Non-continuous Orthogonal Frequency Division Multiplexing Satellite Communication Model and Analysis of Interference to Authorized System

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Abstract. With the aim at improving the efficiency of satellite communication spectrum utilization, this paper proposes a non-continuous orthogonal frequency division multiplexing (NC-OFDM) satellite communication model based on convolutional code and LDPC code. We further analyze the bit error rate performance of the NC-OFDM system and evaluates the interference of the authorized system. Simulation experiment results show that NC-OFDM model can significantly improve the spectrum utilization of satellite communication, which can achieve spectrum compatibility with authorized users by adopting adaptive channel access and spectrum sensing technologies.

1. Introduction
Recently, the satellite communications have received significant attention due to its advantages of wide coverage and increasing data rate \cite{1}-\cite{7}. The satellite communications’ spectrum management commonly adopt the fixed channel authorization allocation method. As the business volume and the number of users increase rapidly, satellite communications are heavily restricted by the limited resources of orbit and frequency bands. The reason is that the current used frequency bands are becoming more and more crowded, and the available spectrum resources are pretty scarce. However, although spectrum resources are badly needed, there are still abundant spectrum holes of satellite communications, which could be utilized. The US Federal Communications Regulatory Commission indicated that the most of satellite spectrum utilization in the authorized frequency bands is only 15\%-85\%. This report showed clearly a prominent contradiction in spectrum management: shortly supplied spectrum resources versus low spectrum utilization.

Different from the traditional OFDM technology, NC-OFDM can overcome its weak points and can improves communication performances. The NC-OFDM model adopts the cognitive radio technology to discover and utilize spectrum holes of satellite communication, and convey signals with non-contiguous subcarriers because of the non-contiguous spectrum holes, which achieve highly-efficient communication of cognitive users. For the NC-OFDM model, although the spectrum resources are shared between the authorized users and cognitive users, the interference from cognitive
users to authorized users should be avoided or limited below a predefined level [8]. To the best of authors’ knowledge, the NC-OFDM technology has only been used among terrestrial communication. Besides, the research on NC-OFDM technology are largely concentrated in synchronization, out-of-band power suppression, peak-to-average ratio suppression, channel estimation and other issues [9]. Furthermore, NC-OFDM technology has not been used in satellite communications so far.

Cognitive radio technique enables primary users to share spectrum with cognitive users in the NC-OFDM system, which can largely improve the spectrum utilization efficiency. By combing NC-OFDM with satellite communications, the NC-OFDM satellite system can be designed. The OFDM satellite communication system will give the revolutionary leap of spectrum utilization filed to the traditional satellite communication systems. On the one hand, the current issue of spectrum resource shortage will be efficiently alleviated. On the other hand, it will also boost the integration between satellite with terrestrial communications, which is the key network architecture of future beyond 5G.

The rest of the paper is summarized as follows. Section II firstly introduces NC-OFDM satellite communication system model. In section III, we propose the Sub-carrier allocation method. Section IV provides the performance analysis. Section V provides interference analysis of NC-OFDM satellite communication system. Finally, section VI concludes the whole paper.

2. NC-OFDM Satellite Communication System Model
As shown in Figure 1, the transmitted source data $d_i$ is channel-coded and PSK/QAM modulated constellation mapping to produce a set of parallel data $\{d_0, d_1, \cdots, d_{M-1}\}$, where $M$ represents the available sub-carriers’ number by using spectrum sensing technique when the source data is generated. Similar to the realization principle of the OFDM technique, the modulation of the transmitted signal of NC-OFDM satellite system can also be achieved by the Discrete Inverse Fourier Transform (IDFT), but it should be noted that, the available frequency band of the sub-carrier is not continuously in the NC-OFDM system. The reason is that the frequency band of the sub-carriers is calculated by the spectrum holes’ number by using spectrum sensing and the sub-carrier allocation algorithm.

By assuming that the allocated sub-carriers’s number in the satellite channel is $N$, by using $N$-point IFFT, the sampled signal of NC-OFDM satellite system is written as follows
Similar to the above equation, the signal $s_k$ at the terminal can be used to restore the original data $d_i$, namely

$$d_i = \sum_{k=0}^{N-1} s_k \exp\left(-j \frac{2\pi ik}{N}\right), \quad i \in \{0, 1, 2, ..., N-1\},$$

(2)

3. Sub-carrier Allocation Method for NC-OFDM Satellite Communication System

3.1. Ku-band communication satellite sub-carrier division scheme

Currently, it is reported that the available frequency range of Ku-band commercial satellite communication is about 500MHz, which is allocated to 122 subcarriers. The interval between subcarriers is 4.125MHz, and we assume that the NC-OFDM satellite system includes 100 data subcarriers, 100 pilot subcarriers, and 10 protection subcarriers, which is shown in Table 1.

| Subcarrier Division Parameters | Definition |
|-------------------------------|------------|
| number of data subcarriers    | 100        |
| number of pilot subcarriers   | 12         |
| number of guard subcarriers   | 10         |
| total number of subcarriers   | 122        |
| subcarrier frequency spacing  | 4.125 MHz  |
| IFFT/FFT period              | 242.42 ns  |
| cyclic prefix                 | 70.08 ns   |

3.2. Ku-band communication satellite sub-carrier division scheme

By using satellite ground stations and spectrum monitoring equipment to monitor the spectrum of Ku-band commercial satellite, we can obtain the real-time used spectrum among 500MHz frequency band of the satellite communication satellite, and extract 15 spectrum holes that were not used by authorized users according to the signal spectrum. Based on the bandwidth of each spectrum hole and the bandwidth of a single subcarrier of 4.125MHz, the number of subcarriers that can be allocated in each spectrum hole is obtained. 15 spectrum holes are allocated a total of 33 subcarriers (as shown in Table 2), of which 20 data subcarriers, 6 pilot subcarriers, and 7 protection subcarriers. Considering the noise bottom level of spectrum holes, the calculated sub-carrier’s channel gain can be viewed as the constraint for allocating the sub-carrier power.

| Spectrum Hole Number | Start Frequency | Cut-off Frequency | Bandwidth | Assigned Sub-carrier Number |
|----------------------|-----------------|-------------------|-----------|-----------------------------|
| 1                    | 12232.6         | 12250.2           | 17.6      | 6-9                         |
| 2                    | 12252.1         | 12269.2           | 17.1      | 11-14                       |
| 3                    | 12325.1         | 12330.2           | 5.1       | 28                          |
4. Sub-carrier Allocation Method for NC-OFDM Satellite Communication System

Table 3 shows the basic parameters used in the simulation experiment, including the signal-to-noise ratio range, the number of sub-carriers (the sub-carriers here are discontinuous sub-carriers, which is the difference from the OFDM system), and the channel coding method, modulation method, frequency center and corresponding sampling frequency.

| Parameters          | Values                      |
|---------------------|-----------------------------|
| signal-to-noise-ratio | -10dB, 10dB                 |
| encoding            | (2,1,6) convolutional code  |
| modulation          | BPSK, QPSK, QAM             |
| center frequency    | 500 MHz                     |
| sampling rate       | 2 GHz                       |
| symbol rate         | 4 Mbit/s                    |

According to the setting of the above parameters, the NC-OFDM satellite communication system is simulated. When QPSK modulation is used, the bit error rate before and after convolutional coding changes with the signal-to-noise ratio is shown in figure 2. As the signal-to-noise ratio increases, Using convolutional QPSK modulation, the bit error rate has been greatly improved, at 10dB, the bit error rate is two orders of magnitude lower than the bit error rate of modulation without convolutional coding. As shown in figure 3, we perform the same simulation as above on LDPC encoding, and obtain the variation curve of the bit error rate with the system signal-to-noise ratio before and after LDPC encoding by using QPSK modulation.
5. Interference Analysis of NC-OFDM Satellite Communication System Pairing and Authorization System

The interference analysis of NC-OFDM signal to authorized user is the critical issue which judge NC-OFDM technique can be applied to satellite communication. The important reason for analysing...
interference is that the NC-OFDM sub-carriers is too close to the authorized frequency of the adjacent channel, resulting in adjacent channel interference, and the second is that the spectrum sensing lags. After the new authorized signal is connected to the satellite channel, the NC-OFDM sub-carrier The carrier failed to exit in time, causing partial or complete overlap of the spectrum.

Define the spectrum overlap rate (SOR) $\Delta F$ as the ratio of the frequency range of the licensed signal and the NC-OFDM signal spectrum overlap to the licensed signal bandwidth. Take the most common MPSK signal in the satellite communication authorization signal as an example, suppose the carrier frequency of the authorization signal is $f_{c1}$, the code rate is $d_{f1}$, and the adjacent NC-OFDM subcarrier carrier frequency is $f_{c2}$ , and the code rate is $d_{f2}$, then we can obtain:

$$\Delta F = \frac{f_{d1} + f_{d2} - |f_{c1} - f_{c2}|}{2f_{d1}}$$

(3)

Assuming that the authorized signal is QPSK modulation, using (2, 1, 6) convolutional coding, the modulation rate is 2MBD, and the frequency spectrum when the adjacent sub-carrier frequency overlap rate of NC-OFDM satellite communication is 0 and 50% is shown in Figure 4 and Figure 5.

Considering that NC-OFDM makes full use of the sub-channel gain, the power spectrum density of the sub-carrier and the authorized QPSK signal carrier is roughly the same. When there is no NC-OFDM signal interference and $\Delta F$ is 0, 25%, 37.5%, 50%, and 1, respectively. Under this conditions, the simulation result of QPSK signal reception error rate is shown in figure 6. It can be seen from figure 6 that comparing the bit error rate curve without NC-OFDM interference, when $\Delta F \leq 25\%$, the NC-OFDM sub-carrier has a slight impact on the QPSK signal receiving bit error rate, $10^{-4}$ demodulation. The threshold is increased by 0.5-1dB. When $\Delta F$ rises to 37.5%, the interference of NC-OFDM subcarriers to QPSK signals deteriorates sharply, and the $10^{-4}$ demodulation threshold is increased by 2.5dB. When $\Delta F \geq 50\%$, QPSK signals can not be demodulated normally.
6. Conclusion

There have been a plenty of advantages of NC-OFDM technique due to its flexible and controllable sub-carriers, which has become one of the hottest and important fields for improving the spectrum utilization efficiency. This advanced technique has not been applied to satellite communication system, thus it is necessary to investigate the problem whether the NC-OFDM technique can be combined with satellite communication systems. This paper proposed a sub-carrier allocation scheme based on real satellite channel spectrum sensing for NC-OFDM satellite system. Through effective utilization of satellite spectrum holes, data transmission can be achieved with more than 70Mbps, which is very impressive for commercial communication satellites with a bandwidth of 500MHz. This paper defined the concept of spectrum overlap rate to describe the mutual interference state between NC-OFDM and the authorized system, and analyzed the bit error rate performance of the authorized system under interference conditions. Simulations results verified that our proposed spectrum sensing sub-carrier power adaptive allocation are flexible and efficient to achieve compatibility. The proposed method can significantly improve the spectrum utilization.

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