Multi-satellite Non-cooperative Communication Based on Transform Domain Communication System

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Abstract. Cognitive communication based on the unoccupied channels of transparent transponders in commercial satellites is a promising method to solve the shortage of satellite spectrum resource. However, most opportunity spectrum access systems cannot obtain real-time channel information from a commercial satellite. Although some systems can achieve non-cooperative communication, they usually utilize single satellite, which limits their overall performance. In this paper, to take full use of unoccupied satellite spectrum without disturbing primary users, a non-cooperative communication method by using satellites of different types is proposed based on transform domain communication system. Compared with existing methods, it is compatible with different transparent transponder parameters, such as frequency, bandwidth, primary user type, and delay. Besides, it also can achieve transmitting rate adaptation without signaling overhead.

Keywords: Non-cooperative communication · Transparent transponder · Transform Domain Communication System (TDCS) · Multi-satellite

1 Introduction

The increasingly rapid growth in wireless communications has made the frequency spectrum an extremely precious resource. Spectrum crowding in commercial satellites is more visible with limited transponder resource [1]. However, recent studies suggest that spectrum congestion is mainly due to inefficient spectrum usage rather than spectrum scarcity [2]. Considering payloads weight and reliability, most commercial satellites carry transparent transponders [3]. Channels of different transparent transponders are allocated to certain primary users or services, which implies that some spectrum would be idle when the corresponding primary users or services are absent. Hence, fully utilizing transparent transponder resource of commercial satellites without disturbing primary users has been the focus of some recent research efforts.

For most opportunity spectrum access systems, the real-time channel information obtaining of commercial satellites is the prerequisite to utilizing unoccupied spectrum. Shi [4] designed a non-cooperative communication system via satellite transparent transponders based on direct sequence spread spectrum (DSSS) technique. It roughly

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lays the DSSS signal on channels whether or not the primary users exist. However, the lack of real-time channel information increases the risk of disturbing primary users. Xie [5] proposed utilizing satellite transparent transponders to achieve covert communication based on transform domain communication system (TDCS). TDCS is an overlay cognitive radio system [6, 7], where spectrum sensing is used to obtain real-time channel condition. Nevertheless, systems above only consider single satellite and the transmitting rate could not change with the real-time channel condition of the transparent transponders, which limits the spectrum efficiency improvement.

In this paper, a multi-satellite non-cooperative communication system is proposed to achieve reliable communication. Transparent transponders from different commercial satellites are analyzed to design a multi-satellite channel model. Based on this model, the system is designed detailedly. Then adaptive transmitting structure is proposed to improve the spectrum efficiency. Finally, delays of different satellites are estimated and compensated to accurately recover the modulated data. Compared with existing methods, the proposed system is compatible with different satellites. Besides, it also can achieve transmitting rate adaptation without signaling overhead.

The next section of this paper will briefly introduce TDCS. The new system is proposed detailedly in Sect. 3, where multi-satellite channel model, adaptive transmitting rate structure, delays estimation and compensation are designed. Simulations and analysis are presented in Sect. 4. The paper is then concluded in Sect. 5.

2 Preliminary

The TDCS model is depicted in Fig. 1. The transmitter and the receiver independently sense the spectrum, to create the spectrum mask $A(k)$, with a value 1 or 0 if the k th frequency bin is unoccupied or interfered, respectively. Pseudo-random phases θ_k are created by a pseudo-random sequence generator and applied element by element to the spectrum mask. The resulting vector is passed through an inverse fast Fourier transform (IFFT) and normalized to obtain the basis waveform. Basis waveform is used to generate cyclic code shift keying (CCSK) symbols. Then data is modulated with the symbols in Gray code. The i th transmitting symbol can be expressed on complex baseband notation as

$$s_{TDCS,i}(n) = \frac{1}{\sqrt{NN_1}} \sum\nolimits_{k=0}^{N-1} A(k) e^{\theta_k} e^{-j2\pi m_i k/M} e^{j2\pi nk/N}, \tag{1}$$

where N and N_1 are the numbers of the total and the unoccupied frequency bins, respectively. $m_i \in [1, M]$ is the i th transmitting data with M-ary CCSK modulation.

In the receiver, data is restored by maximum peak detection based on the correlations between the received signal and local generated CCSK symbols.

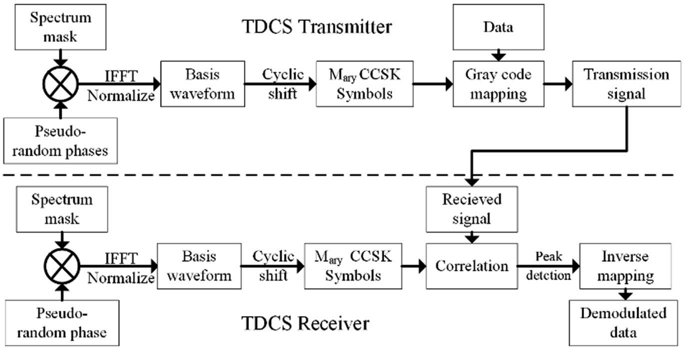

Fig. 1. Diagram of the TDCS.

3 System Structure

As the communication scenario shown in Fig. 2, ground terminal A transmits data to ground terminal B via two maritime satellites and one broadcasting TV satellite, simultaneously. The communication links are composed of uplinks from A and downlinks to B. In the following parts, the key points of the terminals and links are designed detailedly.

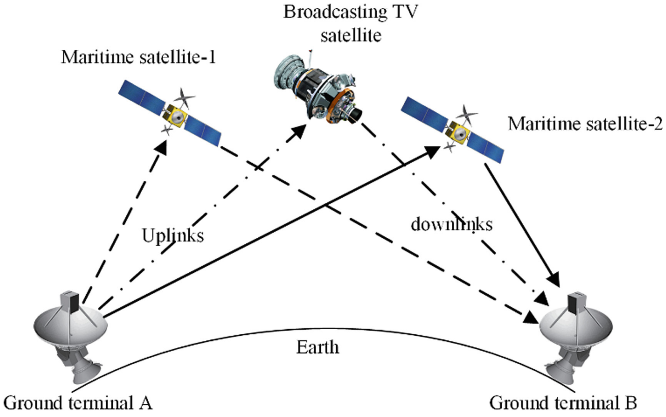

Fig. 2. Communication scenario.

3.1 Non-cooperative Channels Design

In Fig. 3, the non-cooperative channels are designed. Data is divided into three parts depending on the transmitting rates of the three channels. Assume maritime satellites are Inmarsat-4, which use L band (1634–1675/1518–1559 MHz up/downlink) with total relay bandwidth 36 MHz of total 41 MHz. However, due to the transmission rate requirement of primary users and frequency division multiplexing access structure, the beam bandwidth covering certain area is limited within 3.5 MHz. The bandwidths of transparent transponders and guard intervals are 200 kHz and 20 kHz, respectively. For broadcasting TV satellites, their relay bandwidths are much wider, such as 36 MHz, 54 MHz, and 72 MHz in C and Ku band. Considering broadcasting TV signal usually needs 8 MHz bandwidth, the beams are much wider to cover the whole relay bandwidths.

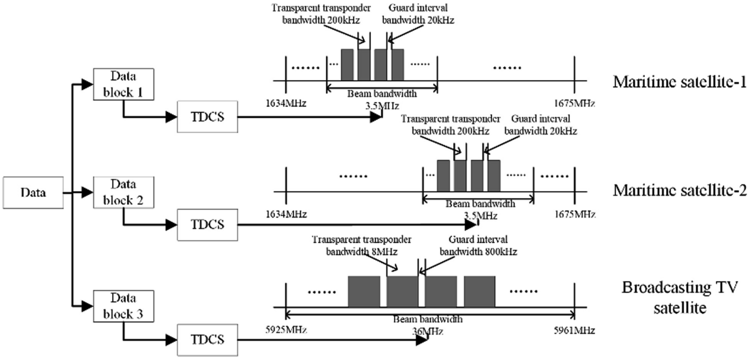

Fig. 3. Non-cooperative channels design.

The communication waveforms are generated based on TDCS. Terminal A and B independently sense the channel conditions of three satellites to generate spectrum masks. The idle transparent transponders are selected as the channels for the proposed communication system. Every satellite owns a unique pseudo-random phase sequence, based on which terminals generate basis waveforms for each satellite. Then data blocks are modulated with corresponding basis waveforms. Terminal B separates composite signal with different down-conversions to demodulate. For signals from the same frequency range, when one signal is demodulating, other signals can be regarded as noise according to the quasi-orthogonal of pseudo-random phase sequences and noise-like waveform characteristics [8].

3.2 Adaptive Transmitting Rate Structure

To achieve data blocks allocation as well as transmitting rate changing with channel conditions, an adaptive transmitting rate structure is proposed in this section. As shown in Fig. 4, synchronizations are used as an index to represent different modulation types. In the receiver, every frame is synchronized in P channels to locate the start point and determine the modulation type. Based on the index information above, signals are modulated in the corresponding way. Obviously, no signaling overhead is need in this structure.

According to [9, 10], the symbol error rate (SER) and bit error rate (BER) of TDCS modulated with CCSK are approximated as

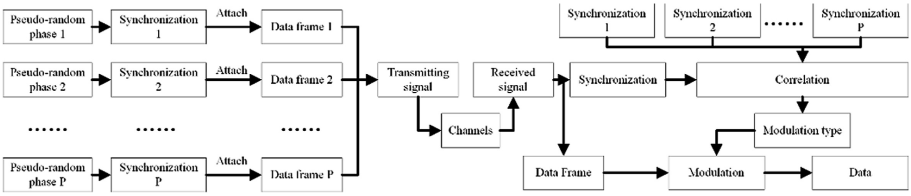

Fig. 4. Adaptive transmitting rate structure.

$$P_s = 1 - \int_0^{\infty} e^{-(x+\gamma)} \cdot I_0\left(\sqrt{4\gamma x}\right) \cdot (1 - e^{-x})^{M-1} dx, \tag{2}$$

$$P_b = \left(2^{b-1} / \left(2^b - 1\right)\right) P_s, \tag{3}$$

where $\gamma = E_s/\sigma_n^2$ is the ratio of symbol energy to noise power (SNR). $I_0(.)$ is the modified Bessel function of the first kind and zero order. M is the order of CCSK, and b is the bits carried by each symbol. The correlating of the synchronization for each satellite is actually the same as data, therefore, the SER of the synchronization P_{syn} and the total BER of one satellite P_e are given as

$$P_{syn} = 1 - \int_0^{\infty} e^{-\left(x+\gamma_{syn}\right)} \cdot I_0\left(\sqrt{4\gamma_{syn} x}\right) \cdot (1 - e^{-x})^{P-1} dx, \tag{4}$$

$$P_e = 1 - \sum \xi_1 (1 - P_{b1})\left(1 - P_{syn}\right) + \ldots + \xi_P (1 - P_{bP})\left(1 - P_{syn}\right), \tag{5}$$

where $\gamma_{syn} = E_{syn}/\sigma_n^2$ is the ratio of synchronization energy to noise power ratio. P is the variety of the modulation types in one satellite. P_{b1}, $P_{b2}, \ldots$, and P_{bP} are the BERs of different modulation types. ξ_1, $\xi_2, \ldots$, and ξ_P are the scales of different modulations in on satellite.

3.3 Delay Estimation and Compensation

The signal space transmission characteristic as well as delays are different with different frequency bands. For maritime and broadcasting TV satellites are Geosynchronous, once the terminals are fixed, the delays would not change much. Therefore, delay estimation can be regarded as a stable multi-path estimation. Terminal A transmits specific preset signals which are known to terminal B via satellites. In terminal B, delays are estimated with the preset signals (as pilots) by correlations. In the demodulation, corresponding delays are composited to recover data from different satellites. The total BER P_{eall} is then obtained,

$$P_{eall} = \zeta_1 (1 - P_{e1}) + \zeta_2 (1 - P_{e2}) + \zeta_3 (1 - P_{e3}), \tag{6}$$

where P_{e1}, P_{e2}, and P_{e3} are the BERs of three satellites as in (5). ζ_1, ζ_2, and ζ_3 are the scales of data allocated to corresponding satellites.

4 Simulations and Analysis

In this section, some numerical examples are simulated to verify the proposed system.

Figure 5 shows the delay estimation of different satellites. According to the communication scenario above, the preset signals of three different satellites reach terminal B with different delays. To simplify the process, N is set as 128, the communication bandwidths are 3.5 MHz and 36 MHz for maritime and broadcasting TV satellites, respectively. Taking the time of the first reached preset signal as standard, the delays are estimated. In Fig. 5, the delay of maritime satellite-1 is regarded as standard with $\tau_{m1} = 0$, whereafter, the delays of maritime satellite-2 and broadcasting TV satellite are estimated as τ_{m1} and τ_b. Then delays are compensated for each satellites to restore the separated data.

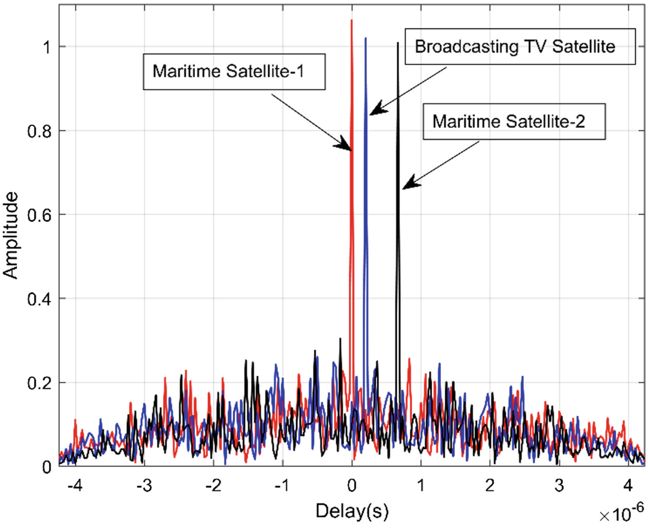

Fig. 5. Delay estimation of different satellites.

Figure 6 illustrates the BER performance of the adaptive transmitting rate structure. To overcome Doppler shift, synchronization is usually much longer than symbols. Simulation parameters are set as $N_{syn} = 1023, N = 128, N_1 = 50,\ 80, P = 2, \xi_1 = 1/3$ and $\xi_2 = 2/3$. According to dimensionality theory [10], without adaptive modulation, satellites use 32CCSK to fit $N_1 = 50$ spectrum condition. Modulation cannot adaptively turns to 64CCSK when spectrum condition is $N_1 = 80$. Based on the proposed method, modulation changes with spectrum condition, as the result, system can carry extra 0.6 bit per symbol on average. Besides, the BER performance is better than 32CCSK based on $N_1 = 50$.

The synthetical transmitting rate can be regarded as the sum of every satellite. According to the scenario above, assume three satellites share the same adaptive modulations, the transmitting rates can be calculated

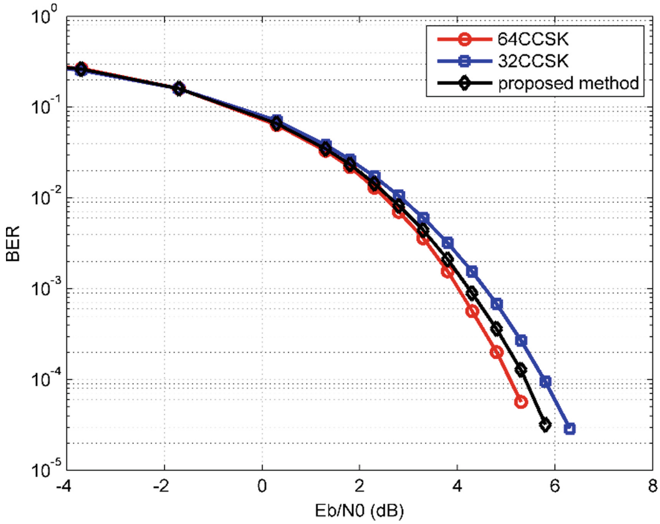

Fig. 6. Bit error rate (BER) performance of the adaptive transmitting rate structure.

$$R_b = \frac{b}{T_s} = \frac{b.B}{N}, \tag{7}$$

where b is the bits carried by each symbol on average in the proposed method. T_s and B are the duration and bandwidth of each symbol. The transmitting rates of two maritime satellites are $R_{b,m1} = R_{b,m2} = 0.155$ Mbps, the transmitting rate of the broadcasting TV satellite is $R_{b,bt} = 1.6$ Mbps, and the total transmitting rate is $R_{b,all} = 1.91$ Mbps. Obviously, the transmitting rate of multi-satellite method is much fast than that with single satellite.

5 Conclusions

This paper shows that cognitive communication system can be designed utilizing multiple satellites in a non-cooperative way. Compared with existing methods, the proposed system utilizes discrete and unoccupied spectrum of transparent transponders to fully use the satellite resource. Besides, the distributed data structure is safer to achieve a low detection and interception characteristic. The transmitting rate is also improved to meet applications requirement on high-speed and large-bandwidth.

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