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Performance Analysis of MAC Protocol for LEO Satellite Networks

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Abstract

Considering that weak channel collision detection ability, long propagation delay and heavy load in LEO satellite communications, a valid adaptive APRMA MAC protocol was proposed. Different access probability functions for different services were obtained and appropriate access probabilities for voice and data users were updated slot by slot based on the estimation of the voice traffic and the channel status. In the proposed MAC protocol limited wireless resource is allocated reasonably by multiple users and high capacity was achieved. Three performance parameters: voice packet loss probability, average delay of data packets and throughput of data packets were considered in simulation. Finally simulation results demonstrated that the performance of system was improved by the APRMA compared with the conventional PRMA, with an acceptable trade-off between QoS of voice and delay of data.

Keywords: LEO Satellites, Adaptive Packet Reservation Multiple Access, MAC Protocol

1. Introduction

Due to various economic and technical constraints, terrestrial mobile networks can only provide communication services with a limited coverage. Recently, in response to increasing demand of real-time multimedia services and the truly global coverage required by personal communication services, there is a vast research on non-geostationary orbit (NGSO) satellites systems, especially on low earth orbit (LEO) satellite constellations with an altitude between 700 km and 1 500 km. LEO satellite constellations equipped with inter-satellite links, such as Iridium, Teledesic, Courier and so on, usually have onboard switching and onboard routing facilities and form an independent network in space. Direct connectivity between any pair of satellite mobile users can be achieved through the satellites and ISLs without any essential usage of the terrestrial core network. For the wide application prospect, they have already been the focus of the research on the satellite communication systems. This LEO system can provide real time voice and data traffics in the global range. It is the trend that various kinds of traffics will be provided by LEO satellites system. It is of great importance that an effective medium access control (MAC) protocol will be required to make full use of limited resource and to provide services with strict quality for users. MAC protocol is used to allow many mobile users to share simultaneously a finite amount of radio spectrum. The sharing of spectrum is required to achieve high capacity by simultaneously allocating the available bandwidth to multiple users. Thus the appropriate access control protocol will be a key problem for wireless mobile communications development.

LEO satellites will provide not only the real-time traffic such as video and voice but also data traffic with burst character. The efficiency of resource utilization will sharply decrease if fixed assignment multiple access is applied. Also, voice and video traffic will not be supported sufficiently if competitive multiple access (ALOHA, CSMA *et al.*) is used completely [1–3]. Since PRMA (Packet Reservation Multiple Access) as an access protocol for wireless local networks was introduced by D.J Goodman *et al*. in 1989 [4], its high efficiency for voice packet transmission captured much attention, since then new versions have been proposed to support multi-media traffic which is very important in the future mobile system. In literature [5] this protocol was researched profoundly and the author pointed out that PRMA is competitive protocol with the limit of traffic and connection number at one time. Three main problems will be encountered if this protocol is applied in

LEO satellites system. They are: 1) The channel collision detection ability is quite weak. 2) The propagation time delay is long comparatively to terrestrial communications system. 3) Heavy load will be supported because of many users in the coverage of the LEO satellites. The three characteristics will bring on increase of packet loss probability, severity of channel congestion and decrease of QoS (Quality of Service).

More improved PRMA protocols were provided based on [4–5]. In literature [6] PRMA-HS with re-transmission character was provided in order to overcome long time delay problem in satellite communication. But the access contention becomes serious and performance of the system degrades under the environment of large number of users or heavy load. Moreover this protocol has a changeable channel access time delay and a certain packet loss probability which are not suitable for services with strict QoS requirement. In literature [7] IPRMA (Integrated Packet Reservation Multiple Access) protocol was proposed for satellite communication. A user can reserve many slots to improve performance of this protocol. But it possibly exists that one user occupies the resource totally. In literature [8] MPRMA (Mini-Packet Reservation Multiple Access) was provided. In the protocol an available slot will be divided into many mini-slots in which competitive packets are transmitted. From [8] we can see that probability of collision in a mini-slot decreases. But this protocol can not support a mass of real-time traffic due to the decline of the efficiency of transmission. In literature [9] the author provided NC-PRMA (Non-Collision Integrated Packet Reservation Multiple Access) protocol which adopted queue model to avoid collision resulted from competition and performance was improved. But this protocol is not perfect in the long propagation delay because implementation of this protocol will be in the environment of short RTD (Round Trip propagation Delay) period.

From the analysis above, we can find that access probability for voice and data is obtained from the same access function, without considering the different traffic characteristics and requirements of voice and data users (voice users require real-time delivery but can accommodate higher bit error rates; data users do not need real-time transmission and can be queued but require low bit error rates or error-free transmission). Therefore it will be expected to be more efficient if priority is given to the transmission of voice, whilst minimizing the effects on the data packets. Considering that weak channel collision detection ability, long propagation delay and a mass of load in communication system in LEO satellites, an adaptive access control protocol improved form PRMA based on channel status, quality of service and estimation of traffic was proposed with priority of voice traffic referred to [10,11]. Thus in this method, voice packets access to the channel with a priority and a updated access probability and then, if the resource is available, data packets can be accepted with an updated access probability slot by slot. Our simulation results show that the efficiency is improved by the new adaptive PRMA protocol.

This paper is organized as follows. In Section 2, two kinds of access probability functions are derived for voice and data traffic respectively. Compared to conventional PRMA protocol, three performance parameters of voice packet loss probability, average delay of data packets and throughput of data packets are analyzed by simulation in Section3. Finally system performance and conclusions are obtained.

2. Protocol Model

2.1. Traffic Analysis

For a voice terminal, the voice source can be characterized by a two-state Markov chain model, as shown in Figure 1. Four parameters are required for the description of the model. They are: the mean duration of a talk burst t_1, the mean duration of the silence t_2, the transition probability from the talking state to the silent state γ and the inverse transition probability δ. The parameters γ and δ can expressed as follows:

$$\gamma = 1 - \exp(-\tau / t_1) \tag{1}$$

$$\delta = 1 - \exp(-\tau / t_2) \tag{2}$$

where τ is the width of one time slot. The empirical values for t_1 and t_2 are 1s and 1.35s. The voice terminal generates one packet per frame which is first composed of an information field with length of $R_s T_f$, where R_s is the bit-rate of voice and T_f is the duration of one frame, and a packet header with length H bits.

Next data users were concerned. A data terminal has a discontinuous stream. Denote the average bit rate of the data terminal by R_s and a data packet which is the same as voice packet is generated independently in each slot with a probability of δ_d. Hence, the mean bit rate of a data terminal is:

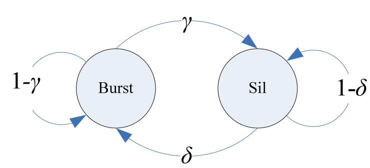

Figure 1. Two states Markov model of voice.

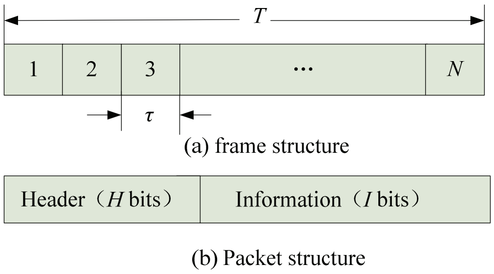

Figure 2. Structure of frame and packet.

$$R_d = \delta_d R_s A \quad (3)$$

where A is the number of slots per frame and can be calculated by:

$$A = \text{int}[R_p T_f / (R_s T_f + H)] \quad (4)$$

R_p is the channel rate before coding.

2.2. Frame Structure

These frames are further subdivided into N time slots as illustrated in Figure 2(a). Information packets transmitted from terminals to satellites consist of both a payload (actual information) and a header (control information) as illustrated in Figure 2(b). The time slot duration is τ and T is the duration of a single frame.

2.3. APRMA Protocol

In the beginning of this paper we have got the conclusion that conventional and improved PRMA protocols supported mixed voice and data traffic with a low efficiency in LEO satellites. In the APRMA protocol, P_v is the access probability of voice and P_d is the access probability of data respectively. Voice user is given priority compared with data user. Appropriate access probabilities P_v and P_d are broadcast from the LEO satellite, which is updated slot by slot based on the estimation of the voice traffic and the channel status.

The purpose of APRMA protocol is to guarantee real-time transmission of voice packets by priority transmission compared with data packets. When the channel load is light, transmitting data packets is allowed. On the other hand, when the channel load is heavy, transmission of data packet is postponed. We assume that the LEO satellites can recognize the total number of users in a cell and the number of users in reservation mode. Then, based on the statistical characteristics of the traffic models, the number of contending voice terminals is estimated and the access probability is calculated. From the voice model described in 2.1, voice terminals are M_v and voice terminals in reservation mode are M_{rsv}, The probability of n new terminals arrival talk burst and one terminal departing from talk burst can be considered as a binomial distribution:

$$\begin{cases} B(n,k,p) = C_n^k (p)^k (1-p)^{n-k} \\ P(n \mid M_{sil}) = B(M_{sil}, n, \delta) \\ M_{sil} = M_v - M_{rsv} \end{cases} \quad (5)$$

where M_{sil} is number of voice terminals in silent mode. When the population of users is large or the probability of p is small, the binomial model approaches the Possion model. Thus $\lambda = M_{sil}\delta$ is arrival rate of the voice users and $u = M_{rsv}\gamma$ is departure rate of the voice users respectively. Hence, in the current time slot the estimated value of M_{rsv} can be expressed by:

$$\begin{cases} M_{rsv} = M_{rsv1} + \lambda P_0 / \mu \\ Max(M_{rsv} - M_{rsv1}) = \Delta C \\ \Delta C = K_{OPT} - K_{RSV} \end{cases} \quad (6)$$

$$\begin{cases} r\gamma_f + c_v \gamma - s_v \delta = 0 \\ r(1-\gamma_f) + c_v P (1-P)^{c_v - 1} (1-r)(1-\gamma) - r = 0 \\ s_v - c_v + Br = M_v \end{cases} \quad (7)$$

where M_{rsv1} is the number of voice users in reservation mode in the previous time slot and P_0 is the access probability of voice users at current time slot. K_{OPT} is the available number of access channel for voice users. In the voice system, the balance equation is shown in the following: Here $\gamma_f = 1-(1-\gamma)^B \approx B\gamma$, P is the access probability. From the Equation (7), the following Equation (8) can be found.

$$(1+\frac{\gamma}{\delta})c_v + (B + \frac{\gamma_f}{\delta})r = M_v \quad (8)$$

For the data system, the probability of a data user to send a data packet successfully is w:

$$w = p_d u_d (1 - r(1 + b / M_d B)) \quad (9)$$

where $u_d = (1-p_v)^c (1-p_d)^{(1-\Gamma)b-1}$. Therefore, the data user and voice user access probability at the balance point can be shown by the Equation (10):

$$\frac{b\Delta}{c(1-\gamma_f)}[cp(1-\gamma)(1-r(1+\frac{b}{M_d B}))] = \delta_d M_d \quad (10)$$

where $\Delta = p_d(1-p)/p(1-p_d)$. In the voice system, the Equation (8) can be shown in the following.

$$h_1 c + h_2 r = M_v \quad (11)$$

where $h_1 = (1+\gamma/\delta)$, $h_2 = (1+\gamma_f/\delta)$. Combination Equations (10) and (11), the relation between b and c is in the following.

$$b = \min\{\frac{c}{\Delta}\delta_d M_d \frac{1-\gamma}{\gamma_f}(\frac{h_2}{M_v - h_1 c}), M_d\} \quad (12)$$

2.3.1. Voice Packet Loss Probability

Packet loss probability is defined as the ratio of the number of loss packets and the number of the generated packets at the terminals.

$$P_{vdrop} = \left\{1 - \frac{\gamma_f[1-(1-\gamma_f)v^{2B}]}{[1-(1-\gamma_f)v^B]^2}\right\}\frac{v^N\gamma_f(1-\gamma_f)}{1-v^B} + \frac{\gamma_f v^B}{[1-(1-\gamma_f)v^B]^2} \quad (13)$$

where N is the maximum time delay of voice packet and v is the successful access probability of voice packet.

$$v = 1-(1-r(1+b/M_d A))\bullet p(1-p)^{c-1}(1-p_d)^{(1-\Gamma)b} \quad (14)$$

2.3.2. Average Time Delay of Data Packet

Average time delay is defined as the lasting time from packet generated to packet received successfully at the LEO satellites. When a data packet arrived at a data user, j data packets were waited for transmission. Average time delay of this data packet was $(j+1)/w$. Therefore the average time delay of data packet is:

$$W_{ad} = \frac{1-\Gamma}{w(1-p_d)} \quad (15)$$

2.3.3. Throughput of Data Packet

Throughput is defined as the ratio of the number of packets received successfully and the number of packets generated at the terminals in a time unit. The Throughput of data packet is defined as the proportion of timeslots that successfully carry information packets.

$$T_{throughput} = r(1+\frac{b^2\Gamma\delta_d}{M_d A}) + \delta_d M_d(1-\Gamma) \quad (16)$$

3. Results Analysis

All the LEO mobile satellites system have taken CDMA technology except Iridium system (TDMA technology was taken). LEO satellites adopt multi-beam formation technology to make full use of the finite radio frequency resource. Therefore many cells are formed and users separated by space can re-use the radio channel. In [12] CDMA channel attenuation model in AGWN was proposed which adopted BPSK modulation technology and BCH coding (511, 229, 38). Figure 3 shows the access probability of voice users in APRMA protocol and Table 1 shows the simulation parameters.

Figure 4, Figure 5 and Figure 6 show the simulation results with equal loads of voice and data traffic. For 2%

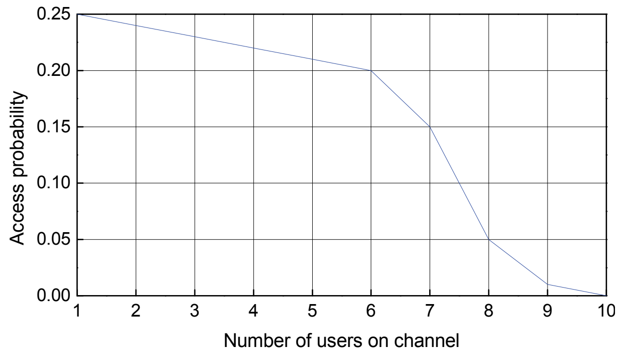

Figure 3. APRMA voice terminals access probability.

Table 1. Simulation parameters.

Parameter	Value
Channel rate	5.3Mbps
CDMA information rate	4599Kbps
Channel rate after coding	1022Kbps
Channel rate before coding	558Kbps
Voice rate	16Kbps
Average data rate	3.4Kbps
Frame duration	10ms
Information bit per packet	160bits
Frame header	69bits
Slots per frame	10
Maximum delay (Voice packet)	20ms
Mean duration of talk burst t_1	1s
Mean duration of silence t_2	1.35s

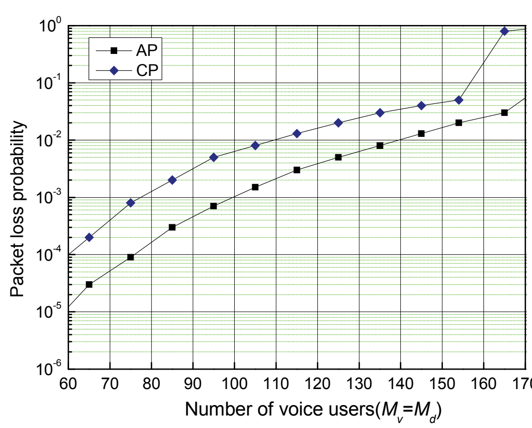

Figure 4. Voice packet loss probability.

packet loss probability as an acceptable level, then the system capacity is improved about 18% by APRMA compared to CP (Convention PRMA). Furthermore, Table 2 shows the comparison between AP and CP protocol. From the performance comparison in the Table 2, the system performance is improved by the APRMA protocol in all three cases.

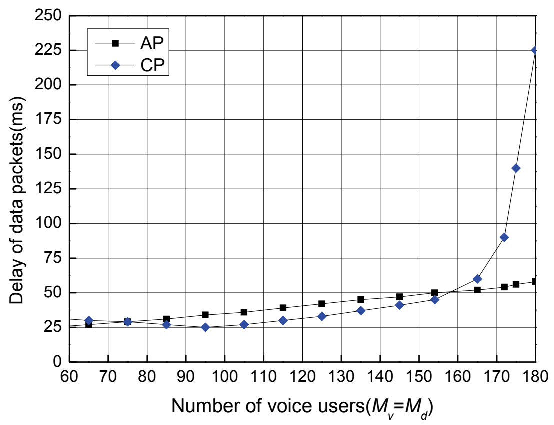

Figure 5. Average time delay of data packets.

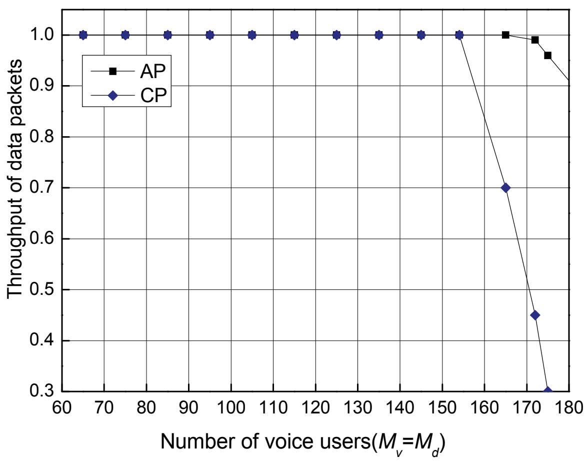

Figure 6. Throughput of data packets.

Table 2. Performance comparison.

Data user		100	150	200
AP	Voice user (PLP)	188	108	78
	Voice user (ATDDP)	282	170	138
	Voice user (TDP)	260	185	160
CP	Voice user (PLP)	142	85	58
	Voice user (ATDDP)	240	134	116
	Voice user (TDP)	220	150	135
Performance improvement (%)	Voice user (PLP)	24.6	21.2	25.6
	Voice user (ATDDP)	14.9	21.7	15.9
	Voice user (TDP)	15.4	18.9	15.6

PLP, ATDDP and TDP stand for packet loss probability, average time delay and throughput of data packet respectively.

4. Conclusions

With the development of LEO satellite communication, it is the base requirement that various kinds of services will be provided. Considering that weak channel collision detection ability, long propagation delay and heavy load in LEO satellite communication system, a valid adaptive access control protocol APRMA is proposed. Different access probability functions for different services are obtained and appropriate access probabilities for voice and data users are updated slot by slot based on the estimation of the voice traffic and the channel status. Simulation results demonstrate that the performance of system is improved by the APRMA compared with the conventional PRMA, with an acceptable trade-off between QoS of voice and delay of data. Also the APRMA protocol will be suitable for HAPS (high altitude platform station) with the character of weak channel collision detection ability, long propagation delay and heavy load.

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