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A Novel Hybrid Access Protocol Based on Traffic Priority in Space-Based Network

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ABSTRACT The space-based network is made up of aircrafts, spacecrafts, and all kinds of satellites in different orbits, which is hierarchical and tridimensional. In this special hierarchical network, a suitable multiple access protocol is required if the satellites with high velocity sharing the limited channel resources reasonably. There are majority kinds of services and traffic required during the disaster or emergent times. Thus, a novel hybrid access protocol based on traffic priority in the space-based network is proposed, where the frequency-time division multiple access (F-TDMA) is introduced into the space-based network first, and some improvements by jointing the time-domain of F-TDMA to meet the specific requirements of the satellite users are in this paper. Moreover, different traffics in the space-based network are considered as well. The analysis and simulation results show that the hybrid access protocol can obtain a higher throughput and a lower collision probability with a lower average delay comparing with the traditional collision avoidance carrier sense multiple access (CSMA/CA).

INDEX TERMS Space-based network, F-TDMA, hybrid access protocol, throughput.

I. INTRODUCTION

The space-based network is made up of aircrafts, the spacecraft and all kinds of satellites in different orbits, which are hierarchical and tridimensional [1]. The characteristics of space-based network including short communication time, enormous business data and intact data communication require that the space-based network can offer reliable and fast access, therefore, how to utilize space communication resources effectively to guarantee the QoS of different terminal users becomes the problems which need to be solved of access algorithm in MAC [2]. Consequently, we need to design a reasonable access scheme aimed at the features of space system to improve the throughput, reduce the collision probability and realize excellent communication for users in space-based system.

Relative works have been done to deal with the problems faced by space-based network including the long communication link, the large transmission delay and enormous business data [3]–[10]. Take many satellites as a satellite sensor network and which has the same principle with the wireless sensor networks on the ground to the spacecraft at LEO, which can be used to work in various spaces [6]. There have been some studies of ISL communication protocols for the space-based network investigation that is transferred between a satellite which has a formation applying TCP/IP and simulation experiments [4]–[10]. FTP and SAFE files transmission among satellites in a circular information, which use either IEEE 802.11 or ATM are introduced in [7]. The authors in [9] model the ISL network by applying either wireless IEEE 1394 or IEEE 802.11 that has the format with the FTP protocol between a terrestrial network and satellites. Space-based network is able to provide traffic at real-time, like voice and video. And also, this network can offer data traffic with the character of burst. If the fixed assignment multiple access is adopted, the efficiency of using resource will be greatly reduced. Also, if multiple access with competition (CSMA, ALOHA et. al) is applied completely, voice and video traffic cannot have a sufficient support [10]. Sidibeh and Vladimirova [11] optimize four inter-frame spacing key types that are named in IEEE 802.11 and propose MAC and physical layers which can be applied for space-based WLAN (Wireless Local Area Network) in IEEE 802.11: the Distributed Co-ordination Function (DCF), the Short Inter-Frame Space (SIFS), the Inter-Frame Space (DIFS), the Extended Inter-Frame Space (EIFS) and the Point Co-ordination Function (PCF) inter-frame space. They concentrate on two different formation flying cases and study effects based on IEEE 802.11 standards of the LEO satellite which is applied in inclined and polar orbits: the circular flower and the triangular constellations. Both of the formats are optimized to contain a configuration which has a master satellite used as an access point called master-slave configuration (similar to WLAN on the earth) and has slave satellites used as nodes that have the sense of mobility. Junqing Qi *et al.* [12] apply extensive simulations and analyze the different configurations.

From the summary of traditional existing multiple access protocols, it can be seen that the access probability about data and voice is acquired from the same principle. And two important aspects have been ignored, the various characteristics of traffic and the user demands of data and voice. In addition, the acquired throughput is still low with the collision probability is fairly high. Thus, firstly, we research the characteristics of space-based network in this paper. Secondly, we consider different users' requirements. Then, we propose a novel hybrid access protocol to solve the problem mentioned above. Finally, the effects that may have in the MAC protocol scheme for data link will also be investigated.

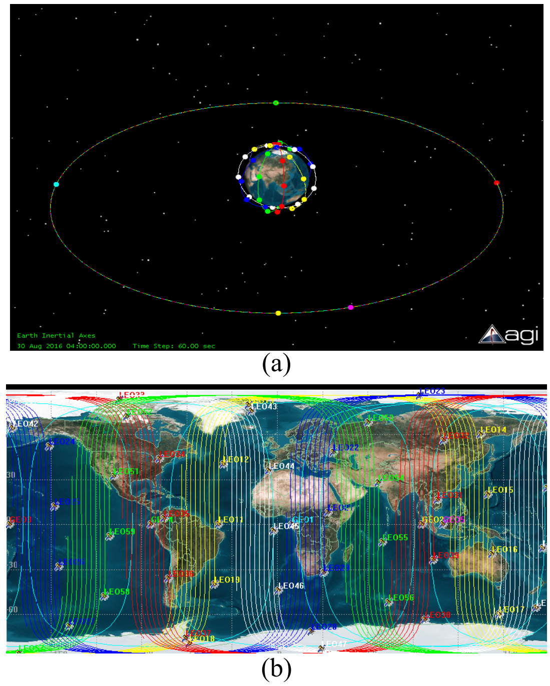

FIGURE 1. GEO/LEO network architecture. a) 3D diagram of the GEO/LEO constellation. b) 2D diagram of the GEO/LEO constellation.

II. SYSTEM MODEL

A. SPACE-BASED NETWORK SCENARIO

The space-based network is made up of aircrafts, spacecrafts and all kinds of satellites working in various orbits, therefore, the space-based network has some different scenarios, all in all, there are three kinds of scenarios:

1) GEO to MEO/LEO;
2) GEO to aircraft in near space;
3) MEO/LEO to aircraft in near space;
4) Aircraft in near space to aircraft in near space;

No matter what kind of users the scenario includes, we can consider them to access points and access terminals [13]. For different satellites in a space-based network, each satellite has its own function. According to flying pattern, there are different structures, Leader-Follower, Cluster, and Constellation, respectively [14].

1) LEADER-FOLLOWER

In this system, many satellites have same orbits. There are specific distances among them. And different satellites have different levels of authority. A detail sample of the flying pattern about this system (Afternoon train) has been given in [15]. There are four active satellites in the A-train, namely, CLOUDSAT, Aqua, Aura and CALIPSO.

2) CLUSTER

This system is consisted by a lot of satellites which are allocated in their own orbit planes and can cooperate with others and work independently. TECHSAT 21 [16] gives an example of this system. That system has three satellites and they operate at a near circular orbit whose altitude is 550 km above the ground. These three satellites have different structures and the distances between them are about 100 m to 5 km.

3) CONSTELLATION

For this system, some satellites which have similar structures can operate with each other by sharing control, so that they are able to overlap well within a coverage area. An example of this system is Global Positioning System (GPS) [17]. The GPS satellite Constellation has six planes and 24 satellites allocated with 4 satellites per orbital plane introduced by Kaplan [18] and Hegarty [19].

And in this paper, we consider constellation configuration. As to GEO satellite, its position is fixed to the earth, and the coverage is definitely wide because of its high location; and for LEO satellite, its round-trip delay is small owing to its fast movement. Therefore, the connectivity of the whole system can be achieved by combining GEO and LEO to form GEO/LEO network.

Fig. 1 shows a GEO/LEO network architecture designed by STK to be as the background to research the access protocol in space-based network. The Fig.1 (a) displays the 3D diagram of the GEO/LEO constellation while the Fig.1 (b) indicates the 2D diagram. Besides some performances are analyzed including the coverage and the data link of inter-satellite.

Fig. 2 demonstrates the results, where Fig.2 (a) is the performance of coverage and the inter-satellite link (ISL) is detected in Fig.2 (b), besides, Fig.2 (c) is the inter orbit

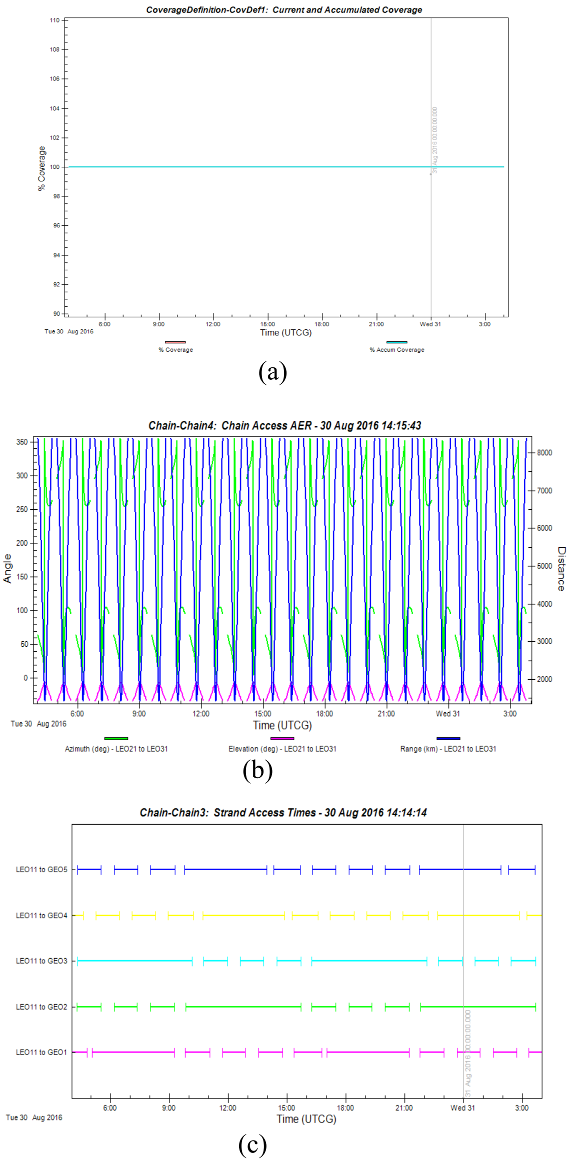

FIGURE 2. GEO/LEO constellation performance. a) Coverage of the GEO/LEO constellation. b) ISL. c) IOL.

links (IOL) performance. As it can be seen from Fig.2, the GEO/LEO constellation performs well.

B. REQUIREMENTS IN SPACE-BASED NETWORK

The space based networks have challenging needs, and these demands are not appeared on the terrestrial networks. And they have the significant network demands as follow. A reliable MAC protocol can deal with them all [20].

1) UNICAST, MULTICAST, AND BROADCAST COMMUNICATION

All of the satellite nodes should be agile to make a link that towards multiple nodes required for control and demand, as well as data transmission.

TABLE 1. Priority classification of traffic.

Priority	Sort	Access category	Classification
The lowest	4	AC_BK	Background
↓	3	AC_BE	Best Effort
	2	AC_VI	Video
The highest	1	AC_VO	Voice

2) VERY HIGH THROUGHPUT

Network capacity is crucial. In the physical layer, it is not enough to only offer high throughput. The MAC's efficiency which decides the physical throughput will be retained in the application.

3) WIDE RANGE WITH OPERATION

This may be anywhere from dozens of meters to hundreds of kilometers. Without losing its efficiency, the MAC need an enough flexibility to deal with such a range (longer ranges may increase the expense of MAC layer). The MAC framework does not need to add a separate radio to deal with the long and short distance links between nodes. Certainly, this requires the PHY to have a function to operate a single radio with both short and long distances.

The network should have an ability to manage and create by itself. It doesn't need any additional manual and external assistance.

C. TRAFFIC ANALYSIS

There are all kinds of satellites in the space.

In addition to communication satellites[21], there are many satellites having various functions: 1) Weather satellites: These satellites have advanced instruments and make weather conditions prediction by providing meteorologists with scientific data [22]; 2) Earth observation satellites: scientists use them to collect useful data about the ecosystem of the earth [23]; 3) Navigation satellites: GPS can be used in these satellites to offer the particular situation of a person on Earth and the error is only a few meters [24].

With the fast development of satellite technology, an increasing number of functions can be supported by satellite nowadays. At first, the satellite system can only support a single traffic, such as voice, but now, it can transmit video, image, data flow and so on. In general, traffic involves widely. In this paper, we classify them into four types according to the requirements for AC-VO, AC_VI, AC_BE and AC_BK, which means voice access category, video access category, access category for best effort and access category for background, respectively where the priorities die down. The table 1 indicates the classification.

D. PROTOCOL ANALYSIS

According to existing research, the Collision Avoidance Carrier Sense Multiple Access (CSMA/CA) is the basic medium

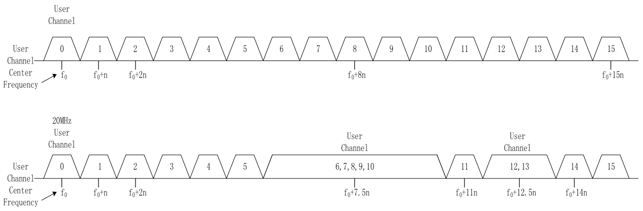

FIGURE 3. F/TDMA access scheme.

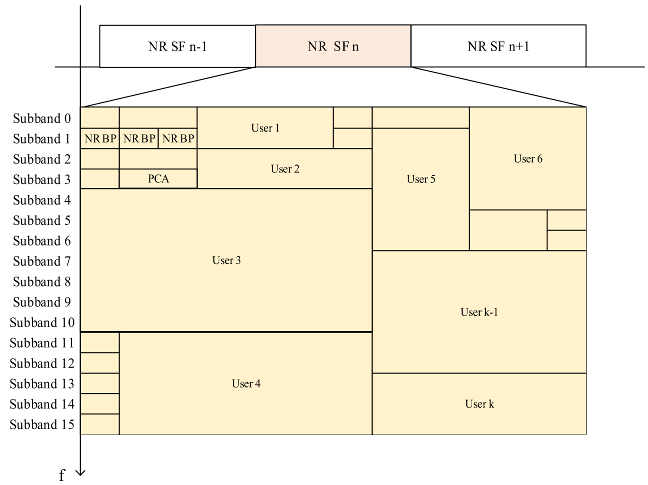

FIGURE 4. 2-D superframe resource allocation in F-TDMA.

access way in space-based network to assure an efficient data transmission for channel without a wire to retain a equal control of the medium access, in which distributed coordination function (DCF) is the main measure [25].

DCF applies a shared-channel model with competition and each STA of this model has a fair medium by competing with others. Before the data transmission, each STA needs to listen to channel. If the channel is busy, STA needs to listen to channel all the time. If not, no signal can be delivered, but to wait for a period, named as IFS (inter frame space). During this period, the STA has to quit the timer and makes postpone to access instantly if other STAs have begun to transmit data. If the vacant channel time is longer than IFS, then, using an algorithm called random evaluation (BO) to choose a given time casually and put off the access. Waiting for the timer of bakeoff (BO) decreases to 0 and the channel is in a vacant state. Then, use the channel to transmit data.

The state of a channel (vacant or not) can be assured by two methods, virtual carrier detection and physical carrier detection, respectively. The former one uses the information about channel state in the future. One of the method is depicted as follows: before the transmission process, they exchange the RTS/CTS frame. RTS/CTS frame has a part used to determine the interval about vacant channel in the next time and that is called as Duration/ID domain. And the occupation state of the channel in the future will be announced by network allocation vector (NAV) [26]. The way using frame Duration/ID to decide the channel state and transmitting data by peer-to-peer is another way.

Obviously, applying the terrestrial wireless protocol (IEEE 802.11) for Inter-Satellite Links (ISL) directly in such systems is not reasonable. Necessary medications are ought to do to adapt space-based network. Here, we refer to the changes of some parameters in [27]. And we still call it as traditional CSMA/CA access method.

III. HYBRID ACCESS PROTOCOL

A. F-TDMA

Instead of a pure TDMA scheme provided by traditional satellite system, a F/TDMA [28] (Frequency-Time Division Multiple Access) scheme is shown in Fig. 3

This multiple access method is useful to operate the ISN modules in a large range. When long distance communication links are restrained by power, it is not necessary to reduce the throughput for that link with decreasing bandwidth that has allocated to any given link, but it can release resources (spectrum) of other links at the same time. The MAC on one node can be allocated to two dimensional time - frequency time slots (TFS) by optimizing cross layer. So, it can communicate with other nodes. Therefore, the throughput of the long distance network can be greatly improved. And then, to increase a given link throughput (PHY modification necessary), a lot of sub-bands can be connected in an OFDM symbol in a considerable short distance.

Therefore, the number of time slots and frequency bands are assigned to any given link which has a two degree freedom of the presented MAC by using in scheduling resources. Fig.4 shows a sample of the resource allocation for a two dimensional superframe. It is should be noted that, in a few slots, at first, beacon slots are assigned to all nodes for receive and transmission. Then, the superframe will be assigned for a particular node to another. Some TFSs can be preserved for PCA operation at the same time.

It can be seen that the F-TDMA mechanism contains 2-D superframe resource allocation of both frequency domain and time domain. To be specific, in the time domain, we refer to common access protocol, such as CSMA/CA and its optimized version; in frequency domain, we take OFDMA technology to access due to it is composed of a series of subcarriers and these subcarriers can be classified into several groups, and a group forms a sub channel. There is no interference because of the orthogonality between sub channels.

Hence, in terms of flexibility and efficiency, MF/TDMA scheme is able to address ISN challenges.

B. IMPROVED BAKEOFF ALGORITHM BASED ON TRAFFIC PRIORITY

CSMA/CA applies a Binary Exponential Back-off (BEB) [29] algorithm and that is implemented in situations as follows, 1) before a packet first transmission, if the node senses the medium as busy 2) after each re-transmission and 3) after each successful transmission. The process of BEB's works can be described as follows: Once the medium is identified

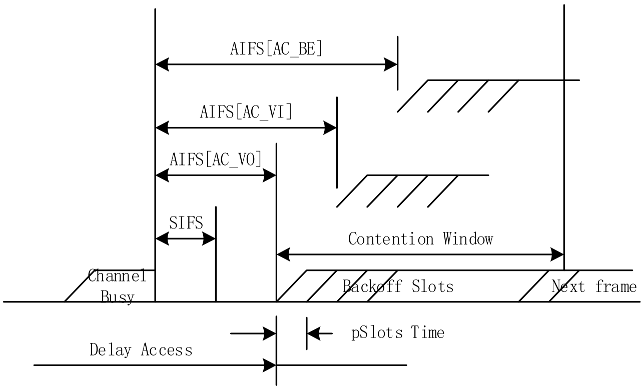

FIGURE 5. Bakeoff algorithm based on traffic priority.

as busy, the node will be delayed to the end of the current transmission. Before the next time to attempt to transmit, the node chooses an optional back-off interval after a successful transmission instantly and that has the same time with Back-off Time which among 0 and the number about a given slot (from CWmin to CWMAX) and this should be finished before accessing medium.

The Contention Window (CW) can be described as the time that is enough for the network to avoid a conflict among packets. After each collision, the CW raises with two factors from 7 to 255. When the medium is free, the interval of back-off will be decremented and when the transmission is detected in the channel, it will be frozen. CW is set as CWmin when a successful transmission is got. The influences about fixing values of inter-frame space by setting CWmin are 1) Throughput that is constrained with big back-off by applying unnecessary MAC delay. 2) Unfairness between contending nodes 3) Long delays of light-loaded network and 4) many collisions in heavily loaded networks.

The expression of the principle of BEB is as follows.

$$\begin{cases} F_{inc} = \min(2CW, CW_{\max}) \\ F_{dec} = CW_{\min} \end{cases} \tag{1}$$

The concrete thinking of the expression is that: if the information transmission is successful, the bakeoff time will decrease, that is the function of F_{dec}; on the contrary, if transmission fails (that is, a collision appears), the bakeoff time will be increased, that is the function of F_{inc}. The disadvantage of BEB is that the node with successful transmission possesses more advantages in the next transmission, which will lead to unfair competition in the channel, and the algorithm can't support traffic priority. The Bakeoff algorithm based on traffic priority [30] is shown in Fig.5.

For this reason, this paper proposes a bakeoff algorithm based on priority of traffic. Each satellite detects channel state before transmission. If the channel is idle, the satellite will wait period of time named AIFS (Arbitration Inter-Frame Space) according to its own traffic where the length of AIFS is associated with the traffic priority, and the bakeoff is carried out at the end of AIFS.

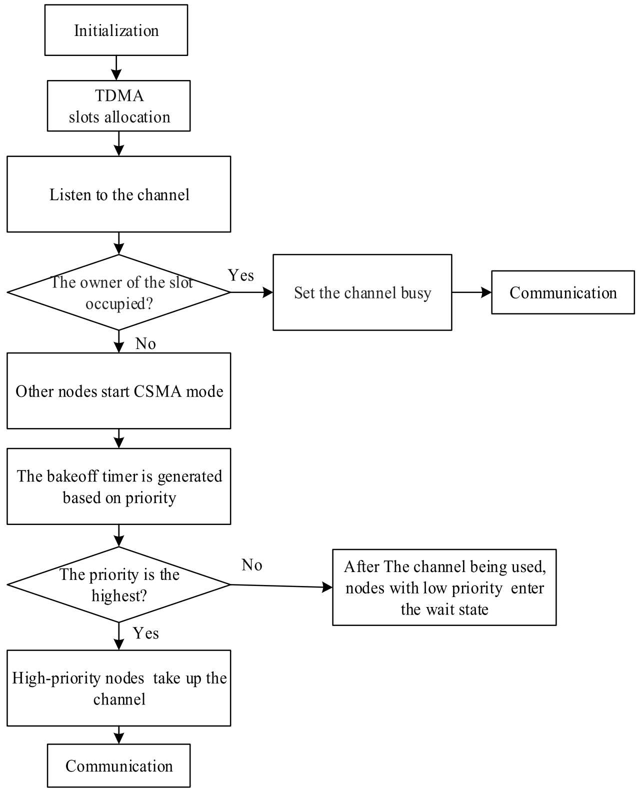

FIGURE 6. Hybrid CSMA/TDMA.

C. HYBRID CSMA/TDMA PROTOCOL IN TIME DOMAIN OF F-TDMA

Differing from the common CSMA/CA scheme in the time domain of F-TDMA, a novel hybrid CSMA/TDMA access scheme is applied by combining CSMA/CA and TDMA in the time domain of F-TDMA. The procedure of the hybrid protocol is shown in Fig. 6.

As to the improved CSMA/TDMA protocol, the fixed slot resource allocation of TDMA is carried out to each satellite node firstly, thus each satellite has its own fixed resource. Because of the rapid movement of satellite, there is phenomenon that no data transmission arises in a certain time slot, at this time, other neighboring satellites with transmission requirements can take up this idle slot by competitive mechanism of CSMA to avoid wasting time resources. When competing the slot, the relevant satellites will make use of the improved bakeoff algorithm based on traffic priority. In other words, to reduce the collision, the slot owner has a higher level of priority to non-owners of the slots for transmission. Then, non-owners are able to use slots when the slot owner doesn't have data to transmit.

Specifically, it can be divided into the following steps:

1) Slots allocation: TDMA. The satellite belonging to the specific slot occupies the time slot resource according to the communication requirement.

2) Slots competition: After the allocation, other satellites with operational transmission requirements have been

TABLE 2. Simulation parameters.

System parameters	value
Physical data rate	2 Mbps
Transmission frequency	2.4 GHz
SIFS	6 ms
DIFS	30 ms
Slot time	12 ms
Contention window	15
Average packet arrival time	110 slots
Data packet arrival	Passion distribution
Average packet length	50 slots
Transmission power	2 W
Range of Inter-satellite	10 km to 25 km
Number of packets simulated	2000 packets per satellite

detecting channels and judging whether the original satellite occupies the time slot. If the original satellite has data transmission requirements, it would send RTS to occupy the time slot. Then other satellites will not make time slot competition. However, if the original satellite does not have data transmission requirements, other satellites will judge that the time channel is free and they will make competitive access. The priority of competition can be obtained through the business differentiation of the different initial value produced by each satellite.

Specifically, all competing satellites will set their own back off counters in Distributed Inter-Frame Spacing, and there will be a back off time based on the priority of transport service. Among them, the initial value of the satellite is represented and the initial value corresponds to the size of the access window. The different types of business will be distinguished by the initial value. The higher the priority of the transport service, the smaller the value and the smaller access window will be. Then, it is easier to access successfully. It indicates the time of time slot.

3) After the beginning of competitive access, the back off counters of each satellite begins to make a self-reduction. The high priority has the small initial value, so the reduction of the satellite with high priority will be quicker than the reduction of other satellite, and it will decrease to 0 first to occupy the channel in advance. Then, the information will pass to other satellites which participate in the competition. Other satellites will hang up counters and stop competition.

IV. COMPUTATIONAL PARAMETERS

In this section, we present a reliable MAC protocol that is used in the network based space. The design of MAC protocol is essential to the system. Many system parameters should to be taken into account, for example, the objective of mission, network structure, satellites number, etc. at the same time, some constraints related to the system should be considered

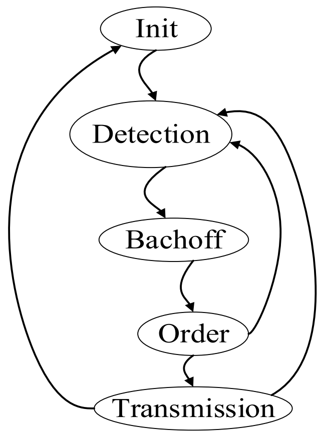

FIGURE 7. State transition diagram of F-TDMA with CSMA/TDMA.

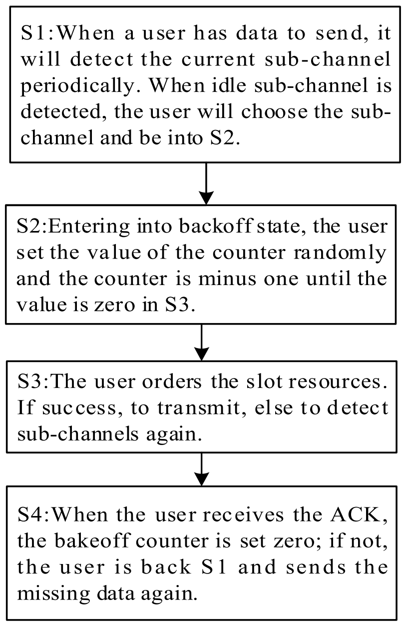

FIGURE 8. Description of F-TDMA with CSMA/TDMA.

to the MAC protocol, such as the limitation of computing resources and on-board power.

We propose a modified Carrier Sense Multiple Access, and Collision Avoidance Protocol which can be used in a distributed satellites network in small size based on the distributed coordination configuration (a service provided by IEEE 802.11 standard). We decide to apply CSMA protocol because compared to other exiting traditional MAC protocols, this protocol can avoid hidden and exposed node problems. Reference [31] has given a specific description of the modified CSMA protocol. Our study mainly focuses on three different small distributions about satellite, namely, cluster, leader-follower, and constellation, respectively.

For our system model, we consider the GEO/LEO network architecture with a transmission power of 2W, and this network is operated at S band with a magnetic spectrum.

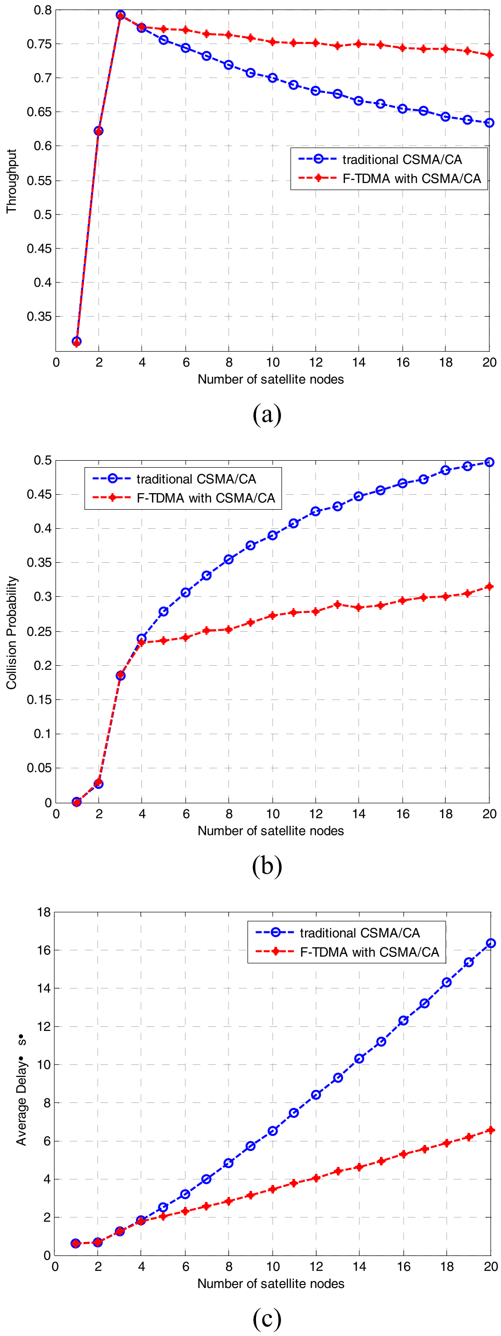

FIGURE 9. **Comparison between F-TDMA with the traditional CSMA/CA. (a) Throughput. (b) Collision Probability. (c) Average Delay.**

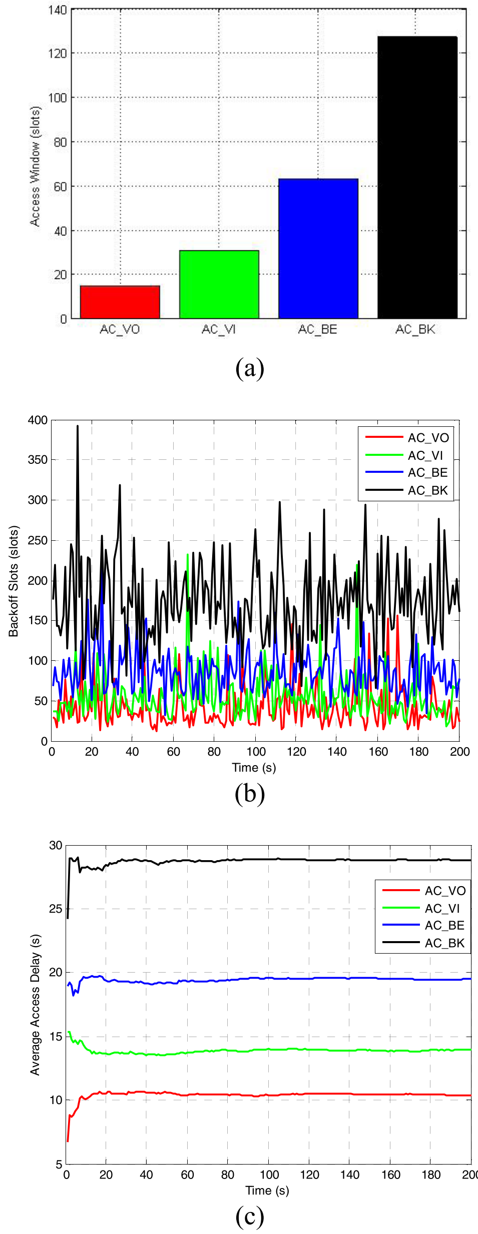

FIGURE 10. **Improved bakeoff algorithm with different traffics. (a) Access Window. (b) Bakeoff Slots. (c) MAC delay.**

We assume that the satellites are LEO satellites. For constellation configuration, we consider N orbital planes, spaced x degrees apart. For constellation formation flying pattern, because we need to avoid the collision at poles, we assume that satellites in different orbits need to join into the network at distinct times. For all satellite configurations, it is assumed that the same transmission frequency will be applied by all satellites. Table 2 gives the different system parameters which may be used for simulation.

As to the F-TDMA with CSMA/TDMA hybrid access protocol, Fig. 7 shows the state transition diagram. Corresponding to the state transition diagramčthe description is demonstrated in Fig. 8.

V. SIMULATION RESULT

This part will compare the improved hybrid access protocol with the traditional CSMA/CA access protocol and shows the optimized bakeoff algorithm results.

A. THE COMPARISON BETWEEN F-TDMA AND THE TRADITIONAL CSMA/CA

In this part, we compare the F-TDMA with the traditional CSMA/CA including the performance of throughput, collision probability and average delay. The results are depicted in Fig. 9. It can be seen from the Fig. 9(a), Fig. 9(b)

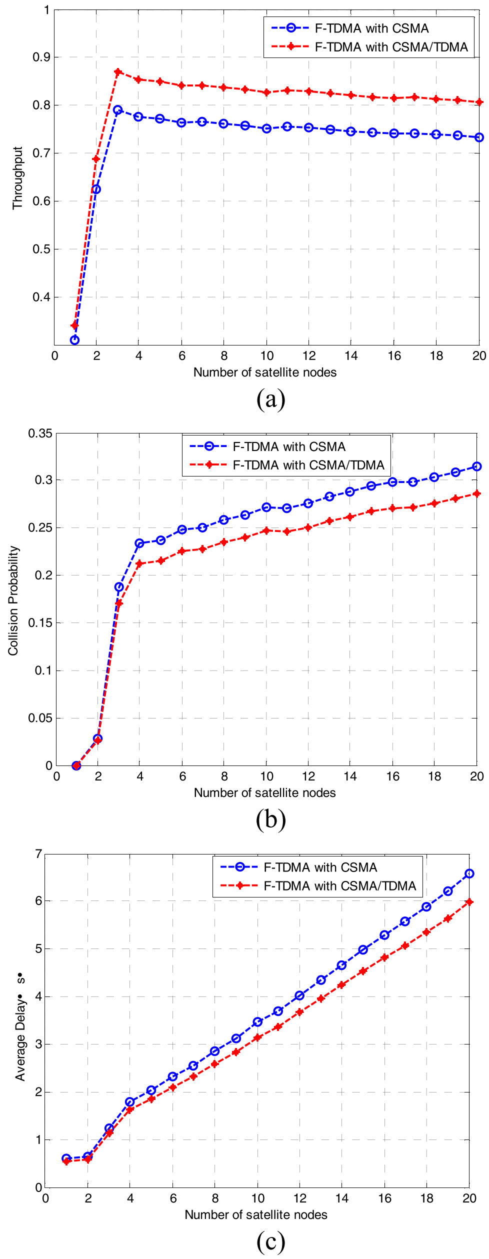

FIGURE 11. Comparison between CSMA/TDMA with CSMA. (a) Throughput. (b) Collision Probability. (c) Average Delay.

and Fig. 9(c), the F-TDMA outperforms the traditional CSMA/CA for the throughput, collision probability and average delay. The reason is that, when the number of sub channel is 1, the F-TDMA scheme is equal to the traditional CSMA/CA. When applying to F-TDMA, each satellite detects the idle sub channel to transfer information to increase the chance of random access, thus the utilization rate of resources is improved to contain more users, which optimizes the system performance.

B. THE IMPROVED BAKEOFF ALGORITHM PERFORMANCE

In order to support the variety of traffics in space-based network, we design the improved bakeoff algorithm based on traffic priority. For the access category of AC_VO, AC_VI, AC_BE and AC_BK, the access window, the bakeoff slots and the MAC delay are shown in Fig. 10(a), Fig. 10(b) and Fig. 10(c), respectively. From the Fig. 10, we can conclude that, the prior the traffic, the access window is smaller and the bakeoff slots are fewer and the delay in MAC is shorter, which meets the requirement of different traffics in space-based network.

C. THE HYBRID CSMA/TDMA ACCESS PROTOCOL

Modeling the CSMA/TDMA hybrid access protocol in time domain of F-TDMA, the performances of the optimized F-TDMA and F-TDMA are compared including throughput and delay in Fig. 11.

Obviously, the novel hybrid F-TDMA with CSMA/TDMA access protocol outperforms the F-TDMA with CSMA in time domain, which means that the hybrid access protocol can make use of resources more effectively by combining the superiorities of CSMA and TDMA. That is, when the time slot resources are allocated on the latitude of the F-TDMA, a combination of fixed and dynamic methods is adopted. Concretely, the fixed allocation adopts the TDMA access mode while dynamic allocation adopts CSMA access mode. The time slot resources can be distributed to all satellites, which are in the network. Through TDMA, the collision is furthest avoided. Besides, resources can be farthest used for avoiding the waste of idle slot through CSMA. The main idea is that the complementary advantages are used to improve the network throughput and reduce the average delay.

VI. CONCLUSION

In this paper, an improved hybrid multiple access protocol based on traffic priority joint frequency and time domain in space-based network is proposed. Some features are concluded as follows. Firstly, F-TDMA scheme is introduced into space-based network, which increases the throughput and decreases the collision and the delay effectively. To be specific, in time domain, CSMA/CA is adopted; in frequency domain, OFDMA is applied because of the orthogonality between sub channels. In addition, we consider the factor of traffic priority in space-based networks. We also improve the back off of CSMA by changing the size of the CSMA access window to support a wide variety of traffic. Furthermore, combining the strengths of CSMA and TDMA access protocol can avoid weaknesses and enhance the performance of throughput and decrease the delay in the whole hierarchical network.

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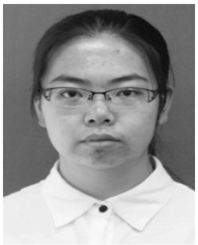

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