Performance Analysis of an Enhanced PRMA-HS Protocol for LEO Satellite Communication*

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Abstract The packet reservation multiple access with hindering state (PRMA-HS) is a protocol suitable for LEO satellite mobile communication. Although working well with light system payload (amount of user terminals), the protocol imposes high channel congestion on system with heavy payload, thus degrades the system’s quality of service. To controlling the channel congestion, a scheme of enhanced PRMA-HS protocol is proposed, which aims to reduce the collision of voice packets by adopting a mechanism of access control. Through theoretic analysis, the system’s mathematic model is presented and the packet drop probability of the scheme is deduced. To testify the performance of the scheme, a simulation is performed and the results support our analysis.

Key words packet reservation; congestion control; satellite communication

Future communication system will be a system that integrates the terrestrial and satellite systems, and provide multimedia services all over the world. This requires the two systems’ architecture being similar as far as possible. The PRMA (packet reservation multiple access) protocol is a MAC protocol which was first proposed for terrestrial communication system[1]. It is proved that the protocol have good performance such as high multiplex efficiency, efficient management for voice and data traffic, transparent behavior with respect to user mobility, etc. A lot of research works has been carried out to implement the protocol in the low earth orbit (LEO) satellite communication systems[2-8].

The main obstacle confronted in applying the PRMA protocol into satellite communication is the long propagation delay between the user terminal (UT) and the satellite, which degrades drastically the protocol’s performance for the real-time service. To overcome this obstacle, a modified PRMA protocol called PRMA-HS were proposed by Enrico and Romano Fantacci et al in Ref.[2]. By introducing a retransmission mechanism, the protocol increases the probability of successful transmission for a voice terminal in active calling state. But this mechanism makes the packet collision between different UTs increased, which ‘hinders’ other terminal’s transmission, and weakens the mechanism’s benefit on system performance[2].

In this paper, we propose a scheme to enhance the performance of PRMA-HS systems. With the introduction of a mechanism to classify the terminals’ different states, the system can keep a higher priority of channel utilization for the calls already in calling process, thus reduces the packet collision between the different types of terminals, increases the efficiency of the channel utilization, and promotes the performance of the protocol.

1 PRMA-HS and Enhancement Scheme

1.1 Overview of the PRMA-HS Protocol

The PRMA-HS protocol can be described with a Markov chain model. We only consider the voice operation in this paper. Fig.1 is the model of a voice terminal’s state. By imposing the voice activating technology and hindering retransmission mechanism, a voice terminal is always in one of the following states: Si, Con, Hin[N-1]Hi, Res[N-1], Res[N-1] and Res[N-1]Res[N].

When a user terminal has no voice packet produced, it is in Si state, which means silent. When it has produced voice packet, it starts to contend at idle slot, and transit into the Con state. The pattern of the contention behavior is as same as that in S-ALOHA protocol. All terminals contend to transmit their packets with probability \( p \) in every time slot. Only
when the satellite receives just one talkspurt packet in a slot, the transmission is successful. Because of the long propagation delay, the terminal cannot receive immediately the satellite’s acknowledgement for the transmission, so the PRMA-HS protocol let the terminal continually send the contention packet at the idle slots even if the transmission is successful. If the terminal contends successfully, it will go into the hindering states $H_{i,n-1}$-$H_{i,n/n}$ ($i$=Frame period/roundtrip delay). From slot $(N-(N/n)-1)$ to slot 0, the terminal can hear the satellite’s answer, and will step into the states $R_{i,n/n}-R_{i,0}$ and stop to transmit. The satellite will record the first successful transmission attempt and informs the reserved slot number to that terminal, and ignore the subsequent ones, so the terminal will acquire and reserve only one slot. In next frame, the terminal will transmit at the reserved slot, and cycles from the state $R_{i,n/n}$ to state $R_{i,0}$. If the user ends his call in one frame, the terminal will return to state $S_{i}$, otherwise it will go into state $R_{i,n-1}$-$R_{i,0}$ and transmit at the reserved slot once again.

![Diagram](image)

Fig.1 Markov model and frame architecture of PRMA-HS protocol

In the state $H_{i,n-1}$-$H_{i,n/n}$, even if its contention for channel is successful, the terminal will continue to transmit contention packet because the ACK packet from the satellite has not arrived yet. This behavior increases the active terminal’s probability to acquire a time slot, but also increases the chance of packet collision with other UTs’, thus ‘hinder’ other terminal’s transmission attempt. The packet collision becomes serious when the amount of user terminals in the system grows large, thus causes the channel congestion and limits the improvement of the quality of service of the system.

1.2 Description of Enhancement Scheme

In PRMA-HS protocol, the slots are sorted in two classes: the idle and the reserved ones, as shown in Fig.1(b), and the terminal has two stages: silent and talking. The terminal contends to transmit packet at the idle slot, and if successfully, the slot becomes reserved and the terminal can go on transmitting at the same slot in every subsequent frame period until it becomes silent. The UTs in Con state include two kinds of terminals, which are the new UTs intending to initialize a call, and the UTs just waking from the silent gap and wanting to talk again in a call process. They contends the slots in the same urgent level, and if more than one user terminal transmit contention packet in a time slot, no one will succeed. The satellite will reserve the slot channel just for the terminal transmitting uniquely in that slot.

However, this manner of slot assignment didn’t consider the different characteristic of the two kinds of terminals which contend for the slot. Generally, the terminal which intends to initialize a new call can wait some time to acquire a time slot when the channels are congested, but a terminal already in active call process quite the contrary, thus the terminal being already in active call process should have higher priority over the new incoming ones. The PRMA-HS treats the two kinds of terminals in the same manner, thus cannot keep the service quality for a call when the packet contention becomes drastic, which inevitably happens in PRMA-HS system with large amount user terminals.

Based on above analysis, we can sort the UTs into two classes: the new coming UTs and the UTs having been in calling process, and label them with two different marks. The mark of the labeling can use the PN code like the spread sequence code. We assume that the signals of new coming UTs are correlated with code $PN_0$ and the ones of UTs in calling process correlated with code $PN_1$.

When two UTs with different mark contend at same time slot, the satellite always selects the packets
to receive from the UTs labeled with PN1. The satellite selects PN0 terminals’ signal to receive only when no other terminals transmit at the same slot, and consider the receipt successful only when one PN0 terminals transmit in that slot. Thus this scheme ensures the UTs’ precedence in calling progress over the new incoming call, and reduces the packet collision between two kinds of terminal. When the new incoming terminal has reserved a slot successfully, the satellite will inform it to change its mark code to PN1 in the downlink channel. When the UT ends its calling, its mark code will return to PN0.

1.3 The Model of PRMA-HS with Enhancement Scheme

According to above description, we can describe the whole communication progress with a new Markov chain, which is added with two terminal states. When a speech terminal exits from the communication process or in long silent period, it is in SilA state. When it’s ready to start a new call, it is in ConA state, where the terminal is marked with PN0 code and contend with all other terminals (marked with PN0 or PN1) at idle slots; when it is just in the brief silent gap in a call process, it is in SilB state; when it has been in an active call progress but just woken from a silent gap and want to continue to talk, it is in ConB state. In SilB and ConB the terminal is marked with PN1 code. According to the described scheme, terminals in state ConB will contend only with ones labeled with mark code PN1. At other time the terminal will operate according to PRMA-HS, and have states HinN−1→HinN−1−Res0, ResN−1→Res0. The model of the terminals’ behavior can be shown in Fig.2.

![Markov Model of PRMA-HS With Enhanced Scheme](image)

The probabilities of state transition from the two silent states SilA and SilB to the corresponding two contending states ConA and ConB are different. Given that the arrival of new coming calls is a Poisson process, and the arrival rate of the new coming calls is $\lambda$, then the interval time of two adjacent new calls conforms to an exponential distribution with the parameter $\lambda$, and the probability that the exit silent state SilA ends during a time slot of duration $\tau$ is

$$\sigma_a = 1 - \exp(-\lambda \tau)$$  \hspace{1cm} (1)

Similarly, the time that a call lasts conforms to an exponential distribution. Assume the mean lasting time of a call is $\mu$. Then the probability that a call in active progress ends during a time slot of duration $\tau$ is

$$\phi = 1 - \exp(-\tau / \mu)$$ \hspace{1cm} (2)

The silent gap between the talk spurt of an active talking conforms to an exponential distribution. With a mean gap duration $t_s$, the probability that a silent gap state SilB ends during a $\tau$ s duration is $[9]$

$$\sigma_r = 1 - \exp(-\tau / t_s)$$ \hspace{1cm} (3)

The probability that a talkspurt with mean duration $t_s$ ends in a time slot of duration $\tau$ is

$$\gamma = 1 - \exp(-\tau / t_s)$$ \hspace{1cm} (4)

and the probability that a talkspurt ends within a frame duration is

$$\gamma_f = 1 - (1 - \gamma)^N$$ \hspace{1cm} (5)

In Fig.2, a UT in ConA remains in the state until its attempt is successful. The UT can leave this state if three independent events occur simultaneously:

1) The packet to initialize a call doesn’t end during the slot duration (probability ($1-\gamma$));

2) The slot is unreserved and the terminal obtains the permission to transmit on it (probability $a$);

3) No other UTs (in the ConA or ConB state or in HinN states) attempts to transmit on the same slot (probability $u_A$).

Let $R$ denote the total number of UT’s which already have a reservation. Then the probability $a$ (i.e., the probability that a UT can make a transmission on the next slot) can be expressed as

$$a = (1 - \frac{R}{N})p$$ \hspace{1cm} (6)

where $p$ denotes the probability that a terminal obtains the permission to transmit on the slot channel.

According to above description of the event 3), the probability $u_A$ can be expressed by
\[ u_\lambda = u_\lambda (H,C) = (1-p)^{C+H-1} \] (7)

where the \( H \) denotes the total number of terminals marked with PN\(_0\) and PN\(_1\) in hindering states respectively and \( C \) the total number of two types of terminals in contention states. If we denote the number of UTs in Con\(_A\) and Con\(_B\) with \( c_A \) and \( c_B \), respectively, then \( C = c_A + c_B \). Thus the probability that a terminal leaves the Con\(_A\) state successfully with can be expressed as

\[ P_A = au_\lambda (1-\gamma) \] (8)

Similarly, the probability that a terminal in Con\(_B\) leaves the state successfully is

\[ P_B = au_\lambda (1-\gamma) \] (9)

where

\[ u_\lambda = u_\lambda (H,c_B) = (1-p)^{c_A+c_B} \] (10)

### 2 Performance Analysis

#### 2.1 Equilibrium Point Analysis

In Fig.2, the state vector of the system can be given by the following set of variables:

\[ \omega = \{ s_A, s_B, c_A, c_B, h, r \} \]

where \( s_A \) and \( s_B \) are the number of terminals in the Sil\(_A\), Sil\(_B\) state, respectively; \( c_A \) and \( c_B \) are the number of terminals in the Con\(_A\), Con\(_B\) state, respectively; \( h, r \) are the mean number of terminals in every state Hini and Resi, respectively, and

\[ R = Nr + Nh \quad h = \frac{n}{N} \]

Because the Markov progress of the system is ergodic, the equilibrium points of states exist. We can analyze the state’s stabilization performance of system with the equilibrium point analysis (EPA) method. In following analysis, we use the small letter to denote the equilibrium number of terminals in the stabilization states. The equilibrium value of state variables is real nonnegative numbers that can be derived by equating the inflow and outflow for each possible sate in the Markov chain shown in Fig.2. Then we have

\[ r\gamma_f \varphi + c_A \gamma = s_A \sigma_1 \quad \text{for Sil}_A \] (12)

\[ c_A au_\lambda + c_A \gamma = s_A \sigma_1 \quad \text{for Con}_A \] (13)

\[ r\gamma_f (1-\varphi) + c_B \gamma + h\gamma_f = s_B \sigma_2 \quad \text{for Sil}_B \] (14)

\[ c_B au_\lambda + c_B \gamma = s_B \sigma_2 \quad \text{for Con}_B \] (15)

\[ r(1-\gamma_f) + (1-\gamma_f)h = r \quad \text{for Res}_{N-1} \] (16)

If the total number of terminals within a satellite’s coverage area is \( M \), then

\[ s_A + s_B + c_A + c_B + Nr + Nh = M \] (17)

With Eq.(11), we can also describe Eqs.(6), (7) and (10) as

\[ a = (1-r-h)p = a(r,h) \] (18)

\[ u_A = (1-p)^{c_A+c_B} = u_A(c_A,c_B,h) \] (19)

\[ u_B = (1-p)^{c_A+c_B} = u_B(c_B,h) \] (20)

Eqs.(12) to (17) form a system of six equations in the six unknown equilibrium state variable \( s_A \), \( s_B \), \( c_A \), \( c_B \), \( r \) and \( h \). They can be simplified to three independent equations by applying Eqs.(18) to (20):

\[ c_A a(h)u_A(c_A,c_B,h) = (1-\gamma_f)\varphi h \] (21)

\[ c_B a(h)u_B(c_B,h) = (1-\gamma_f)(1-\varphi)h + \gamma_f h \] (22)

\[ \frac{(1-\gamma_f)\varphi h + c_A \gamma}{\sigma_1} + \frac{(1-\gamma_f)(1-\varphi)h + \varphi h + c_B \varphi}{\sigma_2} = \frac{Nh}{\gamma_f} \] (23)

There are only three unknown variables in above three equations. They can be numerically solved by the Gauss-Newton recursive method. Variable \( s_A \) and \( s_B \) can then be resolved respectively by substitute \( c_A \), \( c_B \) and \( h \) into Eqs.(12) and (14).

#### 2.2 Packet Dropping Probability

We consider here the packet dropping probability as the one which a call marked with PN\(_1\) code drops with during its calling process. This situation emerges mainly when the user terminals having woken from the silent gap in a progress waits for an available time slot too long. The terminal will drop all packets waiting longer than \( D \) time slots for reservation. Because we only consider the PN\(_1\) terminals, then the packet dropping probability under stable state can be expressed according to Ref.[2] as follows

\[ P_{\text{drop}} = \frac{\gamma_f (1-\varphi)v^\omega}{1-(1-\gamma_f)(1-\varphi)v^\omega} \] (24)

where \( v \) is the probability that a user terminal remains
in the ConB state at the end of a slot:

\[ v = 1 - R_n = 1 - (1 - r) p (1 - p)^{(x + 2/n - 1)(1 - \gamma)} \]  

(25)

3 Numerical Results

To test our scheme’s performance, we have computed the packet drop probability in the case of different amount of user terminals, and performed relevant simulations. In the simulations, we compared the packet drop probability and the system packet throughput rate of our scheme to the PRMA-HS protocol.

The system packet throughput rate is defined as the probability that a slot is reserved, by either a UT in a Res state, or a UT in a Hin state or a UT in a Res state, thus it can be described as

\[ \eta = E \left( \frac{\text{total slots reserved}}{N} \right) = r + h \]  

(26)

The parameters for the system simulation are as follows

Data rate of voice packet \( R_s \): 32 k/bs;
Frame period \( T_f \): 20 ms;
Slots per frame \( N \): 20;
Speech delay threshold for PN0 terminal: 200 ms;
Speech delay threshold for PN1 terminal: 32 ms;
Ratio of propagation delay to frame period \( n \): 3;
Probability of transmitting for user terminal \( p \): 0.3;
Traffic intensity \( \rho = \lambda / \mu \): 1.0;
Mean talkspurt period of a call: 1.0 s;
Mean silent gap of a call: 1.4 s;
The number of user terminals in a sat’s service area: variable.

The results of the two protocols, including the theoretic result of the enhanced PRMA-HS scheme, and simulation results. It is evident that the enhanced PRMA-HS has a lower packet loss probability than the PRMA-HS protocol when the system has a large amount of user terminals.

Fig. 4 shows that in the case of light payload the throughput of PRMA-HS system is slightly higher than one of the enhanced scheme; when the amount of user terminals grows large, the throughput of PRMA-HS lower down quickly, in the meantime the enhanced scheme system declines relatively slowly. These results reveal that the enhanced PRMA-HS system’s performance is more stable than the original PRMA-HS system.

4 Conclusions

In this paper, we first analyze a packet reservation multiple access protocol suitable for low earth orbit satellite communication PRMA-HS. The results of analysis show that the protocol’s performance degrades in the system with large amount user terminals. An enhanced scheme for the protocol is then proposed to control the performance decline. We give the analysis model and carry out a detail analysis for the scheme’s performance. The results of analysis and simulation show that in the case of heavy payload the probability of packet loss of the enhanced scheme is lower than the original protocol, and the throughput of the scheme is higher than original one. Thus the performance of the enhanced PRMA-HS protocol is more stable than the PRMA-HS in system with large amount user terminals.
References


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