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Analysis on Channel Capacity of Transform Domain Communication System

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Abstract

Transform Domain Communication System (TDCS) has caught attention for its characteristics of flexible spectrum application, excellent anti-interference performance and low interception probability. Analysis on channel capacity is one aspect of important basic theory research for TDCS. The fundamental principle of TDCS is studied at first. Then the channel capacity model of TDCS is deduced and built on the background of Gaussian white noise channel with typical interference. The channel capacity of TDCS under different spectrum sensing methods is investigated on the basis of the model. The research indicates that the spectrum sensing methods based on AR model and wavelet-packet transform make more improvement for TDCS channel capacity. Therefore, from the perspective of maximizing TDCS channel capacity, the spectrum sensing methods based on AR model and wavelet-packet transform can be adopted.

Keywords: *cognitive radio, channel capacity, spectrum sensing, wavelet-packet transform*

1. Introduction

Transform domain communication is derived from the “transform domain processing system” propose by a scientist called German from Rome laboratory in 1988, which makes use of the spectrum occupation information of communication environment to modify the waveform of direct sequence spread spectrum(DSSS) signal and to keep away from the area with interference spectrum [1]. The integrated concept of transform domain communication system (TDCS) was proposed by the US Air Force Institute of Technology and the US Air Force Research Laboratory in 1996, whose object was to make sure the military aircraft keep the capability of reliable secure communication within the formation under the condition of strong electromagnetic interference [2]. TDCS is a new technology developed from spread spectrum communication and transform domain processing technology. It senses the environment’s spectrum, avoids the interference in transform domain by combining transmitter and receiver. It realizes the performance of low interception probability through adopting pseudo-random phase sequence. Therefore, TDCS has caught attention for its characteristics of flexible spectrum application, excellent anti-interference performance and low interception probability, and is considered to be one of the candidate technologies of cognitive radio [3, 4].

Presently, the research on TDCS mainly focuses on interference spectrum estimation, transform domain technology, basis function generation, signal modulation and demodulation, system modeling and simulation, system performance analysis and hardware realization, etc[5-9]. Thereinto, the research on analysis of system performance mainly concentrate on analysis of anti-interference performance, multiple access performance and channel adaptability performance. However, there is little research on TDCS channel capacity analysis, though channel capacity is one of the important performance indexes. The channel capacity reflects the maximum information quantity which TDCS channel can transmit. Therefore, the analysis on channel capacity is one of the important TDCS fundamental theory research. In this paper, the TDCS channel capacity is analyzed and studied; the model of TDCS channel capacity is deduced and built; then the channel capacity under different spectrum sensing methods is investigated.

The remaining part of this paper is organized as follows. The fundamental principle of TDCS is introduced in section 2. The model of TDCS channel capacity is deduced and built in

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section 3. The channel capacity under different spectrum sensing methods is investigated in section 4. Finally, conclusions are drawn in section 5.

2. Principle of TDCS

The main thoughts of TDCS is that the waveform is designed through the combination of transmitter and receiver, the transmitter allocates signal energy only to frequency bands without interference and the receiver receives only the spectrum with signal energy, so as to avoid interference or jamming other users. The main functional modules of TDCS includes electromagnetic environment sampling, environment spectrum estimation, magnitude spectra forming of basis function, random phase generation, time domain basis function generated by inverse transform, storage of basis function and data modulation, etc. The principle diagram of DFT based TDCS transmitter is shown in Figure 1. For other transform technologies, the principle frame of TDCS keeps the same and only the transform technology applied in transform module needs to be replaced by corresponding transforms technology [3, 5].

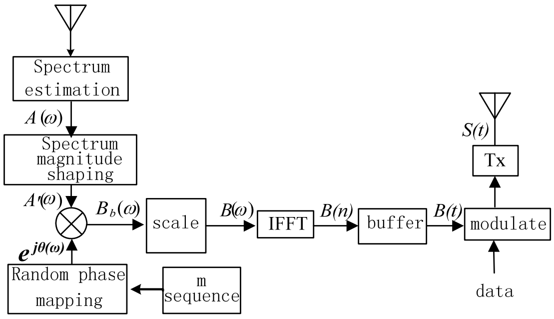


Figure 1. Principle Diagram of TDCS Transmitter

As is shown in Figure 1, firstly the transmitter samples the electromagnetic environment dynamically in the given bandwidth. Then the spectrum estimation to the sampling signal is processed in transform domain and the position of interference is located. The spectrum with interference is suppressed through threshold processing and the pure magnitude spectra vector $A^{'}(\omega)$ is obtained. If the magnitude value of some frequency point exceeds the given threshold, the magnitude value of the frequency point is set to be 0, otherwise set to be 1. The magnitude spectra vector $A'(\omega)$ composed of 0 and 1 is obtained, as shown in (1):

$$A'(\omega) = [a_1, a_2, ..., a_N] \tag{1}$$

Where $a_i \in \{0,1\}$ expresses the magnitude value of the i th frequency point within system bandwidth, $a_i = 0$ expresses that the frequency point exists interference or is occupied, $a_i = 1$ expresses that the frequency point does not exists interference.

Let $A'(\omega)$ do dot product with the equal length complex random phase vector $e^{j\theta(\omega)}$ generated by phase mapping, which makes the transmitting signal have the characteristic of noise. Then the magnitude is scaled in order to ensure the transmitting power and the frequency domain basis function $B(\omega)$ is obtained, as shown in (2):

$$B(\omega) = CA^{'}(\omega) \cdot e^{j\theta(\omega)} \tag{2}$$

Where C expresses magnitude scale factor.

Where inverse fast fourier transform (IFFT) is done and the waveform sequence of time domain basis function $b(n)$ is obtained and stored in the buffer. The basis function is considered to be superposition of many subcarriers. The original phase of every subcarrier distributes randomly in a phase space. Finally, the data is modulated by basis function and transmitted through radio-frequency module. The TDCS modulation manner includes binary bipolar modulation and cyclic shift keying modulation.

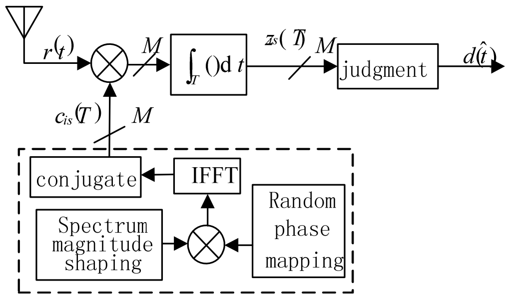


Figure 2. Principle Diagram of TDCS Receiver

The principle diagram of TDCS receiver based on DFT is shown in Figure 2 The signal acquisition, detection and synchronization should be done before demodulation. The synchronization acquisition can adopt direct time correlation technology or technology of German [5-9]. The TDCS demodulator is shown within the dotted line in Figure 2 The basis function generating procedure is the same as in transmitter. The received signal $r(t)$ is correlated with M local reference signals $c_i(T)$. Every one of M correlators generates a statistic $z_i(T)$ and the estimated value of data $d^{'}(t)$ is obtained according to maximum likelihood criterion. The judge criterion is decided according to the manner of data modulation. For example, for binary bipolar modulation, if $z_i(T)$>0, it is judged as $s_1(t)$, otherwise judged as $s_2(t)$; for binary cyclic shift keying modulation, if $z_1(t)-z_2(t)>0$, it is judged as $z_1(t)-z_2(t)>0$, otherwise judged as $s_2(t)$; for M-ary cyclic shift keying modulation, the received signal correlated with M reference signals and the maximum correlation value is judged as the estimated value of corresponding symbol.

3. Model of TDCS Channel Capacity

Cannel capacity is one of the important indexes for TDCS channel. It reflects the maximum information quantity which TDCS channel can transmit with minimum error probability. The model of TDCS channel capacity will be analyzed and deduced in this section.

Under the condition of additive Gaussian white noise channel, the system channel capacity is defined as [10, 11]:

$$\begin{aligned} C_{awgn} &= W\log_2\frac{P+N_0}{N_0} \\ &= W\log_2(1+\frac{P_0}{N_0}) \\ &= W\log_2(1+SNR) \end{aligned} \quad (3)$$

Where W expresses system bandwidth, P expresses average transmitted power of signal, N_0 expresses power spectral density of additive Gaussian white noise, $SNR = P / N_0$ expresses signal-to-noise ratio, the unit of C_{awgn} is bits/s.

When there is other user or interference in the channel, if no interference suppression, the system channel capacity is:

$$\begin{aligned} C_{jam} &= W \log_2 \frac{P + N_0 + J_E}{N_0 + J_E} \\ &= W \log_2 (1 + \frac{P_0}{N_0 + J_E}) \\ &= W \log_2 (1 + SINR) \end{aligned} \quad (4)$$

Where J_E expresses energy of interference, $SINR = P / (N_0 + J_E)$ expresses energy ratio of signal and interference plus noise.

Before TDCS transmits information, it eliminates the frequency band with interference through interference spectrum sensing and magnitude spectra shaping algorithm, and makes use of the remanent frequency band to transmit signal. Therefore, the available bandwidth of TDCS is $W_{TDCS} = (1 - \zeta\%)W$. In addition, TDCS isn't affected by interference signal in the course of information transmission. So the TDCS channel capacity is only related to available bandwidth and signal-to-noise ratio SNR. Under the condition of additive gaussian white noise channel, the TDCS channel capacity is:

$$\begin{aligned} C_{TDCS} &= W_{TDCS} \log_2 (1 + SNR) \\ &= (1 - \zeta\%) W \log_2 (1 + SNR) \end{aligned} \quad (5)$$

4. TDCS Channel Capacity under Different Spectrum Sensing Methods

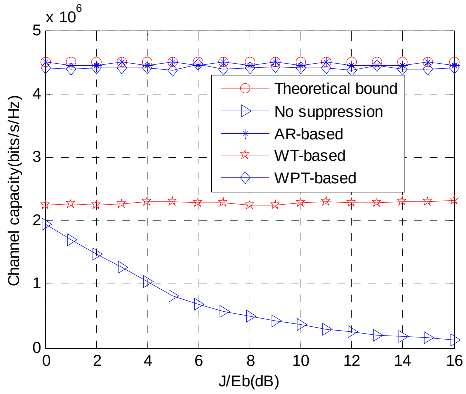
Interference frequency spectrum sensing is the foundation of realizing interference avoidance for TDCS. The existing spectrum sensing methods mainly includes matched filtering detection method, energy detection method, cyclic stationary characteristic detection method and collaboration detection method [12-14]. Thereinto the energy detection method is the most common method. It is a blind detection method and has the advantage of wide application and simple implement. The spectrum sensing methods based on energy detection mainly includes AR model based spectrum sensing method, wavelet transform based spectrum sensing method and wavelet-packet transform based spectrum sensing method [15-17]. In this section, the TDCS channel capacity under different spectrum energy detection methods is studied and analyzed comparatively [18-20].

Supposed that when TDCS works, there is different interference within the transmission channel. Assumed that the signal-to-noise ratio $E_b / N_0 = 4\text{dB}$, the system bandwidth is 25MHz, the variation range of interference-to-signal J / E_b is 0~16dB. After magnitude spectra shaping, the TDCS channel capacity under different spectrum energy detection methods is shown as in Figure 3.

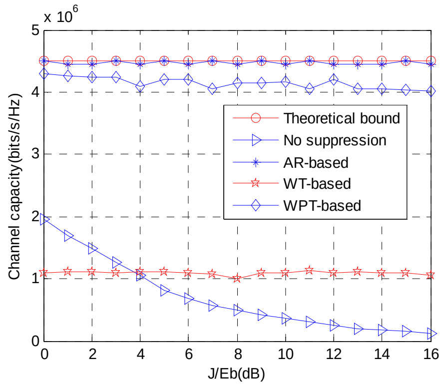
It can be seen from Figure 3 that the maximum TDCS channel capacity is 4.51Mbits/sec/Hz when there is no interference in the channel; the system channel capacity decreases with the increase of J / E_b when there is interference in the channel. The system channel capacity with interference can be improved when the TDCS with spectrum sensing and interference elimination methods. From the simulation results shown in Figure 3(a)~(e), conclusions are drawn as follows:

(1) When there is single-tone interference and multi-tone interference in the channel, after magnitude spectra shaping, the system channel capacity is improved with different spectrum energy detection methods. The TDCS channel capacity based on different spectrum energy detection methods remains constant with the increase of J / E_b. Thereinto, spectrum

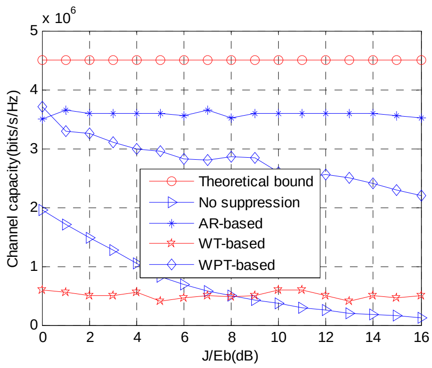
sensing method based on AR model and spectrum sensing method based on wavelet-packet transform have more contributions to channel capacity improvement, and the corresponding channel capacity are close to the theoretical maximum value. While the channel capacity with spectrum sensing method based on wavelet transform improves less.



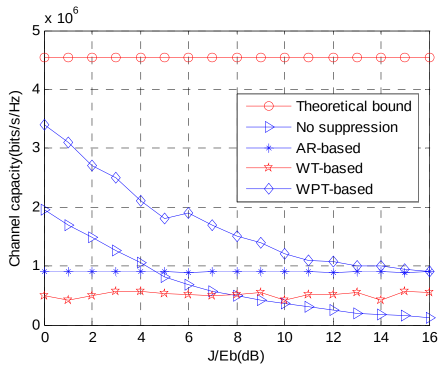
(a) single-tone interference



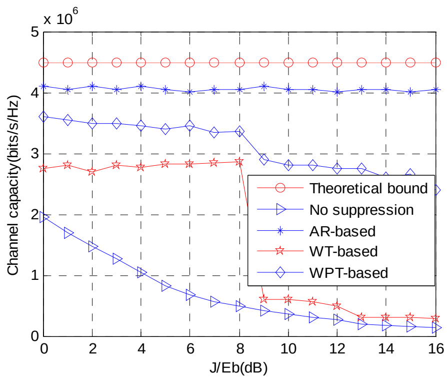
(b) multi-tone interference



(c) 20% broadband interference



(d) 80% broadband interference



(e) Chirp interference

Figure 3. TDCS Channel Capacity under Different Spectrum Energy Detection Methods

(2) When there is broadband noise interference in the channel, after magnitude spectra shaping, the system channel capacity improvement with different spectrum energy detection methods depends on the ratio of jammed band. When applying AR model based spectrum sensing method and wavelet transform based spectrum sensing method, the increase of J / E_b doesn't affect system channel capacity and the former does more contributions to the improvement of channel capacity. While for wavelet-packet transform based spectrum sensing

method, the improvement of system channel capacity is maximum, though it decreases with the increase of J / E_b.

(3) When there is chirp interference in the channel, after magnitude spectra shaping, the system channel capacity improvement with different spectrum energy detection methods is different. When applying AR model based spectrum sensing method, the increase of J / E_b doesn't affect system channel capacity and it makes the most contributions to the improvement of channel capacity, which is close to the theoretical maximum value. While when applying wavelet transform based spectrum sensing method and wavelet-packet transform based spectrum sensing method, although the system channel capacity both improved a lot, it decreases continually with the increase of J / E_b, which is determined by the property of chirp interference. That is because in the course of decomposition, the increase of J / E_b makes the energy of interference signal changes in different sub-bands, which results in constantly changing of system available bandwidth.

5. Conclusion

Channel capacity is one of the important performance indexes for TDCS. Analysis on channel capacity is one aspect of important basic theory research for TDCS. On the basis of research on fundamental principle of TDCS, the channel capacity model of TDCS is built and the channel capacity of TDCS under different spectrum sensing methods is investigated based on the model. The research shows that, when there is single-tone interference and multi-tone interference in the channel, the system channel capacity improves more when applying AR model based spectrum sensing method and wavelet-packet transform based spectrum sensing method; when there is broadband noise interference in the channel, the system channel capacity improves the most when applying wavelet-packet transform based spectrum sensing method, though it decreases with the increase of interference-signal-ratio; when there is chirp interference in the channel, the system channel capacity improves the most and isn't affected by the increase of interference-signal-ratio when applying AR model based spectrum sensing method. Therefore, from the perspective of maximizing TDCS channel capacity, the spectrum sensing methods based on AR model and wavelet-packet transform can be adopted. The research of this paper is accomplished on the background of Gaussian white noise channel with typical interference, which has not taken channel fading factors into account. So the next step is studying and analyzing the channel capacity in different fading channels.

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