Spectrum Sensing of Cognitive Radio for LEO CubeSat Swarm Inter-Communication

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ABSTRACT

Low earth orbit CubeSat swarms provide improvement in the spatial and temporal resolution of remote sensing, rural communication and space exploration due to their innovative and economical satellite design. Unlike conventional large satellites, which demand high transmission power for data exchange, the CubeSat swarm communication system provides interoperability, high data rate between networked nodes, and global coverage with real-time measurement. The main challenges facing CubeSat swarms include inefficient usage of spectrum resources and increased delay of data exchange, and the issues become more severe with increased number of on-orbit CubeSats. Often, Spectrum sensing in cognitive radio is proposed as a critical solution for efficient spectrum utilization and low delay of data exchange. Typically, in spectrum sensing, the secondary user cannot transmit while the primary user is in operation. In this paper, we propose blind source separation (BSS) for multi-user detection with MIMO antennas equipped in all CubeSats, and each antenna receives a mixture of radio signals, including primary and non-primary user signals. Once non-primary signals are removed, the receiver can move on to next step of signal detection. Practical implementation issues of the proposed scheme are studied through computer simulations, with main performance metrics including signal to interference ratio and the BSS algorithm's convergence speed, which can be essential for the communication resource allocation and power budget calculation of CubeSat platform in configuring LEO non-terrestrial network.

Index terms: CubeSat Swarm, Cognitive Radio, Blind Signal Separation (BSS), MIMO Antenna, Signal Interference Ratio (SIR)

INTRODUCTION

Advances in miniaturization technology for air and space systems advocate research in energy-efficient non-terrestrial communication networks. It suggests the application of a small satellite platform in the system deployment. As a rapidly evolving technology since the 1990s, cube satellite (CubeSat), one of the most mentioned small satellite platforms, transfers its functions considerably from teaching and experimental purpose in school [1] to real-world commercial [2] and military [3] application of communication. Standard CubeSat has the dimensions of 10cm*10cm*10cm, referring to 1U CubeSat [4], which weighs less than 2.9lb and orbits on low earth orbit (LEO) from 125miles to 435miles [5]. Due to the limitation of physical size and power harvesting rate, LEO CubeSat restricts its gain of the transmission channel to the ground station to less than 5dB and receiving channel gain less than 2dB.

CubeSat platforms usually serve the functions of a scientific experiment in verifying the concept of space missions. However, with the increasing crowd wireless communication environment in the terrestrial network, a non-terrestrial-based next-generation communication (6G) system is desired. It combines the hierarchical satellite network architecture to provide the extra connection for rural and area short of communication infrastructure (e.g., arctic, antarctic). CubeSat plays an essential role in forming such a space-based network over the LEO track. As proposed by the NASA CubeSat launch initiative [6], the LEO network is combined with several identical CubeSats that networked with each other, which form a swarm or swarms on the orbit. It has mainly three types of distribution: leader-follower, cluster, and constellation [7], in which every type of distribution covers different sensing regions. They provide a short communication window between the ground station and each CubeSat since of the high orbiting speed of the LEO satellite, e.g., 16777miles/s. Furthermore, due to the channel fading effects and limited hardware resources, CubeSat has a lower data rate than Geostationary Earth Orbital (GEO) Satellite in building reliable data links with ground receivers directly. Massive communication packets relaying within the CubeSat swarm network gives the flexibility of configuring reliable links between ground station and non-terrestrial network.

Instead of considering the computing resources offloading scheme from CubeSat, the available spectrum band resources in the overcrowded LEO orbit has become a more severe issue towards building the small satellite-based network in the not far future. Specific band, such as 2m very high frequency (VHF) band and 70cm ultra high-frequency (UHF) band, is used in CubeSat mission [8], making the wireless environment more crowded with the significantly increase of launched on-orbit LEO satellite. Many pressures have been put on licensed spectrum management organizations such as Federal Communication Commission (FCC). A more scalable space communication network is desired for realizing more sustainable space technique development.

Software-defined radio (SDR), a part of realizing cognitive radio, has been proposed for spectrum resource management within the crowded wireless environment in the past decade. Using the onboard field-programmable gate array (FPGA), communication parameters become reconfigurable, enabling the modification of software-defined network and communication protocol according to users' requirement. This paper proposes blind source separation (BSS) for multi-class user detection with multiple MIMO antennas in the CubeSat swarm communication network. Each antenna receives various mixed radio signals, including primary and non-primary user signals from different paths, satisfying the BSS application scenario. Once the non-primary signal is removed, the receiver can jump to the next step of signal separation with other types of the carrier wave and modulation.

The contributions of this paper are listed as follows.

1. We studied the communication characteristics, such as modulations type, number of source transmissions, and word length ahead of digital signal processing (DSP), in affecting the performance of blind signal based signal separation for the communication of CubeSat swarm.

2. We studied the performance of blind signal separation algorithm while environment noise is introduced to the CubeSat communication system in the process of orbiting.

3. We discussed the optimal signal processing block size for the blind signal separation, which relates to the CubeSat power budget calculation and system designation.

The remainder of this paper is organized as follows. Section II briefly describes the related works of cognitive radio in small satellite communication. In section III, we formulate the problem with the model of blind signal separation. Section IV discusses the experimental results and presents ideas of CubeSat communication system design. Finally, we conclude the work and provide our future research direction.

RELATED WORKS

Blind signal separation is one of the conventional approaches for improving the utilization of radio electromagnetic spectrum resources. In [9], the authors reconstruct the primary user (PU) signal from the target channel with uncertain symbol sequences. All PU signals are obtained in the detection channels at one time. Navid, etc., in [10] proposed Kurtosis metric for improving the accuracy of BSS-based spectrum sensing technique and discussed a new framework of spectrum sensing when the cognitive transmitter is in operation. Michael, etc., in [11] simulates a more realistic blind signal separation operation environment for multi-input & multi-output (MIMO) antenna. By employing the independent component analysis (ICA), the modulation types of unknown communication signals can be detected by separating them from the environment. However, massive MIMO operation constraint is barely mentioned in the existed literature, which is a significant and urgent issue needed to be solved within the CubeSat swarm communication scenario.

Power consumption and building reliable multi-access communication links for the CubeSat are becoming significant research topics. In [12], Otilia studied the power budget of CubeSat within ground-CubeSat and inter-CubeSat links, respectively. Novel spaceborne SDR-based designs are proposed in [13], in which the prototype implementation of high data rate SDR operating on S-band reached 60Mb/s with only 2.6 W consuming power. In [14], authors studied the designation of CubeSat antenna towards building inter-satellite links, which makes the links independent from the satellite's orientation. In the end, the results show that conformal beamforming provides the system with 5dBi gains for any desired directions of transmission. Jia, etc., in [15] proposed a collaborative LEO satellite offloading scheme to reduce the constraints of short communication window between CubeSat and ground station.

The network architecture of the CubeSat swarm is also being notified in the studies of recent years. Many techniques have been proposed in discovering the blind signal-based spectrum sensing techniques in different types of the cognitive cellular network. In [16], a centralized cognitive cellular network is discussed over multi-sensing techniques. They studied the signal-to-noise ratio in affecting the probability of successful detection and false alarm of primary user detection. A hybrid satellite-terrestrial network system is mentioned in [17], in which cognitive radio techniques could be used to increase the availability of limited licensed bandwidth. With flexible secondary user choosing in the non-terrestrial network, the terrestrial network could be effectively extended using a satellite system.

PROBLEM FORMULATION

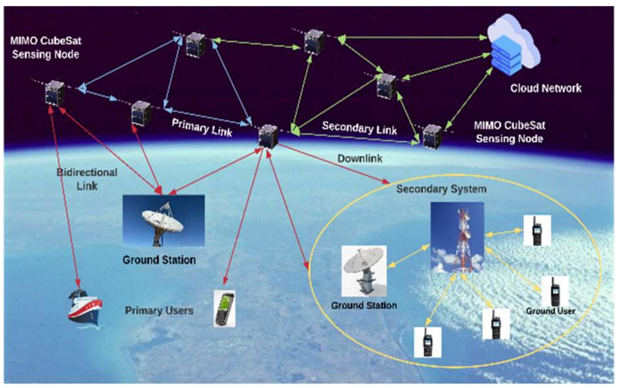


Figure 1: LEO CubeSat based Non-terrestrial Network

In this section, we would briefly describe the wireless sensing environment for CubeSat swarm and formulate the problem with the blind signal separation model.

We assume the MIMO antenna is adopted on each single CubeSat sensing node for inter-CubeSat communication, which operates on S-band. Multiple clusters of CubeSat on LEO orbit form multiple wireless sensing network. Links, not originally belonged to the local CubeSat network are called the secondary link in this case. Ground systems are divided into two types corresponding to the assigned CubeSat network, Primary users and users in the secondary system. For example, as shown in Figure 1, wireless devices in the secondary system cannot access the green CubeSat network since they pass the assigned network's communication window. However, the cyan network is accessible for users in the secondary system. To realize cognitive spectrum management of inter-CubeSat communication, idle channels of primary network (white holes on the spectrum) are used to receive the secondary link data of neighboring CubeSat from other clusters. Here, fast ICA algorithm is applied on separating primary link signal from mixed signal.

Assuming there are N channels of local CubeSat network, the primary signal of every channel are independent without considering the multipath effects and potential mutual interference. Received signal noise obeys Gaussian distribution. Primary link signal in the N channels are represented as $s_1, s_2 \dots s_N$, $s_i = 0$ when the channel is idle. Mixed signals on the different channels are independent. The received signal on i_{th} sensor is:

$$x_i = \sum_{i=0}^{N} H_{N\times N} s_i + n \quad (1)$$

in which, H represents the $N\times N$ channel gain matrix of primary network, and h_{ij} is the gain from primary user j to sensor i. s_i, x_i are the primary link signal, and received signal to sensor i, respectively. Assume n is same for N sensors in the primary network due to their identical hardware design. Space environment noise are assumed to be same for all CubeSat communication system. Our purpose is to find a separation matrix W, and by that, we can obtain the output as the estimation of source signal [18].

$$\hat{y}_i = W_i x_i \quad (2)$$

Specifically in MIMO antenna, H matrix can be defined as H_{li}, in which it represents the channel gain of i_{th} signal on l_{th} antenna. So the received signal can be represented as:

$$r_l = \sum_{i=1}^{N} A_i s_i e^{j\omega_c t_l(\phi_i)} + n = \sum_{i=1}^{N} h_{li} s_i + n \quad (3)$$

Where s_i specifically denotes the sensed signal from source i, and A_i is the complex flat fading channel parameter. Carrier frequency w_c is picked as 3GHz in S band. $t_l(\phi_i)$ is the time delay at antenna l for user i, with direction of arrival ϕ_i. Also $h_{li} = A_i e^{jw_c t_l(\phi_i)}$.

Time delay at antenna is defined as the cosine of angle of arrival primary link signal:

$$t_l(\phi_i) = \cos(\phi_i) \quad (4)$$

EVALUATION METRICS & EXPERIMENT & DISCUSSION

Evaluation metrics

In this section, experiment setup and parameters of the CubeSat MIMO communication system are discussed. Evaluation metrics of the fast ICA algorithm are presented. Due to the physical constraint of the CubeSat power supply system, the evaluation metrics would focus on the efficiency and algorithm running iteration times. Signal interference ratio (SIR) would also be discussed to evaluate the performance of the ICA algorithm.

Evaluation metrics are picked and explained as follows:

1. Computing block size: for a certain number of user symbols processed by DSP, a smaller block size suggests more computing blocks are needed. Although the increment of the number of computing blocks could increase the efficiency and speed of the algorithm, the accuracies of signal separation results could be degraded. Nevertheless, the increase of block size would reduce the number of needed computing blocks. Assume u_i user symbols are processed by the m_i processing blocks in DSP. So the processing block size b_i can be defined as:

$$b_i = \frac{u_i}{m_i} \tag{5}$$

2. Word length (WL): Word length of symbols before and after the input of DSP should be evaluated as one of the factors influencing the performance of the algorithm running on DSP. Three types of world length combinations would be discussed.

3. The number of source transmissions: It represents the number of source signals available for sensor i in local CubeSat network. It is chosen according to the number of available channels of the MIMO antenna.

4. Modulation: Types of modulations picked for evaluating ICA algorithms include: QPSK, 16QAM, 64QAM. Higher orders of quadrature amplitude modulation (QAM) can be used to gain a faster data rate, but if the link deteriorates, lower orders are used to preserve the noise margin and ensure that a low bit error rate is preserved.

5. Signal interference ratio: calculate the ratio between original signal and its difference with estimated primary signal:

$$r_l = 10\log_{10}\frac{|s_i|^2}{\left|s_i - \hat{y}_i\right|^2} \tag{6}$$

Simulation Results & Discussion

We simulated the number of transmission of source signals from 2 to 6 corresponding to the number of MIMO antenna channels. Figure 2 shows the signal interference ratio (SIR) with the variance of computing block size. The performance of the signal separation algorithm becomes better, about 10-15dB, with the increase of block size. Meanwhile, increment of block size works more effectively on enhancing the SIR of the ICA algorithm. Although more transmissions of source signal are more realistic within inter-CubeSat network, this scheme sacrifice the accuracies of signal retrieving. To reach the nearly same SIR value, more transmissions need a larger block size, which reduces the efficiency of the ICA algorithm.

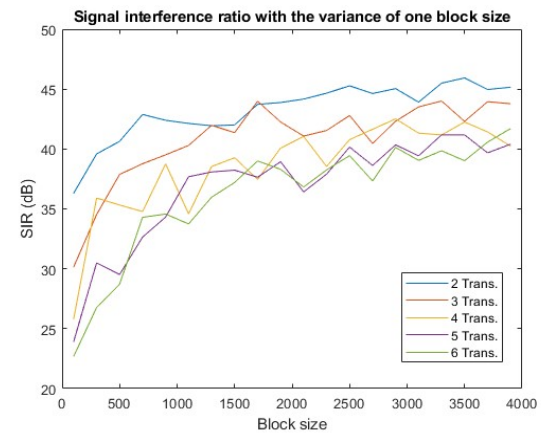
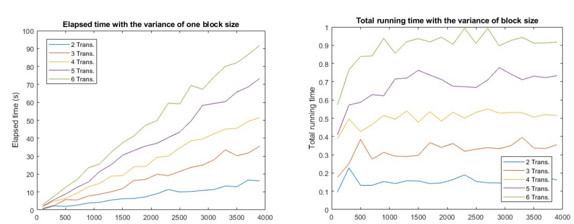


Figure 2: SIR with the variance of block size

This conclusion could be seen more clearly from Figure 3 (a). A larger value of block size and number of transmissions could usually lead to more iteration times. Similar results in Figure 3 (b) reveals the same conclusion. Total running time stands for the computing time of one ICA algorithm block.



(a) (b)

Figure 3: Iteration time and total running time with the variance of block size

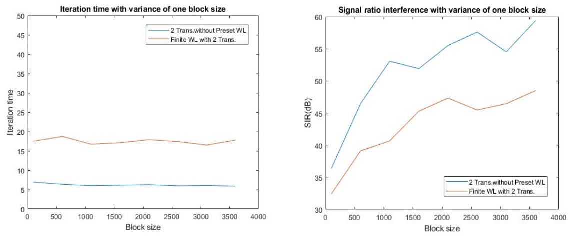


Figure 4: Iteration time and SIR with the variance of block size

Three types of word length before and after the input of DSP are usually considered for choosing the optimal ICA processing block size. Those are, 1) 32bits & 26bits; 2) 16bits & 10 bits; 3) mixing of 32 bits & 26 bits and 16 bits & 10 bits [19]. 1) It has the best SIR value, and 2) It provided the most efficient BSS algorithm processing. 3) It represents the combination of 1) and 2), which reduces the WL before the input of DSP, and has the same accurate symbol description for the mixed-signal separation. Figure 4 simulates the performance of running a mixed WL scheme and non-WL preset BSS algorithm. The preset WL ICA algorithm has a smaller SIR value with two transmissions of the source signal.

Figure 5 shows the SIR with different type symbol modulation techniques. Higher-order of QAM can be used to gain a faster data rate, but if the link deteriorates, lower orders are used to preserve the noise margin and ensure a low bit error rate. Similarly, higher-order of QAM has a lower value of SIR in the BSS task, which suggests a worse performance on detecting the primary user in the inter-CubeSat communication. Furthermore, we investigate the BSS performance by adding Gaussian noise to three types of modulations to simulate the uncertain noise from receiver environment and system noise, in which environment noise includes cosmic radiation, solar noise, man-made noise; system noise includes the circuit elements, front-end band pass filter, low noise amplifier. From figure 5, modulation schemes with added noise show the worse performance of the BSS task. However, modulation type does not affect the performance of retrieving the original signal while block size is large enough. Lower order modulation could extract primary users from mixed-signal more accurately with smaller computing blocks.

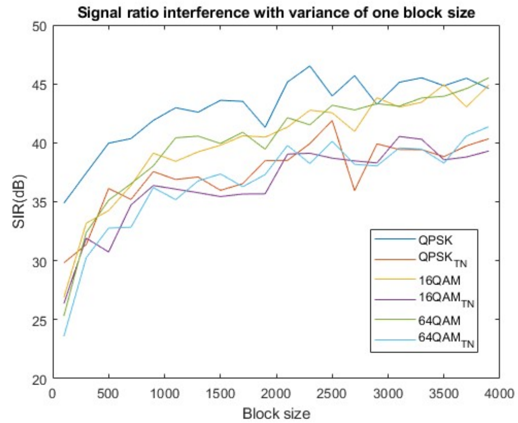


Figure 5: SIR with the variance of block size on different type of modulation

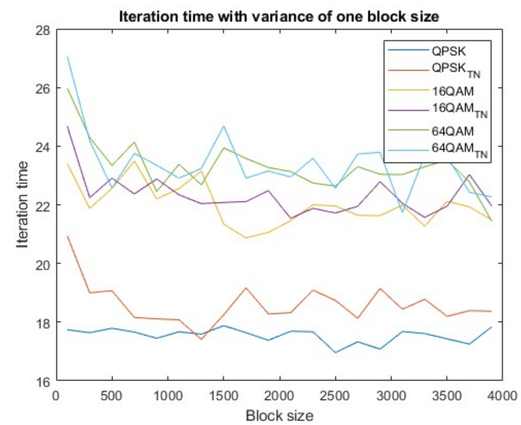


Figure 6: Iteration time with the variance of block size on different type of modulation

Nevertheless, different order of QAM does not show much difference on the iteration times of BSS task. Moreover, adding Gaussian noise actually reduces the iteration times of retrieving primary user signal from mixed-signal, such as QPSK and 64QAM.

CONCLUSION & FUTURE WORK

ICA algorithm-based BSS primary user detection in Inter-CubeSat communication is discussed. Modulation type, word length before the input of DSP on CubeSat, number of transmissions, computing block size are used to evaluate the blind signal separation based primary link signal detection. SIR and iteration times are applied to evaluate mentioned factors on the performance and efficiency of the ICA algorithm.

Hardware limitations given on the limited antenna channels can cause the failure of BSS-based primary link signal detection. That is when the number of a source link is larger than available channels. Available techniques, such as deep neural networks, could be applied to enhance the scalability of the CubeSat-based non-terrestrial network. For example, deep clustering has been successfully used in audio signal recognition with multiple speakers [20].

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