Multiple Access in Broadband Satellite Networks

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***Abstract*— This paper proposes a multiple access algorithm for broadband satellite communication networks. The access channel is the slotted Aloha contention channel. The performance of the algorithm is analyzed considering user terminal time uncertainty, power uncertainty, minimizing co-channel interference as well as non-perfect feedback information from the central receiver. It is shown that reliable access can be achieved with a reasonably small delay by employing the proposed algorithm.**

I. Introduction

Recently several ambitious broadband satellite networks are developed to provide integrated media services at hundreds of megabits per second in North America. Most of these programs have planned to provide broadband communication services to other regions in the world. In North America, each broadband satellite network is designed to provide services to dozens of millions of users. These networks employ IP based packet switching to support bandwidth on demand services. In these networks, each user terminal has to access the network control center before it is allowed to use the network. This requires each user terminal to achieve time synchronization and successful power adjustment to close the link, while trying to access the network and perform registration. All of these requirements have to be satisfied considering the large user population, network security requirements, co-channel interference requirements, the non-negligible time uncertainty and power uncertainty in user terminals [1].

This paper proposes a practical algorithm for user terminals in broadband satellite networks to achieve time synchronization, power adjustment, and successful access to the network.

II. System Model and Access Algorithm

In a broadband satellite network, all of the user terminals within the same cell share a common slotted Aloha channel as the access channel. The access algorithm has to handle the access failures caused by collisions in access processes for a large user population. We assume that the length of each time slot is $T_f = \frac{L}{R_s}$, where L is the length of the access packet in symbols and R_s is the data rate in symbols per second. It is also assumed that all information needed for access is contained in a single packet. The access packet is encoded using block codes. At the beginning of each time slot, there is a time window $[-W, W]$ to take care of the arrival timing uncertainty of the access packet to some degree.

Each user terminal needs to have its location determined by some means before the access process is started. Assume the position determination error for a user terminal has a Gaussian distribution with zero mean and a standard deviation of σ_d kilometers along the path from the user terminal to the central receiver. Then, the initial timing error of the user terminal caused by this position error can be represented by a Gaussian random variable with zero mean and standard deviation of $\sigma_t = \frac{\sigma_d}{3\times10^5}$ second.

On the basis of the user terminal location, the location of the central receiver, the antenna receiving-beam roll-off of the central receiver, and antenna gain of the user terminal, the user terminal in the access process can compute its minimum required power P_T for link closure. The initial transmission power of the user terminal is certainly no less than the minimum power P_{min} of the terminal. Each user terminal has a maximum rated power P_{max}. In order not to interfere with the other co-channel users in the multiple frequency reused networks, there is a maximum allowable power P_A for each terminal to use at a given location. Here, $P_A \leq P_{max}$. Usually the value of P_A should not exceed 3 dB more than P_T. This is due to the fact that higher power than P_T would result into unacceptable interference into other carriers.

The uncertainty of the received power for the access packet from a user terminal can be caused by its location error, power setting error in the user terminal, temperature variation, antenna gain variation, power variation over the broad bandwidth employed in the systems, and the gain variation over temperature in the central receiver. To combat the large uncertainty of the received power at the central receiver from each user terminal, it is desired to adjust the transmission power in the access stage so that each terminal will have enough power to close its link while not to have too much power to interfere with transmissions from other users.

An access packet sent from a user terminal can be demodulated by the central receiver only when all of the following conditions are satisfied: (a) The arrival time of the received packet is in the window $[-W, W]$ relative to the beginning of the time slot; (b) The power of the user terminal has to be no less than the threshold power level P_T with 0 dB bias; (c) There are possibly transmissions from other user terminals in the same slot, but with much less power and still permitting successful packet demodulation. This includes the special case when there is no other user terminal transmitting in the same slot. Assume the central receiver can always demodulate access packet correctly, if there is only one packet appears in a slot of the slotted Aloha channel and the packet

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satisfies all of the above three conditions.

The central receiver demodulates and processes access packets and other uplink transmissions. It will measure the carrier-to-noise power ratio $\frac{C}{N}$ for each time slot, compare the received burst timing with respect to the reference slot timing, and also flag the block decoder failure. The feedback $f_b \in \{\text{Success,Failure}\}$ will be sent back to all user terminals in the same cell via cell casting. The feedback element f_b as "Success" means a packet is successfully received by the central receiver. For network security reasons, the feedback message can not contain the identification number of the user terminal. The block decoder failure indicator can be assumed error free. The block decoder failure can be caused by insufficient carrier-to-noise power ratio in the desired access packet, too much co-channel interference from other co-channel users, or collision with other packets during uplink transmission. The block decoder success may not mean the desired transmission has been successfully received either, since successful reception of an undesired interfering packet will result into a "Success" indication by the central receiver as well.

Assume that the user terminal initial transmission power will be low enough not to cause unacceptable interference to other co-channel carriers. There are five possible regions for the vector $\underline{X} = (P_i^j, t_i^j)$, where P_i^j is the transmission power of the jth user terminal in the ith trial and t_i^j is the corresponding timing. In the region $R0$, $\underline{X} \in \{(P_i^j, t_i^j) | P_T \leq P_i^j \leq P_A, -W \leq t_i^j \leq W\}$; In the region $R1$, $\underline{X} \in \{(P_i^j, t_i^j) | P_{min} \leq P_i^j < P_T, -W_1 \leq t_i^j \leq W_1\}$; In the region $R2$, $\underline{X} \in \{(P_i^j, t_i^j) | P_T \leq P_i^j \leq P_A, -W_1 \leq t_i^j < W\}$; In the region $R3$, $\underline{X} \in \{(P_i^j, t_i^j) | P_T \leq P_i^j \leq P_A, W < t_i^j \leq W_1\}$. In the region $R4$, $\underline{X} \in \{(P_i^j, t_i^j) | P_A < P_i^j \leq P_{max}, -W_1 \leq t_i^j \leq W_1\}$.

The power and timing of a user terminal must be in the region $R0$ or in the region $R4$ with $t_i^j \in [-W, W]$ to receive a possible "Success" feedback for the block decoder. Because the feedback does not contain the user identification number of the sender, the user terminal must reliably determine whether the feedback information is for itself or not on the basis of the feedback information $[\frac{C}{N}, f_T, f_b]$. To enhance the probability of successful access or to minimize delay in the access process for systems having long propagation delays, a user terminal may send $M > 1$ identical access packets before making a decision on whether the user terminal has succeeded in the access process. The user access process can be regarded as completed once the user terminal finds with high confidence that its access packet is successfully received by the central receiver, which implies that both of the following necessary conditions are satisfied: (a) The packet arrival time is in the window $[-W, W]$; (c) The up-link is closed, i.e., the transmission power is not less than the threshold power P_T.

In the region $R1$, the central receiver cannot successfully demodulate access packets from user terminals due to insufficient power. Thus, any user terminal transmitting in the region $R1$ will only generate interference to the transmissions of other user terminals. In addition, it is highly desirable to quickly achieve timing synchronization. The dwell time in this region must be minimized due to the long round-trip delay for each packet. In the region $R2$ or $R3$, the user terminal has enough power but the wrong timing will result in interference to other co-channel carriers in the network and will also create large interference to access packets from other user terminals and may render their transmission unsuccessful. In the region $R4$, the user terminal has too much power causing unacceptable interference.

For such systems, the following access algorithm can be employed by each user terminal to achieve successful access:

```
t = t_0;
P = P_0;
REGISTRATION = 0;
i = 0;
j = 0;
while (REGISTRATION == 0) {
        F = 0;
        sendpacket(t, P);
        F = feedback( );
        if (F == 1) {
                SUCCESS = 1;
                for (k = 1; k < M; k = k + 1) {
                sendpacket(t, P);
                F = feedback( );
                SUCCESS = SUCCESS AND F;
                randomdelay(L);
                }
                if (SUCCESS == 1) {
                        triggerULPC(t,p);
                        REGISTRATION = 1;
                }
        }
        else {
                if (i == 0) l = 0;
                if (i == (2J + 1)) {
                        i = 0;
                        l = 0;
                }
                else if ((i mod 2) ==1) l = (i+1)/2;
                else l = -i/2;
                t = t_0 + l × dT;
                i = i + 1;
                if (j < S) {
                        j = j + 1;
                        p = p + dP;
                }
        }
        randomdelay(L);
}
```

III. Delay

The initial transmission power P_1^j of a user terminal is a random variable. If $P_1^j > P_T$, i.e., the user terminal has enough power to close the link, then the user terminal needs to handle only its timing uncertainty. If $P_1^j < P_T$, the user terminal has to increase its power by $\left\lceil \frac{P_T - P_1^j}{\Delta P} \right\rceil$ steps to have enough power to close the link, where ΔP is the step size of power increment.

Let T_0 be the slot time, and the average waiting time be K slots between the time a failure feedback is received and the time to resend the packet. Before having enough power to close the link, the average time for a user terminal to finish a full search in the time uncertain interval is

$$D_1 = (2J + 1)(T_0 + \tau) + 2JKT_0 \tag{1}$$

where $(2J + 1)$ is the number of time search steps and τ is the round trip delay.

Denote the average time as D_0 to complete access for a user terminal having enough power to close the link, i.e., $P_1^j \geq P_T$. The time to complete access when averaged over initial transmission power is

$$D = \int_{P_{min}}^{P_T} \left\lceil \frac{P_T - p}{\Delta P} \right\rceil D_1 f_p(p)dp + D_0 \tag{2}$$

where P_{min} is the minimum initial transmission power of a user terminal, P_T is the threshold power to close the link and P_A is the maximum allowable transmission power. This average time D is called the *delay* in the access stage and can be rewritten as

$$D = D_1 \int_{P_{min}}^{P_T} \left\lceil \frac{P_T - p}{\Delta P} \right\rceil f_p(p)dp + D_0. \tag{3}$$

The integral in (3) is the average number of power increment steps needed to close the link in the access process, i.e.,

$$N_p = \int_{P_{min}}^{P_T} \left\lceil \frac{P_T - p}{\Delta P} \right\rceil f_p(p)dp. \tag{4}$$

Substituting (1) into (3), we have

$$D = [(2J+1)(T_0+\tau)+2JKT_0] \int_{P_{min}}^{P_T} \left\lceil \frac{P_T - p}{\Delta P} \right\rceil f_p(p)dp+D_0. \tag{5}$$

Consider the situation where a user terminal transmits at a power level high enough to be successfully demodulated by the central receiver when there is no more than one user terminal transmitting in a time slot. When the terminal transmits its first access packet, its packet arrival timing error t_0 relative to the closest slot boundary at the central receiver can be in one of the following three possible states: S_0 = packet timing error inside the time synchronized window $I_0 = [-W, W]$; S_1 = packet timing error satisfying $W < |t_0| \leq W_1$; S_2 = packet timing error satisfying $|t_0| > W_1$.

The parameter W_1 is the maximum value of time uncertainty to be handled by the access algorithm. By choosing W_1 properly, the probability for a user terminal to be in the state S_2 can be negligibly small. Therefore, we can focus on the state S_0 and the state S_1 and ignore the sate S_2 in finding the delay in the access process.

Following the proposed algorithm, assume a terminal turns its power on in the slot $(k - 1)$ and starts its access process in the state S_0 at the slot k with enough power to close the link. If the user terminal receives a failure feedback for its access packet, it has to resend the packet after a random delay. Assume the traffic in the slotted Aloha channel for access has a Poisson distribution with arrival rate $G < e^{-1}$. Let P_s be the probability of successful transmission for each packet. Let E_n be the event that a packet needs to be transmitted for n times until it is successfully received once. The probability of the event E_n has a geometric distribution, i.e.,

$$p_n = \mathrm{P}(\mathrm{E}_n) = (1 - P_s)^{n-1} P_s. \tag{6}$$

The time corresponding to the event E_n is

$$t_n = (2J + 1)(T_0 + \tau + KT_0)(n - 1) + T_0 + \tau. \tag{7}$$

The average delay to have the first packet successfully received is

$$D_{s0} = (2J+1)(T_0+\tau+KT_0)/P_s - 2J(T_0+\tau+KT_0) - KT_0. \tag{8}$$

To reduce the probability of false access, our algorithm requires confirmation packets to be sent until $(M - 1)$ confirmation packets have success feedback. The average delay to have $(M - 1)$ confirmation packets successfully received is

$$D_c = (M - 1)(T_0 + \tau + KT_0)/P_s. \tag{9}$$

The average delay to complete the access process for a user terminal starting in the state S_0 is $D_{r0} = D_{s0} + D_c$ which can be rewritten as

$$D_{r0} = \frac{2J + M}{P_s}(T_0 + \tau + KT_0) - 2J(T_0 + \tau + KT_0) - KT_0. \tag{10}$$

Consider the case when a user terminal starts the access process in the state S_1, i.e., the user terminal timing satisfies $W < |t_0| \leq W_1$. The timing of the user terminal is in any of the following intervals:

$$I_j = (2jW - W, 2jW + W], 1 \leq j \leq J$$

$$I_{-j} = [-2jW - W, -2jW + W), 1 \leq j \leq J$$

where $J = \left\lceil \frac{W_1 - W}{dT} \right\rceil$. Employing the proposed access algorithm, a user terminal having $t_0 \in I_j$ needs to adjust its timing for

$$N_t(j) = 2j \qquad 1 \leq j \leq J \tag{11}$$

times before pulling its timing into the $I_0 = [-W, W]$ time synchronization window. For a user terminal having $t_0 \in I_{-j}$, the corresponding number is

$$N_t(-j) = 2j - 1 \qquad 1 \leq j \leq J. \tag{12}$$

It is understood that adjusting the user terminal timing is driven by the event that a Failure feedback is received for the access packet. After the user terminal pulls its timing into the time synchronization window I_0, the delay to register the user terminal successfully is D_{r0}. Therefore, for user terminals with the initial timing $t_0 \in I_j$, the delay is

$$D(j) = N_t(j)(T_0 + \tau) + N_t(j)KT_0 + D_{r0} \tag{13}$$

which can be rewritten as

$$D(j) = 2j(T_0 + \tau + KT_0) + D_{r0}. \quad (14)$$

Similarly, for user terminals with the initial timing $t_0 \in I_{-j}$, the delay is

$$D(-j) = (2j-1)(T_0 + \tau + KT_0) + D_{r0}. \quad (15)$$

Denote the probability density function of the user terminal initial timing as $f_t(t)$. We assume this function is symmetric, i.e., $f_t(-t) = f_t(t)$. After having enough power to close the link, the delay to complete the access process when averaged over the initial timing is

$$D_0 = D_{r0} + \sum_{j=1}^{J}(N_t(j) + N_t(-j))(T_0 + \tau + KT_0)p(j) \quad (16)$$

where

$$p(j) = \int_{2jW-W}^{2jW+W} f_t(t)dt. \quad (17)$$

Substituting (10), (11) and (12) into (16), we have

$$\begin{aligned} D_0 &= \frac{2J+M}{P_s}(T_0 + \tau + KT_0) - 2J(T_0 + \tau + KT_0) \\ &\quad + \sum_{j=1}^{J}(4j-1)(T_0 + \tau + KT_0)\int_{2jW-W}^{2jW+W} f_t(t)dt \\ &\quad - KT_0. \end{aligned}$$

Here D_0 is the delay to complete the access process after a user terminal has enough power to close the link.

Substituting D_0 into (5), we have the average delay as

$$\begin{aligned} D &= [(2J+1)(T_0+\tau) + 2JKT_0]\int_{P_{min}}^{P_T}\left\lceil \frac{P_T - p}{\Delta P}\right\rceil f_p(p)dp \\ &\quad + \frac{2J+M}{P_s}(T_0 + \tau + KT_0) - 2J(T_0 + \tau + KT_0) \\ &\quad + (T_0 + \tau + KT_0)\sum_{j=1}^{J}(4j-1)\int_{2jW-W}^{2jW+W} f_t(t)dt \\ &\quad - KT_0. \end{aligned}$$

It can be seen that the average delay of the user terminal access process is determined by the initial timing uncertainty, the initial power uncertainty, the traffic of access packets and system parameters of the network.

IV. Probability of False Access

During the user access processes in a broadband wireless network, it can happen that two different user terminals access the system in the same time slot. If the signal power level of one user terminal is much higher than that of the other user terminal, it can happen that the access packet of a higher power can still be demodulated successfully. The central receiver will send a Success feedback to both user terminals. For network security reasons, the feedback from the central receiver does not contain the identification information of the sender. It can happen that the Success feedback for the user terminal of higher power will make the user terminal of lower power to think falsely its access packet were received successfully. This event is called *override*. When override happens and no further steps are taken to handle the user access process, the user terminal of lower power level may mistakenly quit from the access stage, although it has not succeeded in its access process yet.

Assume the ith user terminal and the jth user terminal use the same slot to send access packets. Let $Y = \frac{C_T}{N}$ be the threshold carrier-to-noise power ratio for a user terminal to close the link and $C_a = \eta C_T$ be the maximum allowable carrier power. The following is the sufficient and necessary conditions for the signal of the ith user terminal to override the signal of the jth user terminal:

A. $C_T \leq C_i \leq C_a = \eta C_T, \eta > 1$;
B. $\frac{C_i}{N + C_j} \geq Y$;

where C_i is the carrier power of the ith user terminal. Usually, $Y > 1$. The Condition B implies $C_i > C_j$. Condition B also says C_i increases linearly with C_j.

Let $C_i = \alpha C_j$. To satisfy the Condition B, we have

$$\alpha \geq Y[1 + (\frac{C_j}{N})^{-1}]. \quad (18)$$

This inequality implies the following results.

When the carrier power of the jth user terminal is much larger than the threshold carrier power, i.e., $C_j >> C_T$, or $\frac{C_j}{N} >> Y$, it is sufficient for the signal of the ith user terminal to override the signal of the jth ST, if $C_i \geq YC_j$.

Let $C_j = \beta C_T$. To satisfy the Condition A, we have $C_i = \alpha\beta C_T \leq \eta C_T$, i.e.,

$$\alpha\beta \leq \eta. \quad (19)$$

The Condition B requires $\frac{\alpha\beta C_T}{N + \beta C_T} \geq \frac{C_T}{N}$, i.e.,

$$1 + \beta Y \leq \alpha\beta. \quad (20)$$

Substituting (19) into (20), we have

$$\beta \leq \beta_0 = \frac{\eta - 1}{Y}. \quad (21)$$

Therefore, a signal of carrier power higher than $\beta_0 C_T = \frac{\eta-1}{Y}C_T$ can not be overridden by another signal whose power is bounded by $C_a = \eta C_T$. For example, if $\eta = Y = 2$, then $\beta_0 = 0.5$.

If two user terminals both have enough power to close their links, i.e., $C_i \geq C_T$ and $C_j \geq C_T$, a necessary condition for the signal of one user terminal to override the signal of the other user terminal is $\eta \geq Y + 1$. This result can be obtained by noticing

$$\frac{C_T}{N} \leq \frac{C_i}{N + C_j} \leq \frac{\eta C_T / N}{1 + C_T/N}.$$

In a typical broadband wireless network, $Y \geq 2$, which requires $\eta \geq 3$. If the maximum allowable power of a user terminal is not higher than 3 times of the threshold power, it will not happen that the signal of one user terminal overrides the signal of another user terminal, while both have enough power to close their links.

Consider that two user terminals access a system using the same slot. Assume the signal carrier power of either user terminal in dB scale has i.i.d. distributions with the probability density function $f_p(p)$. The probability for one signal to override the other is

$$P_{ow} = \int_{C_{min}/C_T}^{\beta_0} \int_{1+Yx}^{C_{max}/C_T} f_p(x) f_p(y) dx dy. \quad (22)$$

This probability can be bounded by

$$w_1 < P_{ow} < w_2 \quad (23)$$

where

$$w_1 = \int_{C_{min}/C_T}^{\beta_0} f_p(x) dx \int_{1+Y\beta_0}^{C_{max}/C_T} f_p(y) dy$$

and

$$w_2 = \int_{C_{min}/C_T}^{\beta_0} f_p(x) dx \int_{1+YC_{min}/C_T}^{C_{max}/C_T} f_p(y) dy.$$

Conditioned on more than two user terminals access the system using the same time slot, the probability for the signal of at least one user terminal to be overridden is less than P_{ow}. The necessary condition for the signal of at least one user terminal to be overridden conditioned on more than two user terminals access the system using the same slot is

$$\frac{C_i}{N + \sum_{j \neq i} C_j} \geq Y. \quad (24)$$

Without loss of generality, assume $C_i > C_j \geq C_k$, where $\{k | k \geq j+1\}$ is the index set of users collided with the ith user terminal and the jth user terminal in the same slot. The inequality (24) can be rewritten as

$$C_i \geq Y(N + C_j + \sum_{k \geq j+1} C_k). \quad (25)$$

Assuming the probability distribution of the power of each user terminal is i.i.d., we have

$$\Pr\{\frac{C_i}{N + C_j} \geq Y\} > \Pr\{\frac{C_i}{N + C_j + \sum_{k \geq j+1} C_k} \geq Y\}. \quad (26)$$

This means the probability for one signal to be overridden when more than two user terminals use the same slot is less than the probability for one signal to be overridden when there are only two user terminals using the same slot.

Let Z_1 be the event that the signal of at least one user terminal is overridden by signals of other user terminals accessing the system using the same slot. The probability of this event can be written as

$$\Pr\{Z_1\} = \sum_{X \geq 2} \Pr\{Z_1, X\} = \sum_{X \geq 2} \Pr\{Z_1 | X\} \Pr\{X\} \quad (27)$$

where X is the number of user terminals using the same slot, and $\Pr\{Z_1 | X = 2\} = P_{ow}$. From (26), we have

$$\Pr\{Z_1 | X > 2\} < \Pr\{Z_1 | X = 2\}. \quad (28)$$

Substituting (28) into (27), we have

$$\Pr\{Z_1\} < P_{ow} \sum_{X \geq 2} \Pr\{X\}. \quad (29)$$

Assume that the access packet arrival to each slot has a Poisson distribution. The probability for each slot to have more than one packets is

$$\sum_{X \geq 2} \Pr\{X\} = 1 - \Pr\{X = 0\} - \Pr\{X = 1\} \quad (30)$$

which can be rewritten as

$$\sum_{X \geq 2} \Pr\{X\} = 1 - e^{-G} - Ge^{-G} \quad (31)$$

where G is the access packet arrival rate. Substituting (23) and (31) into (29), we have

$$\Pr\{Z_1\} < g(G) \int_{C_{min}/C_T}^{\beta_0} f_p(x) dx \int_{1+YC_{min}/C_T}^{C_{max}/C_T} f_p(y) dy. \quad (32)$$

where $g(G) = 1 - e^{-G} - Ge^{-G}$.

Let

$$p_{ov} = g(G) \int_{C_{min}/C_T}^{\beta_0} f_p(x) dx \int_{1+YC_{min}/C_T}^{C_{max}/C_T} f_p(y) dy. \quad (33)$$

Define that the event of a successful access for each user terminal is that the user terminal has to send M identical access packets and receive M "Success" feedback messages. To make sure the probability of false user access is less than ϵ_f, which is usually given as a specification in a broadband wireless network, we can choose M as the smallest integer satisfying

$$M = \left\lceil \frac{\log \epsilon_f}{\log p_{ov}} \right\rceil. \quad (34)$$

This number M is the number of times the access packet should be sent by the user terminal. In [1], it is shown that for a real system with $\epsilon_f = 10^{-8}$, having $M = 2$ is enough.

V. Conclusion

A multiple access algorithm is proposed for broadband satellite networks. Delay and probability of false access are analyzed in the presence of time uncertainty, power uncertainty and binary feedback. It is shown that reliable access can be achieved within reasonable delay.

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