error correction coding and interleaving [9]. When synchronization in the receiver is not guaranteed, the performance of the proposed system is degraded due to combining error. The proposed system is mainly for non-real time applications, because some variable delay is inevitable for the ATS process and spectrum sensing.

VI. Conclusion

In this paper, we proposed a CR-based OFDM architecture, featuring ADRF and ATS with stepwise power control capability, which is implemented according to the mutual influence of ACI between the primary system and the CR system. The ADRF process can protect CR users against strong ACI from the primary system, and the ATS process with stepwise power reduction prevents the degradation of performance for nearby primary users. Computer simulations have shown that in terms of throughput and BER performance, the proposed CR OFDM system outperforms the conventional OFDM system with adaptive guard bands. We have also confirmed that, using the proposed architecture, the performance of primary users is maintained without degradation. The proposed CR OFDM architecture can be adaptively configured by considering the BER and throughput

performance.

Appendix. Throughput Analysis of the CR OFDM Systems

Suppose that the numbers of unused subcarriers, $n_{L,K}^F$ and $n_{R,K}^F$, derived in the ADRF process, for the left and right side of the spectrum are given. The total number of subcarriers applied to ADRF, $n_{L,0}^F$ and $n_{R,0}^F$, in the left and right side of the spectrum are also given. Let a subcarrier power allocation map derived in the ATS process be given as

$$\mathbf{S} = \{s_{L,\infty}^T, s_{L,M}^T, \dots, s_{L,1}^T, s_0^T, s_{R,1}^T, \dots, s_{R,M}^T, s_{R,\infty}^T\}.$$

Then, the throughput of conventional CR OFDM system with guard bands can be described as

$$C_{conv} = \sum_{i=GS+1}^{N-GS} \left(r_i \cdot \frac{1}{T} \right),$$

where GS represents the number of guard subcarriers in each side of the spectrum, r_i is the number of bits assigned to the i -th subcarrier, and T denotes OFDM symbol duration [10], [11].

In the proposed CR OFDM architecture, the throughput of a CR terminal depends on the channel condition of nearby primary users, because the ADRF process depends on the signal strength from the primary transmitter, and the ATS process depends on the link budget of the primary receivers. We assume that the modulation mode used for the subcarriers to apply ADRF or ATS is fixed as QPSK modulation.

When the signal strength from the primary transmitter is very strong, the CR terminal applies only the ADRF to protect the CR user from severe ACI. In this case, the throughput equation of the proposed architecture is represented as

$$C_{proposed} = \sum_{i=n_{L,K}^F+1}^{n_{L,0}^F} \left(2 \cdot \frac{1}{T} \right) \frac{1}{2^{k_i}} + \sum_{i=n_{L,0}^F+1}^{N-n_{R,0}^F} \left(r_i \cdot \frac{1}{T} \right) + \sum_{i=N-n_{R,0}^F+1}^{N-n_{R,K}^F} \left(2 \cdot \frac{1}{T} \right) \frac{1}{2^{k_i}},$$

where k_i denotes the ADRF indicator of the i -th subcarrier.

However, when the signal strength from the primary transmitter is moderate, the CR terminal applies both the ADRF and ATS processes. In this case, the throughput equation of the proposed architecture depends on whether the ADRF process is applied more than the ATS.

$$C_{proposed} = \begin{cases} \sum_{i=n_{L,K}^F+1}^{G_L} \left(\frac{2}{T} \right) \frac{1}{2^{(k_i+m_i)}} + \sum_{i=G_L+1}^{n_{L,0}^F} \left(\frac{2}{T} \right) \frac{1}{2^{k_i}} + \sum_{i=n_{L,0}^F+1}^{N-n_{R,0}^F} \left(\frac{r_i}{T} \right) \\ + \sum_{i=N-n_{R,0}^F+1}^{N-G_R} \left(\frac{2}{T} \right) \frac{1}{2^{k_i}} + \sum_{i=N-G_R+1}^{N-n_{R,K}^F} \left(\frac{2}{T} \right) \frac{1}{2^{(k_i+m_i)}}, & \text{if more ADRF than ATS,} \\ \sum_{i=n_{L,K}^F+1}^{n_{L,0}^F} \left(\frac{2}{T} \right) \frac{1}{2^{(k_i+m_i)}} + \sum_{i=n_{L,0}^F+1}^{G_L} \left(\frac{2}{T} \right) \frac{1}{2^{m_i}} + \sum_{i=G_L+1}^{N-G_R} \left(\frac{r_i}{T} \right) \\ + \sum_{i=N-n_{R,0}^F+1}^{N-n_{R,K}^F} \left(\frac{2}{T} \right) \frac{1}{2^{m_i}} + \sum_{i=N-n_{R,K}^F+1}^{N-n_{R,0}^F} \left(\frac{2}{T} \right) \frac{1}{2^{(k_i+m_i)}}, & \text{if more ATS than ADRF,} \end{cases}$$

where G_L and G_R are the total number of subcarriers applied to the ATS process in the left and right side of the spectrum, respectively. They are defined as

$$G_L = \sum_{m=1}^M s_{L,m}^T$$

and

$$G_R = \sum_{m=1}^M s_{R,m}^T,$$

where m_i denotes the ATS indicator of i -th subcarrier.

Finally, when the signal strength from the primary transmitter is very weak, the CR terminal applies only ATS. In this case, the throughput equation of the proposed architecture is represented as

$$C_{proposed} = \sum_{i=n_{L,K}^F+1}^{G_L} \left(2 \cdot \frac{1}{T} \right) \frac{1}{2^{m_i}} + \sum_{i=G_L+1}^{N-G_R} \left(r_i \cdot \frac{1}{T} \right) + \sum_{i=N-G_R+1}^{N-n_{R,K}^F} \left(2 \cdot \frac{1}{T} \right) \frac{1}{2^{m_i}}.$$

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