Interference-Mitigating Broadband Secondary User Downlink System: A Time-Reversal Solution

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***Abstract*—The spatial and time focusing effects of time-reversal technology make it an ideal candidate for the low interference downlink system to relieve the coexistence issues among different wireless communication systems. The transmitting power would be concentrated at the intended receiver and the leakage to unintended receivers would be automatically suppressed. In this paper, a time-reversal based secondary user downlink system with the coexistence of primary users is proposed. The primary user's performance loss is investigated in terms of effective SINR degradation and achievable data rate deduction. It is illustrated through numerical examples that the time-reversal downlink system relieves the primary user's performance loss as well as achieves satisfying power efficiency compared with the traditional direct transmission.**

I. Introduction

The last decade has witnessed the wide spread of wireless devices. With the the current fixed spectrum allocation methodology, the spectrum resource is becoming more and more scare for new devices[1]. Thus, it is imperative for different types of users to share the access to the licensed radio spectrum in some cases. Generally, the licensed users of the spectrum are considered as primary users and the unlicensed users are considered as secondary users. It is required that no harmful interference is caused to the primary users by the activity of secondary users[2].

One of the approaches to spectrum sharing is cognitive radio[3]–[6] that the secondary user network dynamically sense the wireless environment to estimate the activity of primary user and select the best available bands for communication. Although it is effective in some cases, it is not suitable for some applications. The demand of sensing and decision making may call for extra circuit and power, which might not be applicable to the devices require low cost and long battery life. The complex operational algorithms[7]–[9] would potentially make it even harder to implement. Moreover, since the communication of secondary user is conditional on the activity of primary users, it is not an ideal solution to the applications that require constant connection.

Cognitive radio is generally considered as an overlay method. There has also been some underlay approaches for example the ultra-wide band (UWB) communication system that has the merit of low power consumption and low interference to the primary user. However, there are several challenges for the UWB system including the inter-symbol interference due to the multi-path effect that would lead to more complicated receiver design[10]. Moreover, UWB systems usually use time-hopping or code-division methods[11] to enable multiple access, which would increase the implementation difficulty.

Time-reversal communication technology has been shown to have the feature of time and spatial focusing[12], [13]. The time-focusing effect serves to alleviate the inter-symbol interference, which is a universal challenge in broadband communication systems. The spatial-focusing effect concentrates the energy at the intended receiver thus effectively mitigates the interference to unintended users. These features make it a perfect candidate that could potentially be applied to the secondary user downlink system to ensure no harmful interference to the primary users.

In this paper, we investigate the time-reversal based secondary user downlink system and study the interference on the primary users. Instead of considering a specific type of primary user, we define a notion of virtual primary user with exactly the same working band of the secondary user network that has the most severe interference. Therefore, if the performance of the virtual primary user can be guaranteed, any potential primary user is able to achieve satisfying performance. The benefits are shown including causing less degradation in effective SINR and achievable data rate of the primary user as well as increasing power efficiency compared with the downlink system using direct transmission.

The rest of this paper is organized as follows: the time-reversal based multiuser downlink system is modeled in section II; the virtual primary user is formulated in section III and all kinds of interferences of the system are analyzed; in section IV, the secondary user downlink system using direct transmission is analyzed and compared with that using time-reversal to demonstrate the advantages of time-reversal downlink system; several numerical examples are shown in section V; section VI concludes this paper.

II. System Model

In this paper we look at the secondary user (SU) downlink system with the coexistence of primary users (PU). As shown in Fig. 1, the access point (AP) is responsible for delivering information to the SU while inevitably creating some interference to the PUs within the area. Suppose the AP communicate with each SU by the time-reversal (TR) technology so that they compose a TR downlink system.

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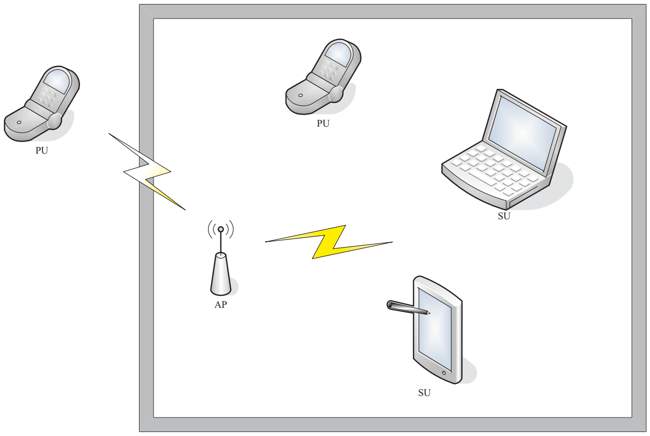

Fig. 1. Coexistence of PU and SU

A. The Broadband Channel for Time-Reversal Downlink System

The channel impulse response (CIR) of the communication link between the time reversal access point (TRAP) and the i-th SU is modeled as

$$h_i[k] = \sum_{l=0}^{L-1} h_{i,l}\delta[k-l] \quad (1)$$

where $h_i[k]$ is the k-th tap of the CIR with length L_s. For each link, we model $h_i[k]$'s as independent circular symmetric complex Gaussian random variables with zero mean and variance

$$E[|h_i[k]|^2] = e^{-\frac{kT_S^s}{\delta_T^s}}, \quad 0 \le k \le L_s - 1 \quad (2)$$

where T_S^s is the sampling period of the SU such that $\frac{1}{T_S^s}$ equals the bandwidth B^s that the SU was using and δ_T^s is the delay spread [14] of the channel.

In order to analyze the interference between the TRAP and the PU, we need to model the CIR between them. Similarly, the CIR of the communication link between the TRAP and the j-th PU is modeled as

$$f_j[k] = \sum_{l=0}^{L-1} g_{j,l}\delta[k-l] \quad (3)$$

where $f_j[k]$ is the k-th tap of the CIR with length L_p. For each link, we model $f_j[k]$'s as independent circular symmetric complex Gaussian random variables with zero mean and variance

$$E[|f_j[k]|^2] = \alpha e^{-\frac{kT_S^p}{\delta_T^p}}, \quad 0 \le k \le L_p - 1 \quad (4)$$

where T_S^p is the sampling period of the PU such that $\frac{1}{T_S^p}$ equals the bandwidth B^p that the PU was using and δ_T^p is the delay spread [14] of the channel from the TRAP to the PU. Note that the PU can be using either broadband and narrow band. Although it is a broadband setting in (3), if PU is using narrow-band, B^p is small and T_S^p is comparable with δ_T^p, then $L_p = 1$ meaning that there is only one tap in the channel response from the TRAP to the PU, corresponding to the one-tap gain for the narrow-band communication.

The attenuation factor $\alpha \le 1$ means that there may be some attenuation between the TRAP and the PU. For example, as shown in Fig. 1, the wall between the AP and one of the PU may naturally serve to suppress the interference such that $\alpha < 1$. However, it will be assumed $\alpha = 1$ in the rest of the paper that corresponding to the case without interference suppression, while the general cases would be better off.

B. Time-reversal Secondary User Downlink System

The TR downlink system has two phases: the recording phase and the transmission phase. During the recoding phase, the N intended users first take turns to transmit an impulse signal to the TRAP. Meanwhile, the TRAP records the channel response of each link and store the time-reversed and conjugated version of each channel response for the transmission phase. For simplicity of analytical derivation, we assume in our analysis that the waveform recorded by TRAP reflects the true CIR, ignoring the small corruption caused by thermal noise and quantization noise.

After the channel recording phase, the system starts its transmission phase. At the TRAP, each of $X_1, X_2, \cdots, X_N$ represents a sequence of information symbols that are independent complex random variables with zero mean and variance θ. Any two sequences are also independent in our model. These sequences are first up-sampled by a back-off factor D at the TRAP, and the i-th up-sampled sequence can be expressed as

$$X_i^{[D]}[k] = \begin{cases} X_i[k] & if \quad k \quad mod \quad D = 0 \\ 0 & if \quad k \quad mod \quad D \neq 0. \end{cases}$$

Then the up-sampled sequence for each user is convolved with $g_i[k]$ which is the time-reversed version of its CIR $h_i[k]$ to be the real transmitted signal

$$S[k] = \sum_{i=1}^{N} \left(X_i^{[D]} * g_i[k] \right). \quad (5)$$

The signal received at the i-th SU is the convolution of $S[k]$ and $h_i[k]$, plus a white Gaussian noise $\tilde{n}_i[k]$ with zero mean and variance σ_i^2. The i-th SU simply apply a one-tap gain adjustment to the received signal and then down-sample it to the same factor D. The down-sampled signal can be expressed as

$$Y_i[k] = a_i \sum_{j=1}^{N} \sum_{l=0}^{(2L-2)} (h_i * g_j)[Dl] X_j[k-l] + a_i \tilde{n}_i[kD] \quad (6)$$

where a_i is the one-tap gain. More details about the two phases of time-reversal division multiple access system can be found in [15].

III. TR Downlink Interference Analysis

While the TRAP periodically transmit the combined signal $S[k]$ to the wireless channel, both the PU and SU would receive the signal. In this section, we will analyze the interferences of the TR downlink system.

Different from cognitive radio that frequently sense the environment to know the activity of PU [3], the SU downlink system using time-reversal is less complicated. The TRAP could keep transmitting regardless of the activity of the PU.

If there was a virtual PU working exactly at B^s, let $S[k]$ denote the received signal. For another PU working at the band partially overlap with B^s, it is equivalent to that the broadband signal $S[k]$ is filtered by a bandpass filter. Denote the bandpass filter as $b[k]$. For the broadband signal at a particular time instant N, the signal power is $|S(N)|^2$. After filtering by the band pass filter $b[k]$, the signal is $S * b[k] = \sum_0^k S[\mu]b[k-\mu]$. The signal power at N_0 is

$$|S * b(N_0)|^2 = |\sum_0^{N_0} S[\mu]b[N_0 - \mu]|^2 \tag{7}$$

where $b[n]$ is a band-pass filter with $\sum_n |b[n]|^2 = 1$ such that does not provide any power gain.

Without loss of generality, assume that $|S * b(N_0)|^2$ is the maximum in $|S * b(k)|^2$ for all k. Then

$$|S * b(N_0)|^2 = |\sum_0^{N_0} S[\mu]b[N_0 - \mu]|^2 \tag{8}$$

$$\leq |\sum_0^{N_0} S[\mu^*]b[N_0 - \mu]|^2 \tag{9}$$

$$= |S[\mu^*]|^2 \sum_n |b[n]|^2 \tag{10}$$

$$= |S[\mu^*]|^2 \tag{11}$$

where $|S[\mu^*]|^2$ is the maximum in the unfiltered signal $|S[k]|^2$ for all k. It is shown that the peak interference power taken at each observation by the PU working at partial overlap with B^s will be no greater than that by the virtual PU working exactly at B^s. If the performance of the virtual PU could be guaranteed, all the general PUs would be better off. In the following of this paper, we will focus on the interference on the virtual PU.

The interference on the PU is composed of the faded version of multiple waves, while earlier waves get more fading. Mathematically, for the PU indexed j, the interference can be expressed by

$$I_j = \sum_{r=0}^{\frac{L_s+L_p-2-\tau}{D}} \sum_{i=1}^{N} \left(X_i^{[D]} * g_i * f_j \right) [\tau + rD] \tag{12}$$

where $\tau \sim U(0, D)$ is a random variable representing the current time in the cycle when the PU samples the wave.

The expected interference power at the j-th PU is

$$E[|I_j|^2] = N\theta \sum_{r=0}^{\frac{L_s+L_p-2-\tau}{D}} |Y_{j,r}^{[D]}[\tau + rD]|^2 \triangleq E[P_{I,j}^{TR}] \tag{13}$$

where $Y_{j,r}^{[D]}[k]$ is the sequence received at the j-th PU by the wave transmitted by TRAP r cycles before the nearest transmission. By the independence of the information at different cycles and it can be further written as

$$E[P_{I,j}^{TR}] = N\theta \sum_{r=0}^{\frac{L_s+L_p-2-\tau}{D}} E\left[|(g_i * f_j)[\tau + rD]|^2\right] \tag{14}$$

by the fact that the information for different users are independent.

It is clear that smaller τ will lead to greater interference because of less fading. Without loss of generality, let $\tau = 0$ and assume that $L_p \leq L_s$, then

$$\begin{aligned} E[P_{I,j}^{TR}] &= N\theta \sum_{r=0}^{\frac{L_s+L_p-2}{D}} E[|(g_i * f_j)[rD]|^2] \\ &= N\theta\Big(\frac{q_1^{L_s-1}}{1-q_1q_2}\Big(\frac{1-q_1^{-(L_p-1+D)}}{1-q_1^{-D}} - q_1q_2\frac{1-q_2^{L_p-1+D}}{1-q_2^D}\Big) \\ &+ \frac{1-(q_1q_2)^{L_p}}{1-q_1q_2} q_1^{L_s-L_p-D} \frac{1-q_1^{-(L_s-L_p)}}{1-q_1^{-D}} \\ &+ \frac{q_2^{1-L_s}}{1-q_1q_2}\Big(\frac{1-q_2^{L_p-1}}{1-q_2^D} q_2^{L_s+D-1} \\ &- (q_1q_2)^{(L_s+L_p-1)} \frac{1-q_1^{1-L_p}}{1-q_1^{-D}} q_1^{1-L_s-D}\Big)\Big) \end{aligned} \tag{15}$$

where $q_1 = e^{-\frac{kT_S^s}{\delta_T^s}}$, $q_2 = \alpha e^{-\frac{kT_S^p}{\delta_T^p}}$.

Equation (15) expresses the interference energy that the j-th PU receive from the TRAP at each observation. Assuming $L_p \leq L_s$ is just for the ease of derivation. In fact, it can be seen from equation (15) that the two vectors g_i and f_j are interchangeable. In case of $L_p > L_s$, equation (15) can be easily applied by treating the shorter vector as g_i and the longer vector as f_j.

For the SU indexed i, the received signal from the TRAP can be viewed as the combination of the intended signal to itself and the signal to other SUs. Therefore, there would be inter-user interference (IUI) and inter-symbol interference (ISI). The IUI and ISI for the TRDMA system was expressed in equations (21) and (22) in [15].

IV. DT Downlink Interference Analysis

To see the advantage of the TR downlink system, we compare it with the downlink system using direct transmission (DT) with Rake receivers. As shown in Fig. 2, the direct transmission access point (DTAP) transmits an impulse through the broadband channel. The user uses a Rake receiver to identify the most significant L_R taps of the received signal where L_R is the number of fingers.

We assume that each rake receiver is ideal that it has perfect channel information. Moreover, it is assumed that each receiver is able to equip unlimited number of fingers. Thus, for the ideal receiver, the optimal case is that the finger weight vector is a normalized version of the channel impulse response

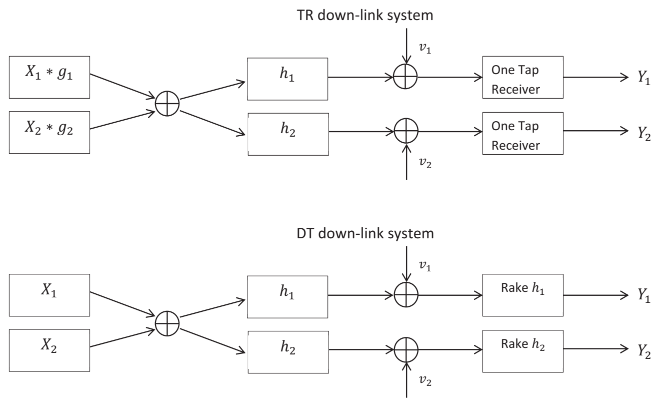

Fig. 2. Two downlink systems

(CIR) vector. Let $w_i[k]$ denote the weight associated with the tap $h_i[k]$, then

$$w_i[k] = h_i^*[k] / \sqrt{\sum_{j=0}^{L-1} |h[j]|^2}$$

$$L_{Ri} = L_i.$$

The signal power received by the ideal Rake receiver is

$$\begin{aligned} P_{SIG}^{DT} &= |X_i|^2 (\sum_{k=0}^{L-1} h_i[k] w_i[k])^2 \\ &= \frac{|X_i|^2}{\sum_{j=0}^{L-1} |h[j]|^2} (\sum_{k=0}^{L-1} |h_i[k]|^2)^2 \\ &= P_{SIG}^{TR} \end{aligned} \tag{16}$$

and certainly

$$E[P_{SIG}^{DT}] = E[P_{SIG}^{TR}]. \tag{17}$$

The ISI for the direct transmission is

$$\begin{aligned} P_{ISI}^{DT} &= |X_i|^2 \sum_{l=1}^{\frac{L-1}{D}} | \sum_{k=0}^{L-1-Dl} h_i[k+Dl] w_i[k]|^2 \\ &+ |X_i|^2 \sum_{l=1}^{\frac{L-1}{D}} | \sum_{k=Dl}^{L-1} h_i[k-Dl] w_i[k]|^2 \\ &= \frac{|X_i|^2}{\sum_{j=0}^{L-1} |h[j]|^2} \sum_{l=1}^{\frac{L-1}{D}} (| \sum_{k=0}^{L-1-Dl} h_i[k+Dl] h_i^*[k]|^2 \\ &+ | \sum_{k=Dl}^{L-1} h_i[k-Dl] h_i^*[k]|^2) \\ &= \frac{|X_i|^2}{\sum_{j=0}^{L-1} |h[j]|^2} \sum_{l=0, l \neq (L-1)/D}^{(2L-2)/D} |h_i * g_i[Dl]|^2 \\ &= P_{ISI}^{TR} \end{aligned} \tag{18}$$

and certainly

$$E[P_{ISI}^{DT}] = E[P_{ISI}^{TR}]. \tag{19}$$

From (16) and (18), the signal power and the ISI power are the same for TR system and DT system. Therefore, in the single user case without the interference from other users, the DT system with ideal Rake receiver is equivalent with the TR system. However, instead of using real fingers, the TR receiver is making use of the virtual fingers provided by the environment which is much easier to implement. In practice, the Rake receiver for the DT system can not be ideal, and the performance would degrade with less fingers. Therefore, the TR system could be viewed as an ideal case of the DT system in the single user case.

Besides the advantage of unlimited virtual fingers in the single user case, the benefit of using TR system is significant in the multiple user case by suppressing the interference to other users. In the presence of multiple SUs, the power of IUI received by each Rake receiver of the DT system is

$$\begin{aligned} P_{IUI}^{DT} &= \sum_{j=1; j \neq i}^{N} X_j^2 \sum_{l=0}^{\frac{L-1}{D}} \sum_{k=0}^{(L-1-Dl)} |h_i(k) h_i(k+Dl)|^2 \\ &= \sum_{j=1; j \neq i}^{N} (P_{SIG}^{DT,j} + P_{ISI}^{DT,j}) \end{aligned} \tag{20}$$

and

$$E[P_{IUI}^{DT}] = (N-1) E[(P_{SIG}^{DT} + P_{ISI}^{DT})]. \tag{21}$$

where N is the number of SUs.

The power of interference to the PU by the DT system is

$$\begin{aligned} P_I^{DT} &= \sum_{i=1}^{N} X_i^2 | \sum_{l=0}^{\frac{L-1}{D}} h_i[Dl]|^2 \\ &= \sum_{i=1}^{N} X_i^2 \sum_{l=0}^{\frac{L-1}{D}} |h_i[Dl]|^2 \end{aligned} \tag{22}$$

and

$$\begin{aligned} E[P_I^{DT}] &= N E[X_i^2] \sum_{l=0}^{\frac{L-1}{D}} E[|h[Dl]|^2] \\ &= N E[X_i^2] \frac{1 - e^{-\frac{T_s(L-1+D)}{\sigma_T}}}{1 - e^{-\frac{T_s D}{\sigma_T}}} \end{aligned} \tag{23}$$

Equation (20) means that the IUI power received by user i is equivalent to $N-1$ times the sum of signal power and ISI power of itself. It could be understood in this way: since the DTAP is using the direct transmission that transmitting the combination of the symbols to all users, the receiver treats the information to itself the same way with the information to other users. Therefore, they play the same role in receiving power and the unintended symbols would contribute significantly to the IUI. It is the same way in equation (22) that the DT system would contribute to the interference to the PU. However, in the TR system, each symbol is preprocessed by the TRAP by convoluting with the CIR of the receiver, which could be viewed as the “natural signature” of the receiver. For a particular receiver, the intended symbol in the received signal would be extracted by the matched channel and the unintended part would be automatically suppressed by the unmatched signature.

V. Numerical Results

In this section, the TR system and the DT system are compared by being applied to the SU downlink system at the same environment. The numerical examples illustrate that the TR system would incur less impact on the PU than the DT system. Moreover, we also show that the TR system achieves better power efficiency than the DT system.

A. Less impact on PU

We define R as

$$R = 10 * log_{10} \frac{P_I^{SU} + \sigma^2}{\sigma^2} \quad (24)$$

where P_I^{SU} is the interference power to the PU caused by the SU, σ^2 is the noise power.

It indicates how much SINR degradation the PU would suffer from the SUs. Let S_1 denote the SINR of a particular PU working at the environment with the SU network and S_2 denote the SINR of the same PU working at the same environment except that free of SUs. Then

$$\begin{aligned} & S_2 - S_1 \\ &= 10 * log_{10} \frac{P_S^{PU}}{P_I^{PU} + \sigma^2} - 10 * log_{10} \frac{P_S^{PU}}{P_I^{SU} + P_I^{PU} + \sigma^2} \\ &\le 10 * log_{10} \frac{P_I^{SU} + \sigma^2}{\sigma^2} \quad (25) \end{aligned}$$

where P_S^{PU} is the signal power of the PU transmission, P_I^{PU} is the interference power caused by the PU network, i.e., the IUI between PUs.

In the first numerical example, R for the PU is constrained to be no more than $5dB$ thus $S_2 - S_1 \le 5dB$. It means the operation of the SUs is regulated to ensure that the SINR loss for each PU can not exceed $5dB$. As shown in Fig. 3, if the two systems are with the same interference constraint on the PU, the TR system is able to support more users than the DT system by fixing the minimum achievable data rate for each SU. Especially, if the required minimum data rate is low for each SU, the TR system has the capability to support a larger volume of SUs. For example, the TRAP is able to support about 25 SUs with $0.01bps/Hz$ each, which is $1Mb/s$ is the downlink system is operating at the bandwidth $B_s = 100MHz$. In contrast, the DTAP can only support no more than 10 SUs. On the other hand, if the number of SUs are fixed in this system, the TR system is able to provide higher achievable data rate for each SU.

The loss of SINR would affect the PU in multiple ways. We take the achievable data rate as an example. In the second numerical example, every single SU's achievable data rate is set at $0.1bps/Hz$. The normalized PU achievable data rate is the ratio of the achievable data rates of the PU with and without the SUs.

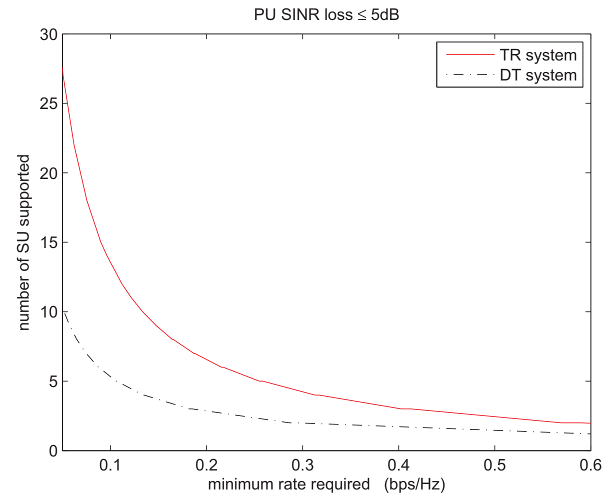

Fig. 3. Number of SU supported with minimum data rate subject to PU SINR constraint

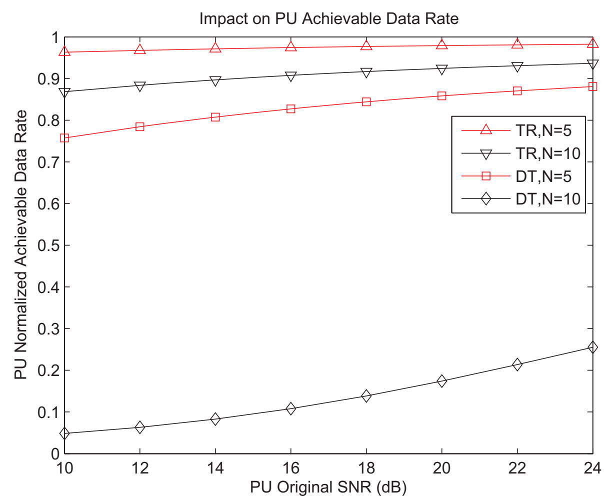

Fig. 4. PU data rate loss with original SNR

Different from the SINR, the achievable data rate loss is not only dependent on the operation of SU, but also dependent on the SNR of the PU originally working with. In Fig. 4, it is illustrated that the PU working at lower SNR would be more vulnerable to the interference from SUs. Moreover, the interference-mitigating feature of TR is make the PU suffer from less data rate loss in each case compared with the DT system.

The benefits of using TR in the SU network demonstrated above are the results of two facts caused by the spatial focusing effect. One is that the power will be concentrated at the intended receiver while low power leakage to the PU. Therefore, more users or higher transmitting power could be permitted comparing with the DT system. Moreover, the power leakage to other SUs would be suppressed by the spatial focusing effect, which helps improve the effective SINR and thus the achievable data rate.

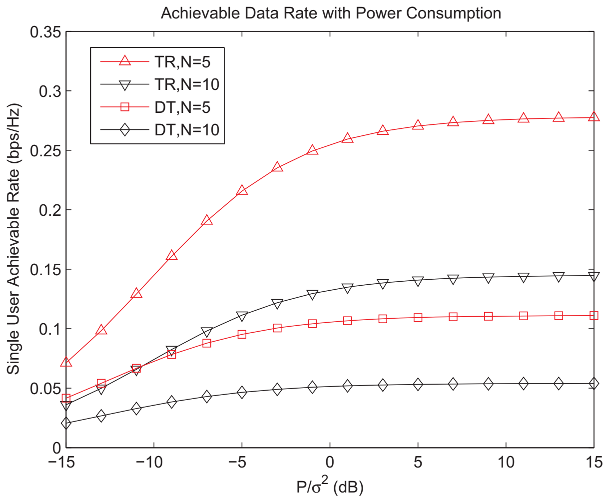

Fig. 5. The single user rate and the power cosumption

B. Power Efficiency

The interference-mitigating effect of the TR system also provides power efficiency. In this numerical example, the TR system and the DT system are implemented with the same amount of SUs. In Fig. 5 it is shown that the TR system is able to provide higher achievable data rate for each SU than the DT system with the same total power consumption. It is because in the DT system, the DTAP transmits the non-discriminating symbols to all users. For each SU observing the signal, the power of the unintended signal might be even greater than that of the intended signal. In other words, the energy used for transmitting unintended symbols would backfire the energy used for the intended symbol. This backfire effect would grow dramatically while increasing the volume of SUs and consequently the power efficiency is poor. For the TR system, convoluting the symbol sequence with the CIR before transmitting would embed the signature of the intended user into the sequence to it. For each SU observing the signal, the power of the unintended signal would be automatically suppressed by the unmatched signature, which serves to relieve the backfire effect and thus improve the power efficiency.

VI. Conclusion

Time-reversal technology has the feature of spatial and time focusing. In this paper, the secondary user downlink system using time-reversal was modeled and the interference on the primary user is analyzed. Different from the approach of using cognitive radio, the time-reversal based downlink system is less complicated to implement. The benefit of time-reversal downlink system was shown by comparing with the downlink system using direct transmission that the time-reversal system has the advantage of being friendly to the PU as well as power efficiency.

In the future, it might be interesting to consider heterogeneous secondary users with different QoS rather than just channel capacity, and some smart way to operate the secondary user network can be developed under this assumption. Moreover, although we used the time-reversed version of the CIR to convolve with the symbol sequence before transmitting, it might not be optimal in some sense[17]. Therefore, waveform design for some specific purposes might be useful. To get a full view of the coexistence of TR network and the licensed users, it might be necessary to investigate the robustness of time-reversal network against the interference from the primary users.

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