User Registration in Broadband Slotted Aloha Networks

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***Abstract*—This paper proposes an algorithm for user terminals in broadband slotted Aloha networks to jointly succeed in time synchronization, power adjustment, and registration to the network control center. The performance is analyzed considering nonnegligible initial time uncertainty, nonnegligible power uncertainty, and minimizing cochannel interference as well as binary feedback from the central receiver. User terminal initial power setting can be performed using the method developed in this paper to make sure the interference generated in the registration stage is negligible. The algorithm is sufficient to keep the false registration probability less than any number required by the network. It can help broadband slotted Aloha networks to significantly reduce system cost through employing a large number of inexpensive user terminals with nonnegligible time uncertainty and nonnegligible power uncertainty.**

***Index Terms*—Broadband slotted Aloha networks, false registration, power adjustment, time synchronization, user terminal registration.**

I. Introduction

RECENTLY, impressive programs have been announced to launch broadband wireless and satellite networks [1], [2]. These networks are designed to provide interactive multimedia and other services based on Internet protocols (IP) at hundreds of megabits per second in North America, Europe, and worldwide [1], [2]. In 1997, the Federal Communications Commission (FCC) awarded 13 licenses to build IP-based broadband satellite networks [1]. In 2000, satellite modems supporting up to 1.6 Gb/s in each channel using quaternary phase-shift keying (QPSK) was demonstrated for broadband satellite networks [3]. In 2002, ultra-broadband wireless systems supporting gigabit Ethernet at 1.25 Gb/s using binary phase-shift keying (BPSK) started service [4]. In Europe and Japan, the progress in developing broadband wireless and satellite networks is also exciting [1], [2]. After a few years of intensive research and development, it is clear that the technical challenges in broadband wireless and satellite networks are much harder than they were expected. One challenge is the user terminal registration in broadband slotted Aloha networks [6], [7].

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In North America, each broadband slotted Aloha network is designed to provide services to tens of millions of users [2]. Packet switching is employed to support bandwidth-on-demand services [1], [2], [5]–[7]. Each user terminal has to register with the network control center before it is allowed to use the network [6], [7]. The access channel is the broadband slotted Aloha contention channel [5]–[7]. The registration process requires each user terminal to achieve time synchronization and successful power adjustment to close the link. All of these requirements have to be satisfied, considering the large user population in each broadband network, network security requirements, cochannel interference (CCI) requirements, and the nonnegligible time uncertainty and power uncertainty in user terminals for broadband wireless and satellite transmissions [6], [7]. Registration algorithms must be designed considering the network layer, the medium-access sublayer, and the physical layer together.

Traditionally, problems in the physical layer, the medium-access sublayer, and the network layer are studied separately. Among topics related to user terminal registration in broadband wireless and satellite networks, multiple access is the only topic which is widely understood [8]–[10]. To focus on the network side of the multiple-access problem, time uncertainty and power uncertainty are ignored in the previous research [8]–[10]. Such treatment is suitable for low-data-rate networks where the timing error and power error can be ignored in the process of accessing the network.

In broadband wireless and satellite networks supporting data rate of around 1 Gb/s [2], [3], [6], [7], the timing uncertainty and power uncertainty of the initial transmissions from user terminals can be so large that they must be handled jointly while the user terminal is trying to access the network to achieve successful registration with the network control center [6], [7]. This problem is new and critical for broadband slotted Aloha networks supporting very high data rates [2], [3], [6], [7].

This paper proposes and analyzes a practical algorithm for user terminals in broadband slotted Aloha networks to jointly achieve successful time synchronization, power adjustment, and registration to the network control center.

II. System Model

In a broadband slotted Aloha network, all of the user terminals within the same service area share a common slotted Aloha channel for registration. The registration algorithm has to handle the access failures caused by collisions in the registration processes for a large population of users. It is assumed that all of the information needed for registration is contained in a single registration packet. The registration packet is encoded using block

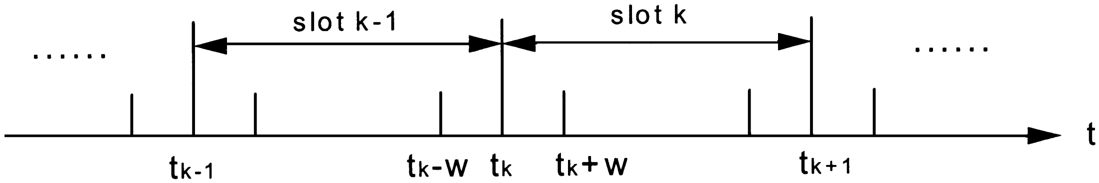

Fig. 1. Slot structure in a broadband slotted Aloha network. There is a detection window $[-W, W]$ centered at each slot boundary.

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 registration packet to some degree. Fig. 1 shows a typical slot structure of the slotted Aloha channel for user terminal registration.

In the new-generation broadband satellite networks employing on-board switching and on-board routing, each spot beam can cover hundreds of kilometers [1], [2]. The propagation delay can vary significantly from one user terminal location to another in the same spot beam, and from spot beam to spot beam [1], [6], [7]. Each user terminal needs to have its location determined by some means before the registration 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. The initial timing error of the user terminal caused by this position error is a Gaussian random variable with zero mean and standard deviation of $\sigma_t = (\sigma_d / 3 \times 10^5)$.

On the basis of the user terminal location, the location of the central receiver, the antenna receiving beam rolloff of the central receiver, and antenna gain of the user terminal, the user terminal under registration can compute its minimum required power P_T for link closure. The initial power of the user terminal is in $[P_{\min}, P_{\max}]$. In order not to interfere with the other cochannel 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.

The uncertainty of the received power for the initial transmission 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 desirable to adjust the transmission power in the registration stage so that each terminal will have enough power to close its link and not generate too much interference.

A registration packet sent from a user terminal in the registration process can be demodulated by the central receiver only when all of the following three conditions are satisfied: 1) the arrival time of the received packet is in the window $[-W, W]$ relative to the beginning of the time slot; 2) the power of the user terminal has to be no less than the threshold power level P_T with 0 dB bias; 3) 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.

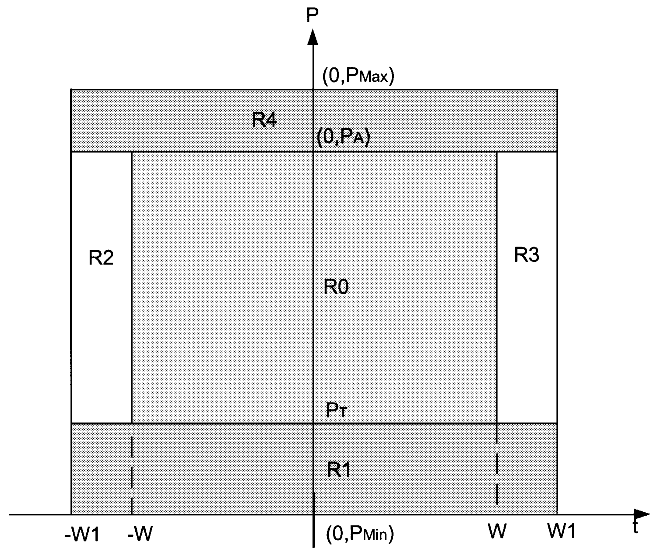

Fig. 2. Range of $\underline{X} = \left(P_i^j, t_i^j\right)$ of user terminal transmission power and timing in the registration process. In the region $R0$, $\underline{X} \in \left\{(P_i^j, t_i^j) | P_T \leq P_i^j \leq P_A, -W \leq t_i^j \leq W\right\}$. In the region $R1$, $\underline{X} \in \left\{(P_i^j, t_i^j) | P_{\min} \leq P_i^j < P_T, -W_1 \leq t_i^j \leq W_1\right\}$. In the region $R2$, $\underline{X} \in \left\{(P_i^j, t_i^j) | P_T \leq P_i^j \leq P_A, -W_1 \leq t_i^j < W\right\}$. In the region $R3$, $\underline{X} \in \left\{(P_i^j, t_i^j) | P_T \leq P_i^j \leq P_A, W < t_i^j \leq W_1\right\}$. In the region $R4$, $\underline{X} \in \left\{(P_i^j, t_i^j) | P_A < P_i^j \leq P_{\max}, -W_1 \leq t_i^j \leq W_1\right\}$.

The central receiver demodulates and processes all registration packets and other uplink transmissions. It sends the binary feedback $f_b \in \{\text{Success, Failure}\}$ to all user terminals in the same cell via cell casting. A cell can be regarded as a spot beam in broadband satellite networks [1], [2] or the physical region where user terminals share the same central receiver located on the Earth's surface [4]. The feedback element f_b of "Success" means a packet was successfully received by the central receiver. For network security reasons, the feedback message cannot 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 registration packet, too much CCI from other cochannel users, or collision with other packets during uplink transmission. Successful reception of an undesired interfering packet will result in 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 cochannel carriers. Fig. 2 shows the possible regions where the pair $\underline{X} = \left(P_i^j, t_i^j\right)$ is, 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. 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. The user terminal must reliably determine whether the feedback information is for itself or not on the basis of the binary feedback. The user registration process can be regarded as completed once the user terminal finds with high confidence that its registration packet is successfully received by the central receiver. Such a success means that both of the following necessary conditions are satisfied: 1) the packet arrival time is in the window $[-W, W]$; 2) the up-link is closed, i.e., the transmission power is not less than the threshold power P_T.

III. Time Synchronization and Power Adjustment

The timing error of the registration packet received at the central receiver can be much larger than the window centered at the boundary of two adjacent time slots. The timing error can be caused by either the position error or the inexpensive electronics of each user terminal [6], [7]. When the arrival time of a registration packet is outside the window centered at the slot boundary, the central receiver cannot demodulate it correctly and will give a "Failure" indication for the registration packet. The multiple-access algorithm has to make sure that a user terminal with initial timing error outside the window can pull its timing into the window within an acceptable time [6], [7].

The power uncertainty of user terminals in broadband slotted Aloha networks can be very large. The following aspects have to be considered to handle the power uncertainty: 1) the initial power setting level for each user terminal; 2) CCI; 3) average time to finish registration; 4) probability of registration failure caused by insufficient power. To minimize CCI, it is better for user terminals to start transmission at a low power level.

This section discusses how to achieve time synchronization, set initial transmission power, and adjust power during the registration process.

A. Time Synchronization

Time synchronization in the registration stage has to satisfy the requirement that the probability of registration failure caused by timing error must be less than a very small number ϵ_t. Let $f_t(t)$ be the probability density function (pdf) of the user terminal initial timing error. Usually, $f_t(t)$ is symmetric, i.e., $f_t(-t) = f_t(t)$. The time synchronization has to make sure that any user terminal having the initial timing error in the window $[-W_1, W_1]$ can pull its timing into the window $I_0 = [-W, W]$ in the registration process, where the parameter W_1 satisfies

$$\Pr\{|t| \geq W_1\} = 2\int_{W_1}^{\infty} f_t(t)dt < \epsilon_t. \tag{1}$$

Consider timing errors in the interval $(t_1 = W, t_2 = W + dt]$. Any user terminal having initial timing error in this interval has to adjust its timing at least once so that its timing will be in the window I_0, i.e., to be synchronized in time. Let the step size to adjust the timing of a user terminal be dT. To make sure that one step can pull any of the possible timing errors in $(t_1 = W, t_2 = W + dt]$ into the window I_0, we need $t_1 - dT \geq -W$ and $t_2 - dT \leq W$. Solving these two inequalities, we have $dt \leq dT \leq 2W$. This means that the maximum step size of time adjustment cannot be greater than the size of the time synchronization window, and the maximum length of the timing error interval which can be covered in each time adjustment step cannot be greater than the size of the time synchronization window. In practice, $2W$ is an integer multiple of the symbol time T_s. We choose the step size of time adjustment as $dT = 2W$. Thus, deducting dT from any timing error in the interval $(t_1 = W, t_2 = W + dt]$ can pull the timing error back to the time synchronization window I_0. Similarly, adding dT to any timing error in the interval $[-W - dT, -W)$ can achieve the same result.

For time synchronization, we quantize the timing-error interval into the following subintervals: $I_0 = [-W, W]$, $I_j = (W + (j-1)dT, W + jdT]$, $1 \leq j \leq J$, $I_{-j} = [-W - jdT, -W - (j-1)dT)$, $1 \leq j \leq J$, where

$$J = \left\lceil \frac{W_1 - W}{dT} \right\rceil \tag{2}$$

and W_1 satisfies (1). For timing error $t \in I_j$, $j > 0$, deducting jdT will reduce timing error and pull the timing into the time synchronization window I_0, i.e., $(t - jdT) \in [-W, W]$. For timing error $t \in I_{-j}$, $j > 0$, adding jdT will reduce timing error and pull the timing into the time synchronization window I_0, i.e., $(t + jdT) \in [-W, W]$.

Time synchronization can be achieved through a full search in the set $I = \cup_{j=-J}^{J} I_j$. The time uncertainty range $[-W_1, W_1]$ to be handled is a subset of I, i.e., $[-W_1, W_1] \subset I = \cup_{j=-J}^{J} I_j$. Let the initial timing error of the user terminal be $t_0 \in [-W_1, W_1]$. Then, $t_0 \in I$. The user terminal sends its first registration packet with the timing error t_0. Then it performs a full search in the set I in the following way.

```
Time Search Algorithm
F = 0;
K = 2J;
i = 0;
while ((F == 0) AND i <= K) {
 if (i == 0) l = 0;
 else if ((i mod 2) == 1)   l = (i + 1/2);
 else l = -i/2;
 t = t_0 + l × dT;
 sendpacket(t);
 F = feedback();
 i = i + 1;
}
```

The function $\mathrm{Sendpacket}(t)$ is for the user terminal to send a registration packet with the timing t. The function $\mathrm{feedback}()$ is for the user terminal to wait until it receives a feedback message from the central receiver. The value of the function $\mathrm{feedback}()$ is one, if the registration packet is successfully demodulated by the central receiver. Otherwise, its value is zero.

The search starts at the initial timing t_0 of the user terminal. For systems where the initial timing error of user terminals has a Gaussian distribution, the probability for $t_0 \in I_0$ is higher than the probability $t_0 \in I_j$, $j \neq 0$. The probability of $t_0 \in I_j$ or the probability of $t_0 \in I_{-j}$ is higher than the probability of $t_0 \in I_{j+1}$ or the probability of $t_0 \in I_{-(j+1)}$. To minimize search time, the search checks the interval I_j and the interval I_{-j} before moving to the interval I_{j+1} and $I_{-(j+1)}$.

B. Power Setting and Adjustment

Let the power that should be received by the central receiver from a user terminal be P_0 when there is no power error. The received power, in decibels, at the central receiver can be written as $P = P_0 + e_1 + e_2 + e_3$, where e_1 is the effective isotropic radiated power (EIRP) variation of the user terminal, which includes power setability, temperature variation, antenna gain variation, a unit-to-unit variation across the several hundred megaherts bandwidth and over all units for the specified temperature range, e_2 is the gain over temperature variation of the central receiver, and e_3 is the power error caused by location error. Usually, the random variable e_1 has a uniform distribution in $[-A, A]$, where A is several decibels. The random variable e_2 is uniformly distributed in $[-B, B]$, where B is a few decibels. The random variable e_3 has a Gaussian distribution with zero mean and the standard deviation as σ_p.

The total power error $e = e_1 + e_2 + e_3$ has zero mean. Its pdf is the convolution of the pdfs of e_1, e_2, and e_3 [15]. The received power at the central receiver has mean P_0 and the pdf

$$\begin{aligned} f_p(p) = & \frac{p - P_0 + A + B}{4AB} \\ & \times \left(Q\left(\frac{p - P_0 + A - B}{\sigma_p}\right) - Q\left(\frac{p - P_0 + A + B}{\sigma_p}\right)\right) \\ & + \frac{1}{2A}\left(Q\left(\frac{p - P_0 - A + B}{\sigma_p}\right) - Q\left(\frac{p - P_0 + A - B}{\sigma_p}\right)\right) \\ & - \frac{p - P_0 - A - B}{4AB} \\ & \times \left(Q\left(\frac{p - P_0 - A - B}{\sigma_p}\right)\right. \\ & \left. - Q\left(\frac{p - P_0 - A + B}{\sigma_p}\right)\right) + \frac{\sigma_p}{4AB\sqrt{2\pi}} \\ & \times \left(\exp\left(-\frac{(p - P_0 + A + B)^2}{2\sigma_p^2}\right)\right. \\ & \left. - \exp\left(-\frac{(p - P_0 + A - B)^2}{2\sigma_p^2}\right)\right) + \frac{\sigma_p}{4AB\sqrt{2\pi}} \\ & \times \left(\exp\left(-\frac{(p - P_0 - A - B)^2}{2\sigma_p^2}\right)\right. \\ & \left. - \exp\left(-\frac{(p - P_0 - A + B)^2}{2\sigma_p^2}\right)\right) \end{aligned} \quad (3)$$

where $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-x} dx$.

In real networks, it is required that the probability that the received power from an individual user terminal is greater than the maximum allowable power P_A, is less than ϵ_p. The initial power of the user terminal should be set to the maximum equivalent power P_0 which satisfies

$$p_I(P_0, A, B, \sigma_p) = \int_{P_A}^{\infty} f_p(p) dp \leq \epsilon_p. \quad (4)$$

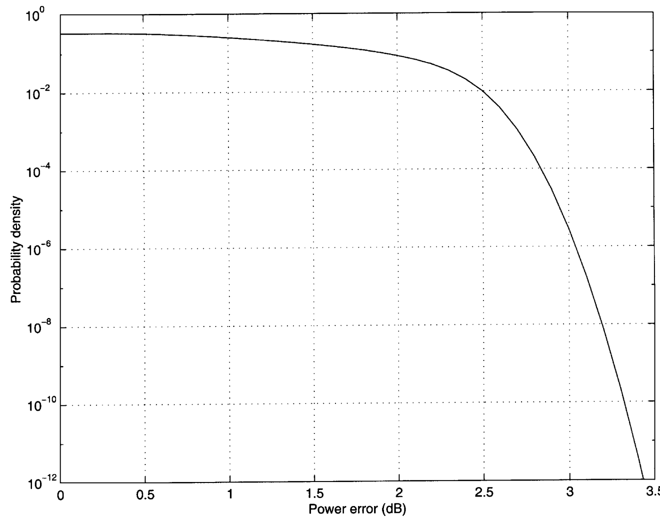

Fig. 3. PDF of the example system with $(A, B, \sigma_p) = (1.5, 1.0, 0.2)$ dB.

TABLE I
PROBABILITY OF THE USER TERMINAL INITIAL POWER ERROR e TO BE GREATER THAN A GIVEN VALUE x IN AN EXAMPLE SYSTEM WITH $(A, B, \sigma_p) = (1.5, 1.0, 0.2)$ IN DECIBELS

x (dB)	3.0	3.1	3.2	3.3	3.4
$\Pr\{e > x\}$	3.0E-7	1.9E-8	7.8E-10	2.2E-11	4.0E-13

Fig. 3 shows the pdf of the power error for an example system where $A = 1.5$ dB, $B = 1.0$ dB, and $\sigma_p = 0.2$ dB. It can be seen that the pdf drops quickly in the region $e \geq A + B$. Table I shows the probability for the initial power error e to be greater than x, i.e., $\Pr\{e > x\}$. To have $p_I(P_0, A = 1.5, B = 1.0, \sigma_p = 0.2) < 10^{-9}$, we can choose $P_0 = -0.2$ dB, relative to the threshold power P_T.

To satisfy (4), the initial transmission power of the user terminal is set to a value $P_0 < P_T$. So with probability greater than 0.5, the received power at the central receiver for the first registration packet from an individual user terminal is less than the threshold power P_T. This will lead to a failure feedback from the central receiver for the first registration packet. After receiving the failure feedback, the user terminal can increase the power level and resend the registration packet. Let the step size of the power increment be ΔP. The maximum number of allowable power increment steps is $S = \lfloor (P_A - P_0)/\Delta P \rfloor$.

IV. ACCESS ALGORITHM

All user terminals in the same cell share one common slotted Aloha access channel for registration. Collisions may occur as in the traditional slotted Aloha systems [9], [10]. An algorithm has to be developed for each user terminal to access the channel, combat the time uncertainty and power uncertainty, and achieve successful access to the network control center and successful registration. The algorithm has to specify when the newly arrived registration request will be transmitted, how to retransmit after access failure occurs [11]–[14], and how to adjust the timing and transmission power in case of access failure [6], [7].

All registration packets that arrive for the first time from user terminals in the ith slot will be sent to the central receiver in the

$(i+1)$th slot. If a user terminal receives a "Failure" feedback for a registration packet, the user terminal has to retransmit the packet. The failure can be caused by collision, or wrong timing of the packet, or insufficient power. However, a user terminal has no way to figure out which one is the exact reason. Therefore, the user terminal has to use one algorithm to handle all of the possibilities for collision, wrong timing, and insufficient power.

In the registration process, the search in the time domain and the power adjustment have to be performed jointly. To minimize interference, a full search in the time domain is performed before the power is increased by one step. After having finished the full search in the time domain, if this user terminal still has not received a "Success" feedback for any of the packets sent, it increases its power by one step and resends the registration packet. To avoid time drifting, the user terminal has to reset its timing to the original timing before resending the registration packet at an increased power level.

For the traditional slotted Aloha channel, many algorithms have been proposed for user terminals to retransmit their packets to combat collisions [9]–[14]. These algorithms assume both the timing of the packets and the power are perfect. When large time uncertainty and large power uncertainty are present, they are too sophisticated to be analyzed. To understand the effects of large time uncertainty and large power uncertainty to multiple access, we employ the random delay and retransmission scheme [9]. More precisely, after receiving a "Failure" feedback, a user terminal waits for a number of D slots and resends its registration packet. Here, D is a random number uniformly distributed in $[1, L]$. The number L is usually around 10 [9].

Assume a user terminal receives a "Success" feedback for its registration packet. Based on the one-bit success feedback for only one time slot, the user terminal cannot decide with high confidence which of the following two hypotheses is true:

1) H_0: the registration packet itself was successfully demodulated;
2) H_1: the registration packet from another user terminal sent in the same time slot with a much higher power was demodulated successfully.

The user terminal may like to send a few more packets using the same timing and power as those for the first registration packet which has obtained a "Success" feedback. A registration packet sent after receiving a "Success" feedback to increase the successful registration confidence is called a confirmation packet.

The following is the algorithm for each user terminal to achieve successful registration with high confidence through combating time uncertainty, power uncertainty, and collision.

```
User Terminal Registration Algorithm
t = t0;
 P = P0;
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 + 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 = t0 + l × dT;
  i = i + 1;
  if (j < S) {
   j = j + 1;
   p = p + dP;
  }
 }
 randomdelay(L);
}
```

The function $\mathrm{sendpacket}(t, P)$ is for the user terminal to send a registration packet using the timing t and the power P. The function $\mathrm{randomdelay}(L)$ is for the user terminal to have a random delay uniformly distributed in the interval $[1, L]$ in packets. The function $\mathrm{triggerULPC}(t, p)$ is for the user terminal to trigger its normal state of communications. Calling $\mathrm{triggerULPC}(t, p)$ means the user terminal thinks it has succeeded in the registration process and can start to transmit and receive packets using the correct timing and correct power level.

V. Delay

User-registration algorithms have to make sure that each user terminal can complete the registration process with the network control center in a reasonably short time [6], [7]. The random delay for retransmission in the proposed access algorithm is practical and widely employed in communications networks [9], [10]. However, it is difficult to analyze the delay [10]. This section analyzes the effect of user terminal power uncertainty and time uncertainty to the delay. The delay performance of the proposed algorithm is simulated for a real broadband satellite network [7].

A. Effect of Power Uncertainty

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 $\lceil (P_T - P_1^j)/\Delta P \rceil$ steps to have enough power to close the link, where ΔP is the step size of the 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 a registration 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

$$D_1 = (2J+1)(T_0 + \tau) + 2JKT_0 \tag{5}$$

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 registration for a user terminal having enough power to close the link, i.e., $P_1^j \geq P_T$. The time to complete registration when averaged over initial transmission power is $D = \int_{P_{\min}}^{P_T} \lceil (P_T - p)/\Delta P \rceil D_1 f_p(p) dp + D_0$. This average time D is called the *delay* in the user terminal registration process, which can be written as

$$D = D_1 \int_{P_{\min}}^{P_T} \left\lceil \frac{P_T - p}{\Delta P} \right\rceil f_p(p) dp + D_0. \tag{6}$$

The integral in (6) is the average number of power increment steps needed to close the link in the registration process, i.e., $N_p = \int_{P_{\min}}^{P_T} \lceil (P_T - p)/\Delta P \rceil f_p(p) dp$. Substituting (5) into (6), we have

$$D = [(2J+1)(T_0+\tau) + 2JKT_0] \times \int_{P_{\min}}^{P_T} \left\lceil \frac{P_T - p}{\Delta P} \right\rceil f_p(p) dp + D_0. \tag{7}$$

Therefore, the delay can be found through analyzing D_0 and computing the integration in (7).

B. Effect of Time Uncertainty

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 slot. When the terminal transmits its first registration 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 $|t_0| > W_1$. In Section II, it is shown that the probability for a user terminal to be in state S_2 can be negligibly small, if W_1 is properly chosen. We focus on the two states S_0 and S_1 in finding the delay.

Assume a terminal turns its power on in slot $(k-1)$ and starts its registration process in the state S_0 at the slot k with enough power to close the link. Assume the traffic in the slotted Aloha channel for registration has a Poisson distribution with arrival rate $G < e^{-1}$ [9], [10]. 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 n times until it is successfully received once. The probability of the event E_n has a geometric distribution, i.e., $p_n = P(E_n) = (1-P_s)^{n-1} P_s$. The time corresponding to the event E_n is $t_n = (2J+1)(T_0 + \tau + KT_0)(n-1) + T_0 + \tau$. The average delay to have the first packet successfully received is

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

To reduce the probability of false registration, 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 $D_c = (M-1)(T_0 + \tau + KT_0)/P_s$. The average delay to complete the registration process for a user terminal starting in the state S_0 is $D_{r0} = D_{s0} + D_c$, i.e.,

$$D_{r0} = \frac{2J+M}{P_s}(T_0 + \tau + KT_0) - 2J(T_0 + \tau + KT_0) - KT_0. \tag{9}$$

Consider the case when a user terminal starts the registration process in the state S_1. In Section III, it is shown that the timing of the user terminal is in any of the intervals $\left(\cup_{j=1}^J I_j\right) \cup \left(\cup_{j=1}^J I_{-j}\right)$, $I_j = (2jW - W, 2jW + W]$, $1 \leq j \leq J$, $I_{-j} = [-2jW - W, -2jW + W)$, $1 \leq j \leq J$, where $J = \lceil (W_1 - W)/dT \rceil$ and W_1 satisfies (1). Employing the proposed algorithm, a user terminal having $t_0 \in I_j$ needs to adjust its timing for

$$N_t(j) = 2j, \qquad 1 \leq j \leq J \tag{10}$$

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

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

It is understood that adjusting the user terminal timing is driven by the event that a "Failure" feedback is received for the registration 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 $D(j) = N_t(j)(T_0 + \tau) + N_t(j)KT_0 + D_{r0}$, which can be rewritten as

$$D(j) = 2j(T_0 + \tau + KT_0) + D_{r0}. \tag{12}$$

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

$$D(-j) = (2j-1)(T_0 + \tau + KT_0) + D_{r0}. \tag{13}$$

Denote the pdf of the user terminal initial timing as $f_t(t)$. After having enough power to close the link, the delay to complete registration, when averaged over the initial timing, is

$$D_0 = D_{r0} + \sum_{j=1}^{J} (N_t(j) + N_t(-j))(T_0 + \tau + KT_0) p(j) \tag{14}$$

where

$$p(j) = \int_{2jW-W}^{2jW+W} f_t(t)dt. \tag{15}$$

Substituting (9), (10), and (11) into (14), we have

$$D_0 = \frac{2J+M}{P_s}(T_0+\tau+KT_0) - 2J(T_0+\tau+KT_0) - KT_0 + \sum_{j=1}^{J}(4j-1)(T_0+\tau+KT_0)\int_{2jW-W}^{2jW+W} f_t(t)dt. \tag{16}$$

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

C. Average Delay

Substituting (16) into (7), we have the average delay of the user registration process as

$$\begin{aligned} D =& [(2J+1)(T_0+\tau)+2JKT_0] \\ &\times \int_{P_{\min}}^{P_T} \left\lceil \frac{P_T - p}{\Delta P} \right\rceil f_p(p)dp \\ &+ \frac{2J+M}{P_s}(T_0+\tau+KT_0) \\ &- 2J(T_0+\tau+KT_0) - KT_0 \\ &+ (T_0+\tau+KT_0)\sum_{j=1}^{J}(4j-1) \\ &\times \int_{2jW-W}^{2jW+W} f_t(t)dt. \end{aligned} \tag{17}$$

The average delay of the user terminal registration process is determined by timing uncertainty, power uncertainty, traffic of registration packets, and system parameters.

The initial timing uncertainty of each user terminal affects the average delay through the integration $\sum_{j=1}^{J}(4j-1)\int_{2jW-W}^{2jW+W} f_t(t)dt$ and the parameter J. The parameter J is chosen using (2) and (1) to satisfy the system specification. The size of the time synchronization window $I_0 = [-W, W]$ is determined by the time synchronization requirements in the system and the time needed for the central receiver to finish the processing of the jth packet and to start the processing of the $(j+1)$th packet. It is preferable to have this window as narrow as possible to have high system time-utilization efficiency. Given the distribution of the user terminal initial timing, decreasing the size of the window I_0 will slightly increase the average delay in the registration process. The entire user registration process takes a short time by employing the proposed algorithm. The slot structure of the network is the same for all types of packets, including traffic packets and registration packets. It is still worth decreasing the size of the window I_0 so that the system time utilization efficiency can be increased.

The contribution of the power uncertainty of each user terminal to the average delay is contained in the integral $\int_{P_{\min}}^{P_T} \lceil (P_T - p)/\Delta P \rceil f_p(p)dp$ and the parameter M. The parameter M is a function of the power uncertainty, as will be shown in Section VI.

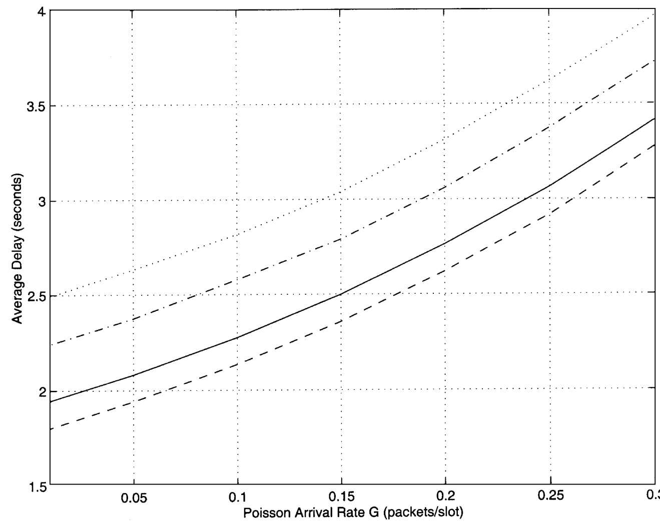

Fig. 4. Average delay of user registration. The dashed line is for $(P_0, \Delta P) = (0, 1)$ dB, where P_0 is the initial power bias and ΔP is the power adjustment step size. The solid line is for $(P_0, \Delta P) = (-0.2, 1)$ dB. The dash–dotted line is for $(P_0, \Delta P) = (0, 0.5)$ dB. The dotted line is for $(P_0, \Delta P) = (-0.2, 0.5)$ dB.

The registration packets having power higher than the threshold power P_T can cause collisions and will affect the delay. The collision rate is determined by the registration traffic. The effect of registration traffic on delay is contained in the second term in (17). Finding a closed form for the probability P_s to have a packet successfully received in the user registration process is nontrivial and will be discussed in future study. We resort to simulation to study the effect of registration traffic on delay. The registration packet traffic is assumed to be a Poisson process with the arrival rate G.

The performance of the proposed algorithm is simulated for a real broadband satellite communications network employing onboard switching [6], [7]. The position determination employed by each user terminal gives a Gaussian error with zero mean and a standard deviation of 2 km. The user terminal initial timing error has a Gaussian distribution of zero mean and a standard deviation as $\sigma_t = 6.6$ ms. The pdf of the user terminal initial power is given by (3) with $(A, B, \sigma_p) = (1.5, 1.0, 0.2)$ in decibels, and the initial power bias P_0 either as 0 dB or -0.2 dB. The threshold power level P_T to close the link is 0 dB. The power adjustment step size is either 0.5 dB or 1.0 dB per step. The slot time is $T_0 = 3.5$ ms per time slot. The round trip delay is 0.5 s. The average number of slots to wait after receiving a "Failure" feedback and before resending a registration packet is $K = 10$. The minimum initial power of a user terminal is $P_{\min} = -5$ dB, and the maximum allowable power is $P_A = 3$ dB. The time synchronization window is $I_0 = [-8, 8]$ μs. The registration failure probability caused by the user terminal initial timing error outside the window $[-W1, W1]$, i.e., the probability $\Pr\{|t| \geq W_1\}$ in (1), is $7.6E-7$ if we choose $J = 1$ in (2), or $3.0E-17$ if we choose $J = 2$.

Fig. 4 plots the average delay. The total number of "Success" feedback received by each user terminal is $M = 2$. For each point $N = 10^5$ user terminals are simulated to complete

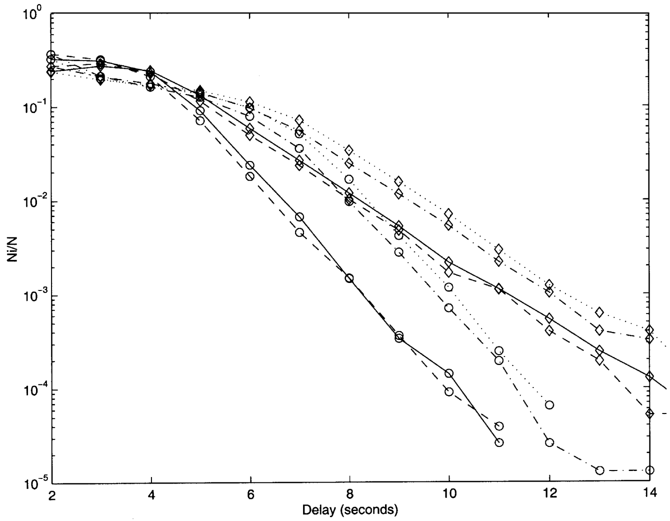

Fig. 5. Probability density of the delay to complete user registration in the example system. The circle lines are for $G = 0.1$, and the diamond lines are for $G = 0.2$.

the registration processes successfully. It can be seen that the average delay increases rapidly with the Poisson arrival rate G. For $G \leq 0.3$, the average delay to successfully complete the user registration process is less than 4 s. For a real system with the registration packet arrival as a Poisson process having $G \leq 0.10$, the average delay is less than 3 s. When the power adjustment step size is $\Delta P = 1$ dB, reducing the user terminal initial power bias P_0 from 0 dB to -0.2 dB increases the average delay slightly, although the probability for the user terminal initial power to be higher than the maximum allowable power P_A decreases from $3.0E-7$ to $7.8E-10$. When the power adjustment step size is $\Delta P = 0.5$ dB, reducing the user terminal initial power bias P_0 from 0 dB to -0.2 dB increases the average delay by about 10%.

Fig. 5 shows the corresponding pdf of the delay in the registration process. The abscissa is the delay t in seconds. The ordinate shows the number N_t of user terminals divided by the total number N of user terminals simulated, where N_t is the number of user terminals whose delay is in the range $(t-1, t]$ seconds and t is the integer. It can be seen that when the arrival rate G increases, the pdf corresponding to the power adjustment step size $\Delta P = 1.0$ dB spreads out apparently quicker than that for $\Delta P = 0.5$ dB. This means the variance of the delay for $\Delta P = 1.0$ increases faster than the variance of the delay for $\Delta P = 0.5$ dB. Reducing the initial power bias from $P_0 = 0$ dB to $P_0 = -0.2$ dB has negligible effect on the pdf of the delay, which means its effect on the variance of the delay is negligible. Therefore, it is preferable for the system to have $(\Delta P, P_0) = (0.5, -0.2)$ dB.

VI. Probability of False Registration

In user registration processes, 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, the registration packet of higher power can still be demodulated successfully. The central receiver will send a "Success" feedback to both user terminals. Such a feedback will make the user terminal of lower power think falsely that its registration packet was received successfully. This event is called *override*. When override happens and no further steps are taken, the user terminal of lower power may mistakenly quit from the registration process, although it has not succeeded yet. This section analyzes the probability of override in slotted Aloha networks.

Without loss of generality, assume the ith user terminal and the jth user terminal use the same slot to send registration packets. Let $Y = C_T/N$ 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 are the sufficient and necessary conditions for the signal of the ith user terminal to override the signal of the jth user terminal: 1) $C_T \leq C_i \leq C_a = \eta C_T$, $\eta > 1$; 2) $C_i/(N + C_j) \geq Y$, where C_i is the carrier power of the ith user terminal. Usually, $Y > 1$. Condition 2) implies $C_i > C_j$, and C_i increases linearly with C_j.

Let $C_i = \alpha C_j$. To satisfy Condition 2), we have $\alpha \geq Y[1 + (C_j/N)^{-1}]$. 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., $C_j \gg C_T$, or $C_j/N \gg Y$, it is sufficient for the signal of the ith user terminal to override the signal of the jth user terminal, if $C_i \geq YC_j$.

Let $C_j = \beta C_T$. To satisfy Condition 1), we have $C_i = \alpha\beta C_T \leq \eta C_T$, i.e., $\alpha\beta \leq \eta$. Condition 2) requires $\alpha\beta C_T/(N + \beta C_T) \geq C_T/N$, i.e., $1 + \beta Y \leq \alpha\beta$. We have $\beta \leq \beta_0 = (\eta - 1/Y)$. Therefore, a signal of carrier power higher than $\beta_0 C_T = (\eta - 1/Y)C_T$ cannot 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

$$\frac{C_T}{N} \leq \frac{C_i}{N + C_j} \leq \frac{\dfrac{\eta C_T}{N}}{\dfrac{1 + C_T}{N}}. \tag{18}$$

In a typical broadband slotted Aloha network, $Y \geq 2$, which requires $\eta \geq 3$. If the maximum allowable power of a user terminal is not higher than three times the threshold power, the signal of one user terminal will not override the signal of another user terminal, but 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 decibel scale has independent, identical distribution (i.i.d.) with the pdf $f_p(p)$. The probability for one signal to override the other is

$$P_{ow} = \int_{C_{\min}/C_T}^{\beta_0} \int_{1+Yx}^{C_{\max}/C_T} f_p(x) f_p(y)\, dx\, dy. \tag{19}$$

This probability can be bounded by

$$\int_{C_{\min}/C_T}^{\beta_0} f_p(x)dx \int_{1+Y\beta_0}^{C_{\max}/C_T} f_p(y)dy < P_{ow} < \int_{C_{\min}/C_T}^{\beta_0} f_p(x)dx \int_{1+YC_{\min}/C_T}^{C_{\max}/C_T} f_p(y)dy. \tag{20}$$

For more than two user terminals accessing 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 accessing the system using the same slot is

$$\frac{C_i}{N+\sum\limits_{j\neq i} C_j} \geq Y. \tag{21}$$

Without loss of generality, assume $C_i > C_j \geq C_k$, where $\{k|k \geq j+1\}$ is the set of users that collided with the ith user terminal and the jth user terminal in the same slot. The inequality (21) can be rewritten as $C_i \geq Y(N+C_j+\sum_{k\geq j+1} C_k)$. Assuming the power of each user terminal is i.i.d., we have

$$\Pr\left\{\frac{C_i}{N+C_j} \geq Y\right\} > \Pr\left\{\frac{C_i}{N+C_j+\sum\limits_{k\geq j+1} C_k} \geq Y\right\}. \tag{22}$$

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

$$\Pr\{Z_1\} = \sum_{X\geq 2} \Pr\{Z_1, X\} = \sum_{X\geq 2} \Pr\{Z_1|X\}\Pr\{X\} \tag{23}$$

where X is the number of user terminals using the same slot, and $\Pr\{Z_1|X=2\} = P_{ow}$. From (22), we have

$$\Pr\{Z_1|X>2\} < \Pr\{Z_1|X=2\}. \tag{24}$$

Substituting (24) into (23), we have

$$\Pr\{Z_1\} < P_{ow} \sum_{X\geq 2} \Pr\{X\}. \tag{25}$$

Assume that the registration packet arrival to each slot has a Poisson distribution. The probability for each slot to have more than one packet is $\sum_{X\geq 2}\Pr\{X\} = 1-\Pr\{X=0\}-\Pr\{X=1\}$, which can be rewritten as

$$\sum_{X\geq 2} \Pr\{X\} = 1 - e^{-G} - Ge^{-G} \tag{26}$$

where G is the registration packet arrival rate. Substituting (20) and (26) into (25), we have

$$\Pr\{Z_1\} < \left(1-e^{-G}-Ge^{-G}\right) \int_{C_{\min}/C_T}^{\beta_0} f_p(x)dx \times \int_{1+YC_{\min}/C_T}^{C_{\max}/C_T} f_p(y)dy. \tag{27}$$

Let

$$p_{ov} = \left(1-e^{-G}-Ge^{-G}\right) \int_{C_{\min}/C_T}^{\beta_0} f_p(x)dx \times \int_{1+YC_{\min}/C_T}^{C_{\max}/C_T} f_p(y)dy. \tag{28}$$

Define that the event of a successful registration for each user terminal is that the user terminal has to send M identical registration packets and receive M "Success" feedback messages. To make sure the probability of false user registration is less than ϵ_f, we can choose M as the smallest integer to satisfy $p_{ov}^M \leq \epsilon_f$, i.e.,

$$M = \left\lceil \frac{\log \epsilon_f}{\log p_{ov}} \right\rceil. \tag{29}$$

which is usually given as a specification in broadband slotted Aloha networks. This number M is the number of times a registration packet should be sent by a user terminal using the registration algorithm in Section IV.

For the example system shown at the end of Section V, we choose $\eta = Y = 2$, i.e., 3 dB. Then $\beta_0 = 0.5$, i.e., -3 dB. Applying (28) at $G = 0.3$, we have $p_{ov} = 1.7E-8$. If the system requires that the false registration rate is lower than 10^{-8}, then $M = 2$ identical registration packets have to be sent from each user terminal in the registration process, and two "Success" feedback messages have to be received.

VII. Conclusions

The proposed algorithm can jointly achieve time synchronization, power adjustment, and user terminal registration for broadband slotted Aloha networks having very large numbers of user terminals. Each user terminal can have nonnegligible timing uncertainty and nonnegligible power uncertainty. Initial power setting for each user terminal is provided to make sure the probability of the initial user terminal power is higher than a certain level, is less than any value specified by network interference requirements. The quantization of user terminal timing error is discussed to have the probability of registration failure caused by a large timing error less than any prespecified value. The effect of time uncertainty and power uncertainty to the average delay of the user terminal registration process is analyzed. It is shown that the average delay is a few seconds in a real broadband slotted Aloha network with the registration packet arrival rate not higher than 0.3. The registration packet arrival is assumed to be a Poisson process. The probability of false registration is analyzed, including the probability of override in the traditional slotted Aloha system. By employing the proposed algorithm, broadband slotted Aloha networks can use a large number of inexpensive user terminals having otherwise nonnegligibly large time uncertainty and large power uncertainty. The system cost can be reduced tremendously. The proposed algorithm makes it possible to use very small guard time between adjacent time slots to increase the efficiency of using system time.

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