BROADBAND HYBRID SATELLITE-TERRESTRIAL COMMUNICATION SYSTEMS BASED ON COGNITIVE RADIO TOWARD 5G

MIN JIA, XUEMAI GU, QING GUO, WEI XIANG, AND NAITONG ZHANG

ABSTRACT

The development of 5G terrestrial mobile communications technology has been a driving force for revolutionizing satellite mobile communications. Satellite mobile communications, which carry many unique features, such as large coverage and support for reliable emergency communications, should satisfy the requirements for convergence between terrestrial mobile communications and satellite mobile communications for future broadband hybrid S-T communications. On the other hand, CR is an attractive technique to support dynamic single-user or multi-user access in hybrid S-T communications. This article first discusses several key issues in applying cognitive radio to future broadband satellite communications toward 5G. Then we present an overview of future broadband hybrid S-T communications systems, followed by an introduction to a typical application scenario of futuristic CR-broadband hybrid S-T communication systems toward 5G. Moreover, we propose a space segment design based on a spectrum-sensing-based cooperative framework, in consideration of the presence of MUs. An experiment platform for the proposed CR-based hybrid S-T communications system is also demonstrated.

INTRODUCTION

Terrestrial mobile communications technology has undergone a rapid growth in the past 20 years. In these decades, modern terrestrial mobile communications have been evolved from the first generation (1G), which is analog systems, to 4G, which supports broadband mobile communications. Currently, 4G systems have been widely deployed by telecommunications operators all over the world. At present, the planning and standardization efforts for 5G mobile systems are underway. The Third Generation Partnership Project (3GPP), IEEE, International Mobile Telecommunications (IMT), and many other standardization bodies are working together with manufacturers and telecom operators in an effort to standardize 5G mobile communications systems. Meanwhile, the International Telecommunication Union (ITU) has started to call for 5G proposals. New proposals need to satisfy the requirements of high spectrum utilization and energy efficiency. The data rate of 5G will also need to be much higher than that of 4G. In addition, 5G systems should meet many other requirements, including capacity, tolerance of transmission latency, system security, and user experience. According to the IMT-2020 plan, considering the need to support various services for both fixed and mobile devices, we can summarize key 5G technical metrics as follows. First, its transmission rates should be up to 10 to 100 times those of 4G, which equates to user experienced data rates up to 1 Gb/s and the peak rate up to 10 Gb/s. Second, the latency should drop 10 to 20 percent to the millisecond level. Third, it will support mobile speeds up to 500 km/h, which is important to enable seamless mobile calls in high-speed trains. Furthermore, the emerging 5G wireless systems should have enough flexibility, self-networking, self-adjustment, and other intelligent abilities. Obviously, it is not easy for the 5G terrestrial systems alone to achieve all the aforementioned performance goals. Therefore, it has been suggested that 5G terrestrial wireless systems must cooperate with the space segment and other suitable mobile communications technologies so as to satisfy all the requirements expected for the next generation 5G mobile networks.

Due to its unique merits of satellite communications, including large-scale coverage as well as superb ability to support emerging communications services, both opportunities and challenges exist for satellite communications, which should speed up its evolutional pace to keep up with the rapid growth of terrestrial wireless communications. A major issue is how to take advantage of innovative techniques in satellite communications to ensure seamless integration between satellite networks and terrestrial cellular systems. Thus, it is imperative to find a way to share the resources of space-based networks with the terrestrial cellular systems, and to utilize satellites as an important space segment more effectively. As a result, it is indeed an urgent issue to develop future broadband hybrid satellite-to-terrestrial (S-T) communications systems, which should work closely with the terrestrial segment to share global information.

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The Federal Communications Commission (FCC) granted Mobile Satellite Ventures (MSV), the first ever Ancillary Terrestrial Component (ATC) license; one of the characteristics of MSV lies in its direct support for 4G technologies, such as WiMAX, which is based on orthogonal frequency-division multiplexing (OFDM) [1]. The aforementioned research suggests that innovative terrestrial-based satellite communications systems may be adopted as a potential solution for joint terrestrial and satellite communications. Meanwhile, GlobalStar also proposed the so-called Globalstar plan, which enriches a constellation–ground network through the ATC. The National Aeronautics and Space Administration (NASA) recently announced worldwide WiFi networking based on satellites in February 2015, and will launch these satellites in 2016, 2017, and 2018. Meanwhile, the United States has decided to pursue the development of broadband anti-interference satellite communications for U.S. military communications systems. Besides, NASA, NTT DoCoMo in Japan, and ETRI in Korea are also actively working on advanced mobile communications technologies based on broadband hybrid S-T communications [2, 3].

On the other hand, cognitive radio (CR) [4] was proposed to enhance spectral efficiency, and has attracted much attention from researchers all over the world [5–7]. From an industry perspective, Project Cognitive Radio for Satellite Communications (CoRaSat) [8, 9] aims to implement a flexible and smart spectrum usage and management mechanism to exploit unused and underused frequency resources assigned to satellite services as primary or secondary allocation. In [8, 9], the potential applications of CR techniques in satellite communications to increase the bandwidth for future-generation satellite networks without interfering with incumbent services were investigated. Moreover, the authors state that the potential spectrum opportunities can cover up to 2.4 GHz of bandwidth on the downlink and 2 GHz of bandwidth in the uplink for fixed satellite services. The component of the space segment is only one independent geostationary orbit (GEO) satellite as mentioned in [9], which is only concerned with fixed satellite services of high density.

This article is motivated by the following facts. First, the component of the space segment is almost one independent GEO satellite, which was not available for seamless global coverage. Thus, a comprehensive review on the fundamentals of future broadband hybrid S-T communications systems, which are composed of three GEO satellites, is presented in this article. Moreover, limited shared spectra for both terrestrial and space segments are also insufficient for global communications. Therefore, a future broadband hybrid S-T communications system based on CR is proposed. In this article, we also describe the space segment design based on a cooperative framework and spectrum sensing for mobile users, which coexist with malicious users (MUs). Furthermore, almost all existing research works on theoretical analysis of various application scenarios. Thus, applications and an experimental platform for CR-based hybrid S-T communications systems are the primary interest of this article.

Broadband Hybrid S-T Communications Systems

Although existing satellite networks are able to provide global coverage without dead zones, most of them are too expensive and support only low data rates. Current satellite networks are mainly for covering regions that are without terrestrial signals and require emergency communications. Meanwhile, the resources for GEO satellites are limited.

A growing interest in terrestrial mobile communications encourages further enhancement in space-based satellite networks [10, 11]. For better fusion of space-based systems, cooperative S-T communications should be taken into consideration throughout the system design process. However, satellite mobile communications techniques should neither duplicate the terrestrial-based techniques [12–14] nor aim to replace the latter either. In general, there are two main unique features of space-based systems detailed as follows.

The first feature is the latency caused by a relatively long time delay. The latency from a GEO satellite to the Earth is about 256 ms, and that from a medium Earth orbit (MEO) or low Earth orbit (LEO) with a height less than 10,000 km to the Earth is nearly 71 ms, which is comparatively shorter but still not negligible. This is why researchers have been much more interested in MEO and LEO satellites in recent years;

Another important feature of terrestrial mobile communications systems is their ability to support large-scale mobility. The main nodes of space-based networks are satellites and high-altitude aircraft at various heights. Therefore, a sufficiently large Doppler has an effect on the data links from the satellites or high-altitude aircraft.

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When the communication nodes are satellites, the space-based networks carry the following features.

- Stable motion orbits: Transmission links are predictable in terms of time and communications coverage, but with large mobility.
- Up- and downlinks: Both up- and downlinks in cooperative S-T communications can make use of relays to improve the link quality and thus signal detection efficiency.
- Distribution on different orbits: Satellites for different tasks or services have different velocities and communication coverages, so the communication links between nodes may connect or disconnect frequently. This is an issue unique to S-T communications, and thus needs more investigation.

When the communications nodes are high-altitude aircraft, the features of the space-based network include the following.

- High irregularity: If the space-based network comprises high-altitude aircraft, their orbits are uncertain. The same is true for its coverage areas and communications latency.
- Up- and downlinks: A relay can be used as an option to improve the overall link quality.
- Dynamic effect on network topology: If a space-based node moves in or out of the network, its transmission links may be subject to unpredictable interruptions, and the probability of interruptions may be relatively high.

Based on the above discussions, it can be con-

The locations of MEO and LEO satellites, used as active nodes in space-based networks, change constantly in a dynamic environment in terms of their channels, spectral resources, and node heights. It is important to ensure the fair access of these highly dynamic nodes to the satellite networks with quick response.

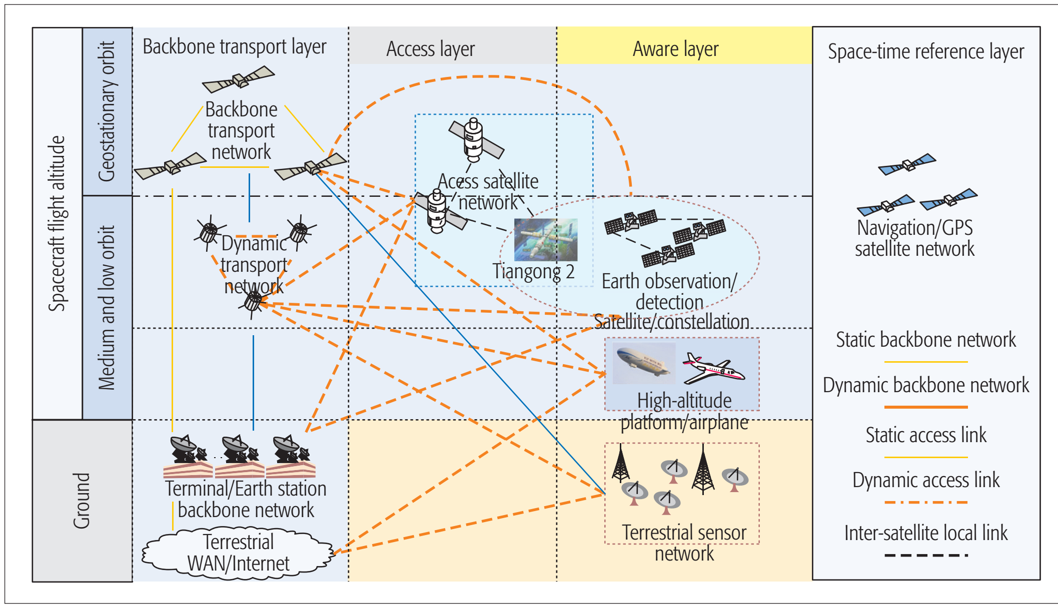

FIGURE 1. Hierarchical structure of space-based networks in China.

cluded that if the ultimate goal is seamless global coverage, hybrid S-T cooperative communications systems must consist of satellites and high-altitude aircraft at orbits of different heights, which forms a multi-level space structure. This article proposes a hierarchical structure of space-based networks based on our working experiences in China. The entire space segment can be divided into three layers: the backbone transport layer, access layer, and aware layer. The hierarchical structure of the space-based networks consists of various kinds of satellites and aircraft at orbits of different heights, as shown in Fig. 1.

The hierarchical structure illustrated in Fig. 1 is able to make full use of satellites in orbits of different heights between the perception layer and access layer. The configuration of MEO and LEO nodes is one of the most important issues. A lot more investigations need to be conducted on the distribution of these active nodes with relay capabilities. We also need to consider the issues of meeting users' requirements for a given quality of service (QoS). The issues of allocating spectral resources in satellite networks is also important. Based on previous analyses and studies, we summarize some main challenges for future broadband satellite communications systems as follows.

Configuration of MEO and LEO Satellites: The locations of MEO and LEO satellites, used as active nodes in space-based networks, change constantly in a dynamic environment in terms of their channels, spectral resources, and node heights. It is important to ensure the fair access of these highly dynamic nodes to the satellite networks with quick response. This means that all dynamic satellite nodes should respond quickly to gain access to the backbone network at proper times.

Requirements of Spectral Resources: The current broadband S-T communications systems need more and more spectral resources to meet the requirements of wider bandwidth, higher speeds, and better QoS.

Receiving Information in Time: A satellite system is limited in power and bandwidth, and suffers from large transmission delay. A hidden or visible cross-layer optimization model should be considered so as to avoid excessive latency. The cross-layer model aims to optimize all end-to-end satellite links in an effort to distribute resources in a fairer manner.

Optimized Solutions Required: Considerable room exists for significant improvements in achieving more efficient spectral utilization. Toward this end, innovative optimized fusion techniques are needed to better utilize limited spectral resources due to an exponential increase in the number of users.

Interference-Mitigating Capability: The higher the data rate, the shorter the symbol period of the transmitted signal. Thus, the possibility of being interrupted during transmission is decreased. Modulation or other techniques that have interference-mitigating or anti-interference capabilities should be considered.

Complex Characteristics of Space Channels: Fading at high frequencies and millimeter-wave bands is much more severe, especially when a communications node has high mobility on a large scale. Satellite communications usually rely on line of sight (LOS) links, which are prone to frequency-selective fading. Large-scale mobility may cause severe problems in signal transmissions.

Multiple Access and Resources Allocation at S and Ka Band Satellite Communications

Current broadband satellite communications systems need more spectral resources to provide large bandwidths, higher data rates, greater capacity, and better QoS for emerging broadband hybrid S-T communications systems toward 5G. To satisfy these requirements, the dual mode for the S/Ka frequency band should be taken into consideration in the system design. The services and resources of radio frequencies for the S and Ka bands in China, including Mainland China, Macao, and Hong Kong, are summarized in Tables 1 and 2, respectively.

It is known that the technologies of the space segment are driven by different services, for example, both terrestrial fixed/mobile wireless services and native satellite communication services. Thus, how to share limited spectrum between the terrestrial and space segments in broadband hybrid S-T cooperative communications systems toward 5G is a crucial issue. There are two multiple access techniques considered to be suitable for S-T cooperative communications systems, which are discussed as follows.

Orthogonal and Non-Orthogonal Multiple Access Techniques

Orthogonal multiple access techniques can be applied to satellite communications to satisfy the requirements of different users with different services in various regions. In contrast, non-orthogonal multiple access techniques allow the use of the same frequency carrier to provide different user services. Thus, in addition to known orthogonal multiple access techniques, some novel non-orthogonal multiple access techniques should also be considered to increase system capacity, especially for emergency services with a larger number of users.

Sparsity and Multiple Access Techniques

There are two sparse multiple access methods, low density signature multiple access and sparse code multiple access, both of which are non-orthogonal multiple access techniques. However, it is noted that their code designs are very complex. How to make full use of the sparsity in multiple access techniques for future broadband hybrid S-T communications still needs further study. Next, we discuss the compressive sensing (CS) technique in exploiting sparsity in satellite communications.

Compressive Sensing and Cooperative Spectrum Sensing in Satellite Communications

This section focuses on the issues related to CS and cooperative spectrum sensing in satellite communications. In particular, for cooperative spectrum sensing in satellite communications, we discuss methods to ensure reliable communications even in the presence of malicious users, who may intercept user data or intrude on the systems.

Compressive Sensing

The essential idea behind CS is to perform high-dimensional sensing through uncorrelated observations of sub-Nyquist sampling in a low-dimensional space with low resolution. CS theory indicates that so long as an original signal can be sparsely represented, the signal can be reconstructed via several random observed linear data values. The CS techniques suggest a paradigm shift away from conventional signal processing of high-speed sampling and reconstruction.

If the data from transmitting terminals are related, the received signal can be expressed as a linear combination of sparse vectors in a given domain [15]. It can be shown that the signals from different transmitting terminals can easily be distinguished from one another when an orthogonal multiple access technique is employed. Thus, the key issue is how to maintain the orthogonality of the channel and the synchronization among the transmitters. Moreover, it has been shown that CS is well suited for channel estimation due to the sparsity inherent in wireless channels [16]. Therefore, CS theory is instrumental in the signal reconstruction processes. In this article, satellite communications systems acting as the space segment are configured at multiple levels as mentioned earlier, and the orbits and communications coverage in the time domain are predictable. Thus, active satellite nodes with large-scale mobility behave like moving nodes. At a given moment, only a few senders are transmitting data. Since the transmitted data arrive at random, the assembly of active transmitting terminals cannot be predicted in advance. Thus, the sparsity condition in CS theory can be justified.

Another important application of the CS technique is to remove redundant information through high-speed sampling, and to preserve only the information that cannot be obtained from other information sources. Thus, sampling resources can be saved in this way without having to use complex and expensive fast sampling equipment. Not only can it result in higher energy efficiency, it can also achieve quick response to users' access requests.

Cooperative Spectrum Sensing

Cognitive radio is an intelligent technique to improve the utilization of radio spectra via dynamic spectrum access. The CR technique aims to facilitate the access of nodes to broadband satellite networks, when the channels and spectrum resources are dynamically changing. The essential idea behind CR techniques is to enable quick response via spectrum sensing techniques in the radio context. Cooperative communications are a new diversity technology, helping improve the quality of communications among distributed nodes. Cooperative communications bring in diversity gains to the system with the aid of relaying nodes through cooperative transmission.

Combining CR with cooperative techniques can make full use of the advantages of both techniques, and thus significantly improve spectral efficiency of the end-to-end system. This will enable the system to reap more diversity gains, and help increase the probability of opportunistic spectrum access in fading channels through collaborative sensing, resulting in increased system capacity and reduced energy consumption [17]. This article aims to propose a CS framework through integrating CR and cooperative techniques so that multiple nodes can fairly access satellite networks, while satisfying the needs for quick accessi response among network nodes.

In consideration of seamless global coverage, three GEOs are taken as the backbone network of the space segment, while the terrestrial segment is a 3G/4G heterogeneous network. Cooperative techniques and CR are applied to the S-T communications network, as shown in Fig. 2, which illustrates some typical scenarios of cooperative S-T communications. The cognitive inter-satellite link L_{CSS}, cognitive satellite-terrestrial link L_{CST}, pri-

The CR technique aims to facilitate the access of nodes to broadband satellite networks, when the channels and spectrum resources are dynamically changing. The essential idea behind CR techniques is to enable quick response via spectrum sensing techniques in the radio context.

<table>
<tr><th rowspan="2">Frequency bands (MHz)</th><th colspan="6">Service</th></tr>
<tr><th colspan="2">Mainland</th><th colspan="2">Macao</th><th colspan="2">Hong Kong</th></tr>
<tr><td>1525–1559</td><td colspan="6">MSS (space-Earth)</td></tr>
<tr><td>1559–1610</td><td colspan="4">ARNS (space-Earth) (space-space)</td><td colspan="2">ARNS (space-Earth)</td></tr>
<tr><td>1610–1613.8</td><td>Radio astronomy</td><td rowspan="2">MSS (Earth-space)/ARNS/RDDS (Earth-spacd)</td><td colspan="4">MSS (Earth-spacd)</td></tr>
<tr><td>1613.8–1626.5</td><td>MSS (space-Earth)</td><td colspan="4">MSS (Earth-space)/[MSS (space-Earth)]</td></tr>
<tr><td>1626.5–1660.5</td><td colspan="2">MSS (Earth-space)/radio astronmy service</td><td colspan="4">MSS (Earth-space)</td></tr>
<tr><td>1660.5–1668</td><td colspan="4">Radio astronomy service/space research (passive)/[FS]/[MS (Except AMS)</td><td colspan="2" rowspan="4">Radio astronomy service
MSS (Earth-space)</td></tr>
<tr><td>1668–1668.4</td><td colspan="4">Radio astronomy service/space research (passive)/[MSS {Earth-space)]/[MS (except AMS)]</td></tr>
<tr><td>1668.4–1670</td><td colspan="4">FS/radio astronomy service/meteorological aids service/MS (excepet AMS)/[MSS (Earth-space)]</td></tr>
<tr><td>1670–1675</td><td colspan="4">FS/satellite meteorology (Earth-space)/meterological aids service/MS/[MSS(Earth-space)]</td></tr>
<tr><td>1675–1690</td><td colspan="4">Meterological aids service/FS/satellite meterology (Earth-space)/MS (except AMS)</td><td colspan="2" rowspan="3">Satellite meteorology (Earth-space)</td></tr>
<tr><td>1690–1700</td><td colspan="4">Meteorological aids service/satellite meteorlogy (Earth-space)</td></tr>
<tr><td>1700–1710</td><td colspan="4">FS/satellite meteorlogy (Earth-spacd)/MS (except AMS)</td></tr>
<tr><td>1710–1980</td><td rowspan="2">MS</td><td></td><td rowspan="2">FS/MS</td><td colspan="3"></td></tr>
<tr><td>1980–2010</td><td>MSS (Earth-space)</td><td colspan="3">MSS (Earth-space)</td></tr>
<tr><td>2010–2025</td><td colspan="3">MS</td><td colspan="2">FS</td><td>KS</td></tr>
<tr><td>2025–2110</td><td colspan="3">Space operation service/EESS/space research (space-Earth)(space-space)</td><td colspan="3">FS/MS</td></tr>
<tr><td rowspan="2">2110–2170</td><td rowspan="2">MS</td><td>space research (deep-space)(Earth-space)</td><td colspan="4" rowspan="2">FS/MS</td></tr>
<tr><td>[FS]</td></tr>
<tr><td>2170–2200</td><td colspan="6">FS/MS/MSS (space-Earth)</td></tr>
<tr><td>2200–2290</td><td colspan="3">Space operationservice/EESS/space research (space-Earth)(space-space)</td><td colspan="3">FS/MS</td></tr>
<tr><td>2290–2300</td><td colspan="4">Space research (deep-space)(space-Earth)/[FS]/[MS (except AMS)]</td><td colspan="2">FS</td></tr>
<tr><td rowspan="4">2300–2483.5</td><td colspan="4">FS/MS/radiolocation/[amateur]</td><td colspan="2" rowspan="3">FS/MS</td></tr>
<tr><td colspan="2"></td><td colspan="2">FS/[amateur]</td></tr>
<tr><td colspan="3">FS/MS/radiolocation/[amateur]</td><td></td></tr>
<tr><td colspan="3">FS/MS/radiolocation</td><td>Industry science</td><td colspan="2">Industry science medical (ISM)</td></tr>
<tr><td>2483.5–2500</td><td colspan="4">FS/MS/MSS (space-Earth)/radiolocation RDSS (space-Earth)</td><td colspan="2">MSS (space-Earth)</td></tr>
<tr><td rowspan="4">2500–2655</td><td colspan="3">FSS (space-Earth)/MS (except AMD)/MSS (space-Earth)</td><td colspan="2" rowspan="6">FS</td><td rowspan="6">MS</td></tr>
<tr><td colspan="3">FSS (space-Earth)/MS (except AMS)/satellite broadcasting</td></tr>
<tr><td rowspan="2">MS (Except AMS)</td><td></td><td rowspan="2">MS (except AMS)/satellite broadcasting</td></tr>
<tr><td>Satellite broadcasting</td></tr>
<tr><td rowspan="2">2655–2690</td><td>Satellite broadcasting</td><td colspan="2" rowspan="2">FSS (Earth-space)/MS (except AMS)/[EESS (passive)]/[radio astronomy service]/[space research (passive)]</td></tr>
<tr><td>MSS (Earth-space)</td></tr>
<tr><td>2690–2700</td><td colspan="4">EESS (passive)/radio astronomy service/space research (passive)</td><td colspan="2">Prohibition</td></tr>
<tr><td>2700–2900</td><td>ARNS</td><td colspan="3" rowspan="2">Radiolocation</td><td colspan="2">ARNS/meterological</td></tr>
<tr><td rowspan="2">2900–3300</td><td>RNS</td><td colspan="2" rowspan="3">Radiolocation</td></tr>
<tr><td colspan="4">Radiolocation/[EESS (active)]/[space research (active)]</td></tr>
<tr><td>3300–3400</td><td>FS/MS</td><td colspan="3">Radiolocation/[amateur]</td></tr>
</table>

TABLE 1. Services and radio frequencies in the S band in China.

<table>
<tr><th rowspan="2">Frequency bands (GHz)</th><th colspan="4">Service</th></tr>
<tr><th colspan="2">Mainland</th><th>Macao</th><th>Hong Kong</th></tr>
<tr><td>25.25–27</td><td colspan="3">EESS (space-Earth)/FS intersatellite service/MS/space research (space-Earth)/[satellitestandard frequency and time signal satelite service (Earth-space)]</td><td>FS</td></tr>
<tr><td>27–28.35</td><td colspan="3">FS/FSS (Earth-space)/intersatellite service/MS</td><td>FS/FSS (Earth-space)</td></tr>
<tr><td>28.35–28.5</td><td colspan="3">FS/MS/FSS (Earth-space)</td><td rowspan="2">FSS (Earth-space)</td></tr>
<tr><td>28.5–29.1</td><td colspan="2">FS/MS/FSS/[EESS (Earth-space)]</td><td></td></tr>
<tr><td>29.1–29.25</td><td colspan="3">FS/MS/FSS (Earth-space)/[EESS (Earth-space)]</td><td>FS/FSS (Earth-space)</td></tr>
<tr><td rowspan="2">29.25–30</td><td rowspan="3">[FS]/[MS]</td><td colspan="2">FSS (Earth-space)/[EESS (Earth-space)]/[MSS (Earth-space)]</td><td rowspan="3">FSS (Earth-space)</td></tr>
<tr><td colspan="2">MSS (Earth-space)/FSS (Earth-space)/[EESS (Earth-space)]</td></tr>
<tr><td>30–31</td><td colspan="2">FSS (Earth-space)/MSS (Earth-space)/[satellitestandard frequency and time signal satellite service (space-Earth)]</td></tr>
<tr><td>31–31.3</td><td colspan="3">[Satellite standard frequency and time signal satellite service (space-Earth)/[space research]</td><td>FS</td></tr>
<tr><td>31.3–31.5</td><td colspan="3">EESS (passive)/radio astronomy service/space research (passive)</td><td>Prohibition</td></tr>
<tr><td rowspan="3">31.5–33</td><td colspan="3">EESS (passive)/radio astronomy service/space research (passive)/[FS]/[MS (except AMS)]</td><td rowspan="3">In planning</td></tr>
<tr><td rowspan="3">Radiolocation</td><td colspan="2">FS/RNS/space research (deep space) (space-Earth)</td></tr>
<tr><td colspan="2">FS/intersatellite service/RNS</td></tr>
<tr><td>33–33.4</td><td colspan="2">FS/RNS</td><td>RNS</td></tr>
<tr><td>33.4–34.2</td><td colspan="4">Radiolocation</td></tr>
<tr><td rowspan="2">34.2–35.2</td><td colspan="3">Radiolocation/space research (deep space)(Earth-space)</td><td rowspan="2">Radiolocation</td></tr>
<tr><td colspan="3">Radiolocation/[space research]</td></tr>
<tr><td rowspan="3">35.2–37</td><td colspan="3">Meteorological aids service/radiolocation</td><td rowspan="3">In planning</td></tr>
<tr><td colspan="3">Meteorological aids service/EESS (active)/radiolocation/space research (active)</td></tr>
<tr><td colspan="3">EESS (passive)/FS/MS/space research (passive)</td></tr>
<tr><td rowspan="2">37–38</td><td colspan="3">FS/MS (except AMS)/space research (passive)</td><td rowspan="3">FS</td></tr>
<tr><td colspan="3">FS/FSS (space-Earth)/MS (except AMS)/space research (space-Earth)/[EESS (space-Earth)]</td></tr>
<tr><td>38–39.5</td><td colspan="3">FS/FSS (space-Earth)/MS/[EESS (space-Earth)]</td></tr>
<tr><td>39.5–40</td><td colspan="3">FS/MS/MSs (space-Earth)/FSS (space-Earth)/[EESS (space-Earth)]</td><td>In planning</td></tr>
</table>

TABLE 2. Services and radio frequencies in the Ka band in China.

mary inter-terrestrial link L_{PT}, and interference link L_{IT} are also shown in Fig. 2. For the satellite downlink and uplink, there are various frequency bands that can be used, such as the Ka-band, Ku-band, C-band, and S-band. Importantly, which band to choose depends on various application scenarios that have different service demands or requirements (i.e., broadcasting, mobile personal communications, and emergency communications) for different countries.

Since a satellite is far from the Earth, an Earth station can detect the primary user (PU) and send the detection results back to the satellite. The path between the Earth station and the satellite may be shadowed and subject to severe multipath fading, leading to significantly reduced sensing performance. As shown in Fig. 2, cooperative spectrum sensing is able to improve the Earth station's detection performance by enabling cooperative sensing for the PU in multiple Earth stations.

Cooperative spectrum sensing based on energy detection has two key performance metrics: the false alarm probability P_f and the detection probability P_d. It can be seen that P_f is not related to the PU's signal power, and modulation or coding types. This is because P_f is just defined as a probability that the PU is absent. P_d is only related to the mean PU's signal power when the powers of the noise, the samples, and the thresholds are kept the same. However, even if the PUs' transmit powers are the same, the channel conditions vary in accordance with the modulation types. Thus, the received signal powers at the secondary users (SUs) are different. The frequency band is associated with the number of samples, and P_d is related to the number of samples.

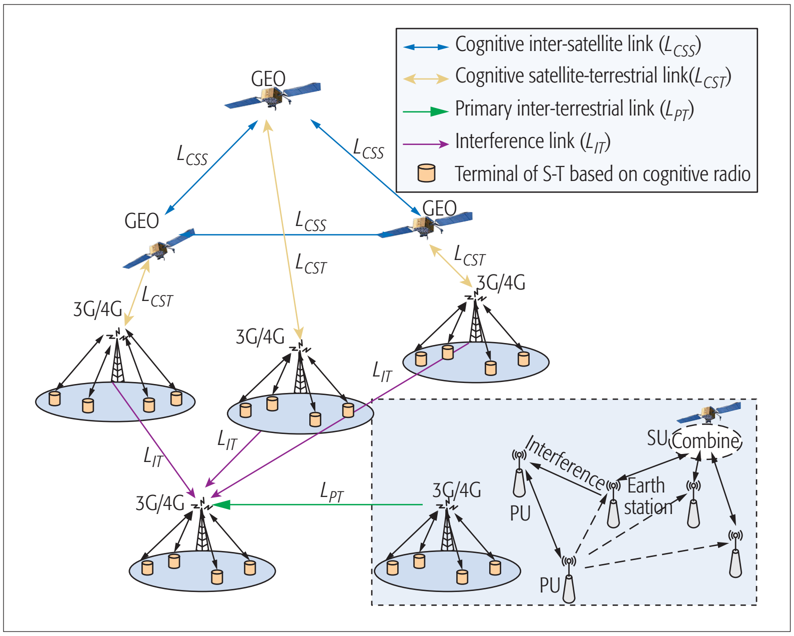

FIGURE 2. Scenarios of CR-based hybrid S-T communications networks integrated with terrestrial heterogeneous networks.

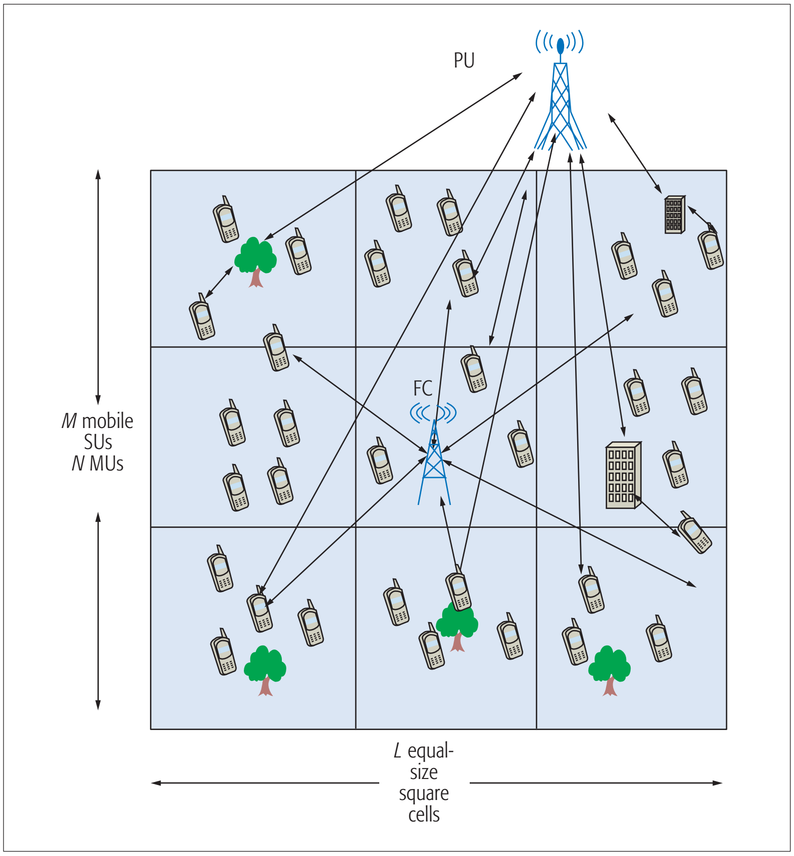

FIGURE 3. A CRN scenario with a static PU and multiple mobile SUs.

In cooperative spectrum sensing, each Earth station detects the PU's transmitted signal through energy detection [18], and then reports its local detection results to the satellite, which receives and processes the sensing information from all the cooperative Earth stations. The satellite will make the final decision about the PU's state by combining all the received detection results, and then broadcast the final decision back to all the Earth stations.

The essential function of a CR node in a cognitive radio network (CRN) is spectrum sensing, which aims to detect the presence of the PUs, and the available unoccupied spectral bands. In the CRN, final decisions made by the fusion center (FC) may be affected by fake detection results uploaded by malicious users (MUs). The FC is prone to attacks by MUs. A CRN scenario with a static PU and multiple mobile SUs is shown in Fig. 3.

In traditional cooperative spectrum sensing techniques, MUs tend to interfere with one another during their decision processes. Conventional trust value based cooperative algorithms [7], which are proposed for static CRNs to combat malicious attacks, cannot distinguish whether a reliable user (RU) moves into a deep-fading area or a mobile SU's detected results become unreliable. Thus, conventional cooperative sensing algorithms based on trust values would regard the users as MUs, which have results different from the majority of other users. That is, these algorithms cannot distinguish the MUs from the RUs accurately. This will greatly affect the detection probability P_d.

It should be noted that the channel conditions of each site in the whole region of interest can be quite different, and so are the detection results of the RUs. To tackle this challenge, the essential idea behind the proposed algorithm is that the whole region is divided into cells according to their actual channel conditions so that all the user detection results in a single cell are very similar, but those in different cells would be different. Also, the sites in each cell have similar channel conditions. Thus, our proposed approach is able to remove MUs in each cell based on their trust values. Larger weighting coefficients will be given to cells with better channel conditions. Then the RUs in each cell transmit similar results so that the MUs can be excluded by finding the users with transmit results different from those of most other users in the same cell. We consider the use of cooperative spectrum sensing for the CRN as shown in Fig. 3, which consists of a static PU, an FC, and N mobile SUs including M MUs. Assuming that the ratio of M/N is less than 1, the entire area is divided into L equal-size square cells, each of which is assigned a unique number through positioning technology. The performance can be improved by using the areas' actual channel conditions and by taking channel location differences into consideration, since the small cells are at different locations and under different channel conditions. The detected results of SUs in different cells differ considerably, even by several orders of magnitude.

The energy values detected by the SUs are forwarded to the FC along with the cell numbers of the cells to which they belong. These values and

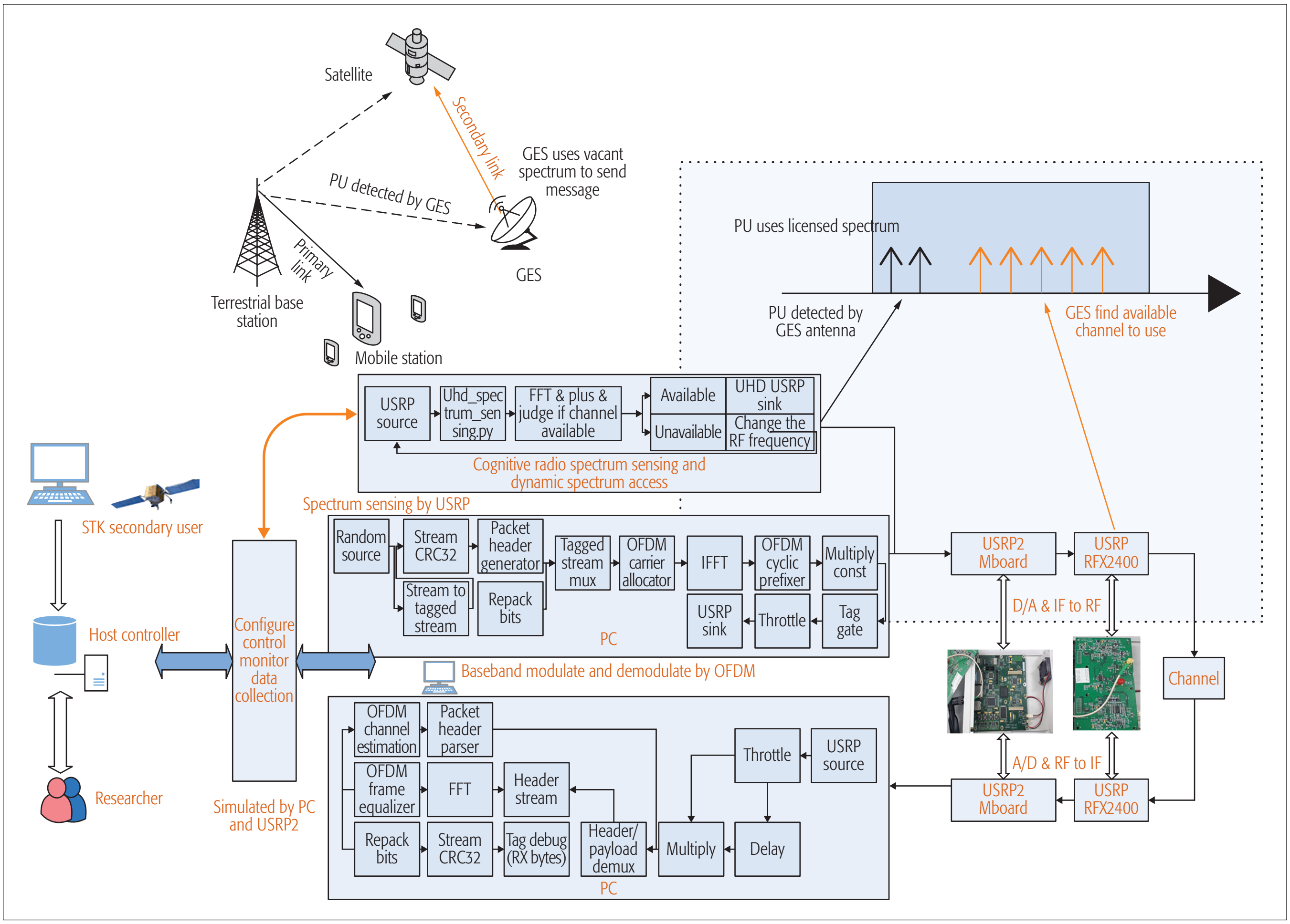

FIGURE 4. Experimental setup for the CR-based cooperative S-T communications system.

numbers are assumed to be free of transmission errors. The FC decides whether the PU is active or not. It is assumed that the noise power received by each cell is identical, and the PU signal power is related to the received channel condition.

Demonstration of an Experimental Platform

Hybrid S-T communications in the S and Ka bands are the focus of this article. We consider the downlink of the terrestrial base station (BS) to mobile terminals, and the uplink of the ground Earth station (GES) to the satellite, where the terrestrial link is considered as the PU, and the GES is allowed to use licensed spectrum without disturbing licensed PUs. The satellite system can coexist with terrestrial communications systems such as LTE systems by using cognitive techniques without interfering with the PU. The experimental configurations for the CR-based cooperative S-T communications systems are shown in Fig. 4.

In our experimental setup, the Universal Software Radio Peripheral (USRP) in a PC is used to act as the SU in the cooperative S-T communications system. First, the USRP detects the spectrum utilization of the surrounding environment. Then the spectrum sensing algorithm based on energy detection is used to determine whether or not the channel is occupied by the PU. Moreover, we adopt the USRP combined with the Satellite Tool Kits (STK) software, which can reflect the status of the satellite nodes for the space segment. If the channel is available, the SU, which is a satellite or a terrestrial mobile user, will use it to transmit signals. Otherwise, the USRP changes its frequency and then continues to sense the available channels at other frequencies.

In our experiments, the USRP is used to act as the cognitive orthogonal frequency-division multiplexing (OFDM) transmitter and receiver. The PC processes the baseband signal in a communications system through the GNU Radio in the Ubuntu system. The GNU Radio is flexible to integrate with Simulink blocks so as to process the OFDM baseband signal. The USRP model used in our experiment is USRP2, which is equipped with a Xilinx Spatran3 field programmable gate array (FPGA) board to implement A/D (4 Mb/s) and D/A (16 Mb/s) frequency conversion. The front is an RFX2400 board, supporting the frequencies from 2400 MHz to 2900 MHz. In our experiment, the PU is set as a dynamic impulse in the channel. Thus, an SU needs to use the UHD function to sense the environment and decide whether the channel is available. Moreover, the threshold is set to –70 dB, and 0.5 MHz is taken as the incremental frequency step size.

The uplink communications from the GES to the satellite are simulated by three USRP2s, as illustrated in Fig. 4. The system works at the S band matching the working frequency of USRP2

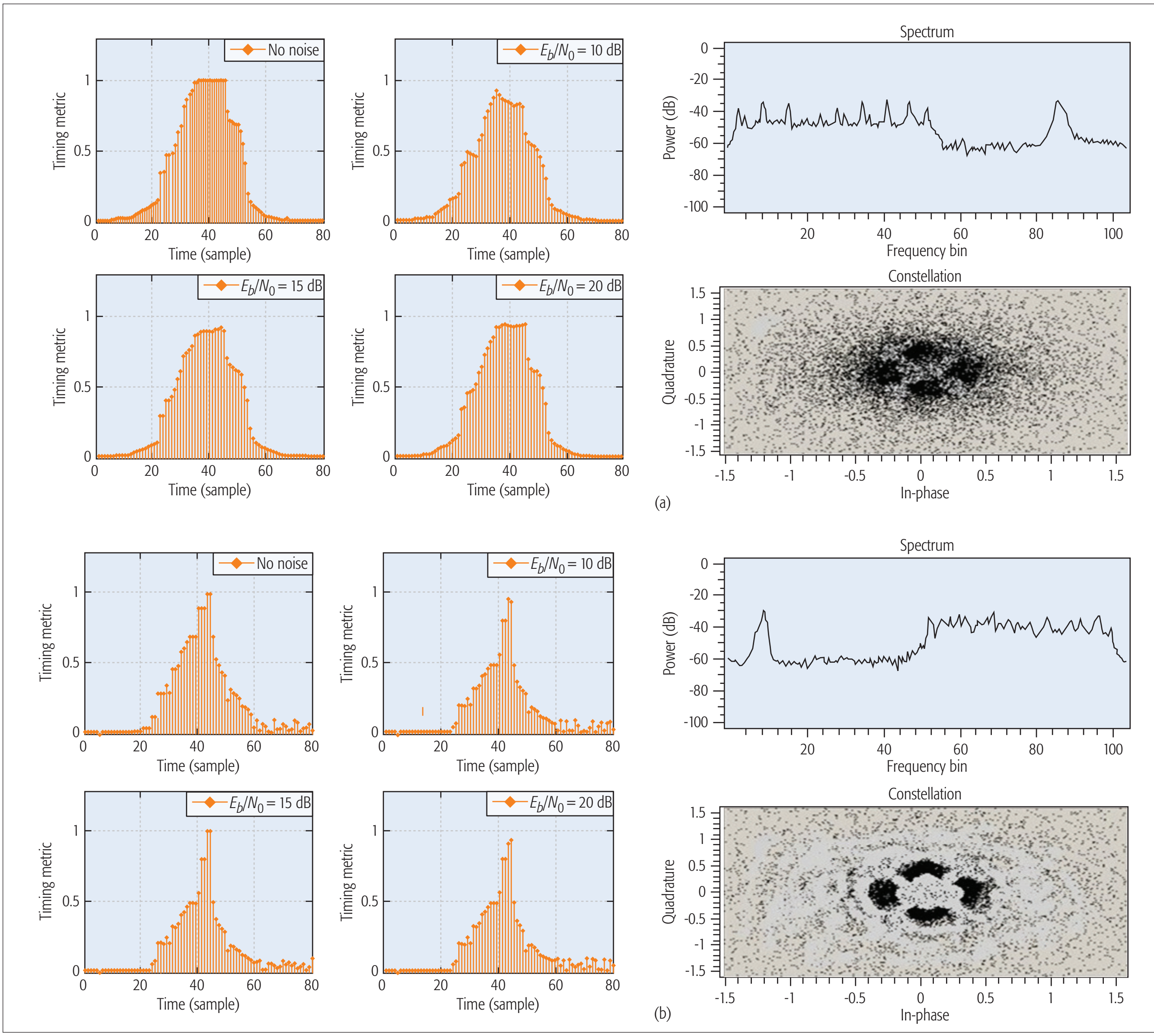

FIGURE 5. Performance improvements of CR-OFDM for the GES: a) time metric and performance of the traditional Schmidl & Cox algorithm at various E_b/N_0; b) time metric and performance of the modified Schmidl & Cox algorithm.

RFX2400 (i.e., 2.4–2.9 MHz). The sampling rate is 1 MHz. The PU sends an impulse at 2433 MHz with a dynamic change of frequency around 0.75 MHz (i.e., 2432.25–2433.75 MHz). The OFDM signal's bandwidth is 0.4 MHz, and the initial transmit frequency is set to 2433 MHz. The licensed channel is divided into subchannels of 0.4 MHz, from 2432 MHz to 2435 MHz. The sender will determine whether the channel is being used through energy detection at –55 dB. After spectrum sensing, if the PU is using the channel, the GES will change its frequency to send messages at the frequency of 2434.2 MHz.

As can be observed from Fig. 4, random bits are generated by the GNU radio block using cyclic redundancy check (CRC) encoding. Then the header bits and payload bits are multiplexed into the stream. The OFDM transmitter is compatible with IEEE 802.11 to distribute the subcarriers, using quadrature phase shift keying (QPSK), 52 subcarriers, and the 64-point fast Fourier transform (FFT). There are 48 data subcarriers, 4 pilot subcarriers, and 12 other subcarriers sending zero sequences. The CP is added and sent to USRP IF. The FPGA board implements the digital-to-analog (D/A) conversion and sends the signal to the TX.

The receivers use the modified Schmidl & Cox sync algorithm [19]. Figures 5a and 5b show the improvement of the modified Schmidl & Cox algorithm. As can be observed from Fig. 5b, the shaper points in time metric with better performance in time synchronization. It is also observed from Figs. 5a and 5b that the platform area is at the maximum of the timing metric, and when the signal-to-noise ratio (SNR) is low, it seems difficult to identify. When we use the inverse FFT (IFFT) to transform the sequences to the time domain, the platform effect in the Schmidl & Cox algorithm could affect the performance of this system due to the CP, especially the accuracy of the synchronization point by the training sequence. In this article, we aim to design the training sequence to improve the performance of synchronization. The training sequence in the time domain consists of A, C, B, $\overline{C}$, A^*, C^*, B^*, and $\overline{C}^*$ in order, in which A and B are complex elements, $\overline{C}^*$ denotes the reverse order of the conjugate sequence of C, C^* denotes the conjugate sequence of C, and $\overline{C}$ denotes the reverse order of C.

The structure of the data packet consists of a preamble, a payload, and a 3-byte postamble sync word, in which the preamble consists of a 16-byte Sync word 1, a 2-byte src address and dest address (src address and dest address work for USRP simulation), a 4-byte packet number, and 16-byte Sync word 2, and the payload consists of forward error correction (FEC) data and 4-byte CRC. The communications between the GES and satellite are modeled as an LOS model, and from the Earth to the satellite the communications delay is almost 256 ms. The frame should be designed to be long enough to overcome large delay fading, and thus we choose the frame length to be 262 ms. Furthermore, the length of the symbol period is added to the Rice channel. There are 10,240 b/frame. The preamble period can be up to 7.78 ms to ensure the success of GES access.

When employing the 64-point FFT, the maximum throughput is 39.083 kb/s in theory (1024 bits × 1 s/262 ms). In the simulation device, the PC's capacity of signal processing determines the number of subcarriers. This system's performance can be improved by increasing the number of FFT points for the link from the GES to the satellite. For instance, the throughput limit can be improved to 1.25 Mb/s when using the 2048-point FFT.

The bit error rate (BER) performance of traditional OFDM transmission is better than CR-OFDM because of the deactivated subcarriers, and we try to modify the training sequences in the sync part to improve the benchmark. The BER of modified CR-OFDM is lower than that of CR-OFDM at the same E_b/N_0, and traditional OFDM is better than modified CR-OFDM. When E_b/N_0 is 20 dB, the BER of CR-OFDM is reduced to 10^{-4}, and those of modified CR-OFDM and CR-OFDM are about 10^{-5}. In general, the BERs of traditional OFDM, CR-OFDM, and modified CR-OFDM decrease with the increase of E_b/N_0. When E_b/N_0 is increased to 25 dB, the BER of CR-OFDM can reach 10^{-5}, and the BER of modified CR-OFDM can be reduced to 10^{-6}.

The USRP detects in the environment that the noise sound is about –60 dB, so the fixed SNR at the RX is kept constant at 15 dB by increasing the TX gain. Our experimental results demonstrate that CR can achieve significant gains in the continuous spectrum transmission environment. Our experiments also verify the GES to satellite uplink dynamic spectrum access.

Conclusion

Broadband hybrid S-T communications systems composed of terrestrial and space segments can satisfy the requirements of a large number of users with diversified services in future 5G networks. In this article, we present an overview on the fundamentals of future broadband hybrid S-T communications systems using three GEO satellites, and propose a hierarchical structure of the space network based on the experiences in China. We analyze both orthogonal and non-orthogonal multiple access techniques based on CS. Several key issues related to the applications of CR to future broadband satellite communication systems toward 5G are also discussed, along with the application scenarios of the proposed systems. Moreover, we propose a cooperative spectrum sensing algorithm for mobile users of the terrestrial and space segments. Finally, we demonstrate a CR-based experimental platform using USRP and PC for hybrid S-T communication systems.

Broadband hybrid S-T communications systems composed of terrestrial and space segments can satisfy the requirements of a large number of users with diversified services in future 5G networks.

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References

[1] A. Ansari, S. Dutta and M. Tseytlin, "S-WiMAX: Adaptation of IEEE 802.16e for Mobile Satellite Services," *IEEE Commun. Mag.*, vol. 47, no. 6, Jun. 2015, pp. 150–55.

[2] Y. Okano *et al*., "Novel Hybrid Antenna for Broadcasting Satellite and Terrestrial HD-TV," *IEEE Trans. Antennas & Propagation*, vol. 63, no. 4, Apr. 2015, pp. 1425–35.

[3] J. P. Choi and C. H. Joo, "Challenges for Efficient and Seamless Space-Terrestrial Heterogeneous Networks," *IEEE Commun. Mag.*, vol. 53, no. 5, May. 2015, pp. 156–62.

[4] J. Mitola and G. Q. Jr. Maguire, "Cognitive Radio: Making Software Radios More Personal," *IEEE Personal Commun.*, vol. 6, no. 4, Aug. 1999, pp. 12–18.

[5] C. Sun, W. Zhang, and L. Khaled, "Cooperative Spectrum Sensing for Cognitive Radios under Bandwidth Constraints," *Proc. IEEE Wireless Commun. Networking Conf.*, Mar. 2007, pp. 1–5.

[6] P. Kaligineedi, M. Khabbazian, and V. K. Bhargava, "Malicious User Detection in a Cognitive Radio Cooperative Sensing System," *IEEE Trans. Wireless Commun.*, vol. 9, no. 8, Aug. 2010, pp. 2488–97.

[7] S. Jana *et al*., "Trusted Collaborative Spectrum Sensing for Mobile Cognitive Radio Networks," *IEEE Trans. Info. Forens. Security*, vol. 8, no. 9, Sept. 2013, pp. 1497–1507.

[8] M. J. A. Rahman, M. Krunz, and R. Erwin, "Exploiting Cognitive Radios for Reliable Satellite Communications," *Int'l. J. Satellite Commun. Networking*, vol. 33, no. 3, May/June 2015, pp. 197–216.

[9] S. Maleki *et al*.,"Cognitive Spectrum Utilization in Ka Band Multibeam Satellite Communications, " *IEEE Commun. Mag.*, vol. 53, no. 3, Mar. 2015, pp. 24–29.

[10] R. H. Wang *et al*., "Which DTN CLP Is Best for Long-Delay Cislunar Communications with Channel-Rate Asymmetry?" *IEEE Wireless Commun.*, vol. 18, no. 6, Dec. 2011, pp. 10–16.

[11] Q. Yu *et al*., "The Effect of DTN Custody Transfer in Deep-Space Communications," *IEEE Wireless Commun.*, vol. 20, no. 5, Oct. 2013, pp. 169–76.

[12] S. Kandeepan *et al*., "Cognitive Satellite Terrestrial Radios," *Proc. IEEE GLOBECOM*, Dec. 2010, pp. 1–6.

[13] M. K. Arti and M. R. Bhatnagar, "Beamforming and Combining In Hybrid Satellite-Terrestrial Cooperative Systems," *IEEE Commun. Lett*., vol. 18, no. 3, Mar. 2014, pp. 483–86.

[14] K. An *et al*., "Performance Analysis of Multi-Antenna Hybrid Satellite-Terrestrial Relay Networks in the Presence of Interference," *IEEE Trans. Commun*., vol. 63, no. 11, Aug. 2015, pp. 4390–4404.

[15] D. L. Donoho, "Compressed Sensing," *IEEE Trans. Info. Theory*, vol. 52, no. 4, Apr. 2006, pp. 1289–1306.

[16] A. J. Goldsmith and P. P. Varaiya, "Capacity of Fading Channels with Channel Side Information," *IEEE Trans. Info. Theory*, vol. 43, no. 6, Nov. 1997, pp. 1986–92.

[17] A. Ghasemi and E. S. Sousa, "Opportunistic Spectrum Access in Fading Channels through Collaborative Sensing," *J. Commun.*, vol. 2, no. 2, Mar. 2007, pp. 71–82.

[18] F. F. Digham, M. S. Alouini, and M. K. Simon, "On the Energy Detection of Unknown Signals over Fading Channels," *IEEE Trans. Commun*., vol. 55, no. 1, Jan. 2007, pp. 21–24.

[19] C. Zhang and K. K. Pang, "Synchronization Sequence Generated by Modified Park Algorithm for NC-OFDM Transmission," *IEEE Signal Processing Lett.*, vol. 22, no. 4, Apr. 2015, pp. 385–89.

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