PACKET DELIVERY THROUGH DIFFICULT WIRELESS CHANNEL

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ABSTRACT

An algorithm is proposed for user terminals to overcome time uncertainty, power uncertainty and to achieve successful access to network through the slotted Aloha contention channel in broadband wireless and satellite communication networks. For security reasons, the network feedback does not contain user identification information. Each user terminal has to figure out whether its packet is successfully received. It is shown that packets can be successfully delivered within a reasonably small delay by employing the proposed multiple access algorithm.

I. INTRODUCTION

In packet switched broadband wireless and satellite communication networks, each user terminal has to register with the network control center before it is allowed to use the network services. The access channel is usually the slotted Aloha contention channel. The user population is very large. The data rate is hundreds of megabits per second, which can be gigabits per second for future applications [1]. When a user terminal uses the access channel, it has to combat the time uncertainty and power uncertainty. A user terminal has to achieve time synchronization and successful power adjustment to close the link, while trying to access the network and perform registration. All these tasks have to be completed considering the large user population, network security requirements, co-channel interference requirements, the non-negligible time uncertainty and power uncertainty in user terminals in broadband wireless and satellite communication networks [2]. Therefore, the access algorithms for user terminals in broadband wireless and broadband satellite networks must be designed jointly considering requirements in network layer, medium access sub-layer and physical layer.

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

II. SYSTEM MODEL

In broadband wireless and satellite networks, all user terminals within the same cell share a common slotted Aloha access channel. The registration algorithm has to handle access failures caused by collisions in access processes for a large population of users. We assume that the length of each time slot is $T_f = \frac{L}{R_s}$, where L is the length of each packet in symbols and R_s is the data rate in symbols per second. It is also assumed that all of the information needed for accessing the network is contained in a single packet. 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. This can be achieved by implementing a receiver employing the Global Positioning System in each user terminal or by inputting the pre-estimated location data into the user terminal. 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 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 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 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 in the access process can be demodulated by the central receiver only when all of the following conditions are satisfied:

1) The arrival time of the received packet is in the window

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$[-W, W]$ 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.

Assume the central receiver can always demodulate an access packet correctly, if there is only one packet appears in a slot of the slotted Aloha channel and the packet satisfies all of the above three conditions.

The central receiver demodulates and processes all 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 triplet of $[\frac{C}{N}, f_T, f_b]$ in a status message, $f_T \in$ {Early,Late}, $f_b \in$ {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 registration 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. The pair $\underline{X} = (P_i^j, t_i^j)$, 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, can be in any of the following five regions. 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 user 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 accessing the network. 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:

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.

In the region $R1$, the central receiver cannot successfully demodulate 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 access 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.

III. Time Synchronization and Power Adjustment

The timing error of the access 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. When the arrival time of access packet at the central receiver is outside the window centered at the slot boundary, the central receiver cannot demodulate it correctly and will give a failure indication for the packet. This failure indication is sent back in the feedback message to all of the user terminals in accessing stage in the same cell. Therefore, the algorithm used for user terminals to access the network has to combat the time uncertainty in each user terminal to make sure that a user terminal with initial timing error outside the window can pull its timing into the window within an acceptable amount of time.

The power uncertainty of user terminals in broadband wireless and satellite networks can be very large, as will be seen in this section. The following aspects have to be considered to handle the power uncertainty:

1) The initial power setting level for each user terminal;
2) Co-channel interference;
3) Average time to finish the access process;
4) Probability of access failure caused by insufficient power.

The initial power setting level can be different than the power needed to close the link and will affect the co-channel interference, the time needed to finish accessing the network and the probability of access failure caused by insufficient transmission power. To minimize co-channel interference, it is better for user terminals to start transmission at low power level. However, this approach increases the risk of having insufficient power, which in turn will need more time to ramp up power and can result in a higher probability of access failure.

Time synchronization has to satisfy the requirement that the probability of access failure caused by timing error must be less than a very small number ϵ_t. Let $f_t(t)$ be the probability density function 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 access process, where the parameter W_1 satisfies:

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

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 for 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:

1) $t_1 - dT \geq -W$;
2) $t_2 - dT \leq W$.

Solving these two inequalities, we have

$$dt \leq dT \leq 2W \quad (2)$$

which means: (A) The maximum step size of time adjustment can not be greater than the size of the time synchronization window; (B) The maximum length of the timing error interval which can be covered in each time adjustment step can not 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

$$J = \left\lceil \frac{W_1 - W}{dT} \right\rceil \quad (3)$$

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 $I = \cup_{j=-J}^{J} I_j$. Apparently the time uncertainty range $[-W_1, W_1]$ to be handled is a subset of I, i.e.,

$$[-W_1, W_1] \subset I = \cup_{j=-J}^{J} I_j. \quad (4)$$

Let the initial timing error of the user terminal to be $t_0 \in [-W_1, W_1]$. Then, $t_0 \in I$. To focus the problem on time synchronization at the present time, assume the user terminal transmits at a power level enough to close the link and the access packet will be demodulated successfully if the timing error of the packet is within the window I_0. Assume the user terminal sends its first packet with the timing error t_0. The user terminal perform 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 = t0 + l × dT;
        sendpacket(t);
        F = feedback();
        i = i + 1;
}
```

The function sendpacket(t) is for the user terminal to send a packet with the timing t. The function feedback( ) is for the user terminal to wait until it receives a feedback message from the central receiver. The value of the function feedback( ) is 1 if the 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 $I_{-(j+1)}$. As this full search covers all of the subintervals in the interval I, it can pull any initial timing error $t_0 \in I$ into the time synchronization window I_0 and make sure the timing of each user terminal to be synchronized.

Let the power that should be received by the central receiver from a user terminal to be P_0 when there is no power error. The received power in dB at the central receiver can be written as

$$P = P_0 + e_1 + e_2 + e_3 \quad (5)$$

where e_1 is the EIRP variation of the user terminal, which includes power setability, temperature variation, antenna gain variation, an 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 dB; The random variable e_2 is uniformly distributed in $[-B, B]$, where B is a few dB; The random variable e_3 has a Gaussian distribution with zero mean and the standard deviation as σ_p. The parameter σ_p can be less than 0.2 dB if the GPS system is employed to determine the user terminal position or can be larger if other less accurate methods are used for position determination.

The total power error $e = e_1 + e_2 + e_3$ has zero mean. Its probability density function is the convolution of the probability density functions of e_1, e_2 and e_3 [8]. It can be shown that the probability density function of e can be written as

$$f_e(e) = \frac{e + A + B}{4AB}\left(Q\left(\frac{e + A - B}{\sigma_p}\right) - Q\left(\frac{e + A + B}{\sigma_p}\right)\right) \quad (6)$$

$$+\frac{1}{2A}(Q(\frac{e-A+B}{\sigma_p})-Q(\frac{e+A-B}{\sigma_p}))$$
$$-\frac{e-A-B}{4AB}(Q(\frac{e-A-B}{\sigma_p})-Q(\frac{e-A+B}{\sigma_p}))$$
$$+\frac{\sigma_p}{4AB\sqrt{2\pi}}(e^{-\frac{(e+A+B)^2}{2\sigma_p^2}}-e^{-\frac{(e+A-B)^2}{2\sigma_p^2}})$$
$$+\frac{\sigma_p}{4AB\sqrt{2\pi}}(e^{-\frac{(e-A-B)^2}{2\sigma_p^2}}-e^{-\frac{(e-A+B)^2}{2\sigma_p^2}})$$

where $Q(x)=\frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-x}dx$. Therefore, the received power at the central receiver has the mean as P_0 and an error whose probability density function is given in (6). The probability density function of the received power at the central receiver is:

$$f_p(p) = \frac{p-P_0+A+B}{4AB}(Q(\frac{p-P_0+A-B}{\sigma_p})-Q(x(p)))(7)$$
$$+\frac{1}{2A}(Q(\frac{p-P_0-A+B}{\sigma_p})-Q(\frac{p-P_0+A-B}{\sigma_p}))$$
$$-\frac{p-P_0-A-B}{4AB}(Q(\frac{p-P_0-A-B}{\sigma_p})-Q(y(p)))$$
$$+\frac{\sigma_p}{4AB\sqrt{2\pi}}(e^{-\frac{(p-P_0+A+B)^2}{2\sigma_p^2}}-e^{-\frac{(p-P_0+A-B)^2}{2\sigma_p^2}})$$
$$+\frac{\sigma_p}{4AB\sqrt{2\pi}}(e^{-\frac{(p-P_0-A-B)^2}{2\sigma_p^2}}-e^{-\frac{(p-P_0-A+B)^2}{2\sigma_p^2}})$$

where $x(p)=\frac{p-P_0+A+B}{\sigma_p}$ and $y(p)=\frac{p-P_0-A+B}{\sigma_p}$.

In a broadband wireless network, it is required that the probability that the received power from an individual user terminal at the central receiver to be greater than the maximum allowable received 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

$$p_I(P_0, A, B, \sigma_p) = \int_{P_A}^{\infty} f_p(p)dp \leq \epsilon_p. \quad (8)$$

Table 1 shows the probability for the initial power error e to be greater than x, i.e., $\Pr\{e > x\}$, for an example system. 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.

TABLE I

PROBABILITY FOR 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 DB.

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

Usually the maximum allowable transmission power P_A is only 3 dB higher than the threshold power P_T to close the link. However, to satisfy (8), 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 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 packet. When the user terminal receives this failure feedback, it can increase the transmission power level and resend the packet. Let the step size of the power increment be ΔP. The maximum number of allowed power increment steps is

$$S = \left\lfloor \frac{P_A - P_0}{\Delta P} \right\rfloor. \quad (9)$$

Each user terminal is allowed to increase its power by at most S steps in the access process.

IV. ACCESS ALGORITHM

All the user terminals in the same cell share one common slotted Aloha access channel to send the access packets.

Collisions may occur as in the traditional multiple access systems using the slotted Aloha [3], [4]. Therefore, an algorithm has to be developed for each user terminal to access the channel, combat time uncertainty and power uncertainty, and achieve successful access to the network. The algorithm has to specify when the newly arrived access request will be transmitted, how to retransmit after access failure happens [5], and how to adjust the timing and transmission power in case of access failure.

All packets arrived for the first time from user terminals in the ith time slot will be sent to the central receiver in the (i+1)th slot. This is the so called *free-access protocol* [6]. If a user terminal receives a failure feedback from the central receiver for an access 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 for the failed packet. Therefore, the user terminal has to use one algorithm to handle all of the possibilities for collision, wrong timing and insufficient power.

In the previous section, it is shown that a full search in the time domain can handle the time uncertainty. It was also shown that a user terminal needs to start transmission with a power level lower than the threshold power to close the link. The user terminal can increase its transmission power gradually until it has enough power to make its packet demodulated successfully. In the access process, the search in the time domain and the power adjustment have to be performed jointly. To minimize interference, a full search in time domain is performed each time before the power is increased by one step. For example, assume the feedback for the first packet sent by a user terminal is failure. Then, this user terminal adjusts its timing using the algorithm provided in the previous section. After having finished the full search in time domain, if this user terminal still has not received a success feedback for any of the transmitted packet, it increases its power by one step and resends the packet. To avoid time drifting, the user terminal has to reset its timing to the original timing before resending the access packet at an increased power level.

A user terminal can receive a failure feedback caused by collision with the packet sent by another user terminal in the same time slot. This event can happen even when the timing of its packet is in the $[-W, W]$ window and its power is enough to close the link. In this case, the user terminal has to keep resending its access packet until the user terminal receives a success feedback. For the traditional slotted Aloha channel, many algorithms have been proposed for user terminals to retransmit their packets and combat collisions [5], [7]. These algorithms can bring obvious gain in throughput for the traditional slotted Aloha channel. However, 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 [5]. More precisely, after receiving a failure feedback, a user terminal waits for a number of D slots and resends its packet. Here, D is a random number uniformly distributed in $[1, L]$. The number L is usually around 10 [5].

Assume a user terminal receives a success feedback for its access packet. For network security reasons, the feedback message does not contain the identification number of the sender. Based on the success feedback for only one time slot, the user terminal can not decide with high confidence which of the following two hypothesis is true:

H_0: The registration packet of itself was successfully demodulated;

H_1: The registration packet from another user terminal sent in the same time slot with a much higher power was demodulated successfully.

Therefore, the user terminal may like to send a few more packets using the same timing and power as those for the first access packet which has obtained a success feedback. A packet sent after receiving a success feedback just to increase the confidence of successful registration is called a *confirmation packet*.

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

Access 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 = 0;
                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 = t0 + l × dT;
                i = i + 1;

                if (j < S) {
                        j = j + 1;
                        p = p + dP;
                }
        }

        randomdelay(L);
}
```

The function sendpacket(t, P) is for the user terminal to send a packet using the timing t and the power P. The function feedback() is for the user terminal to wait until receive a feedback message from the central receiver. The function randomdelay(L) is for the user terminal to have a random delay uniformly distributed in the interval $[1, L]$ in packets. The function triggerULPC(t, p) is for the user terminal to trigger its normal state of communications in which a user terminal assumes it has succeeded in the access process and can start to transmit and receive data packets using the correct timing and correct power level in the traffic channels, which are different than the access channel.

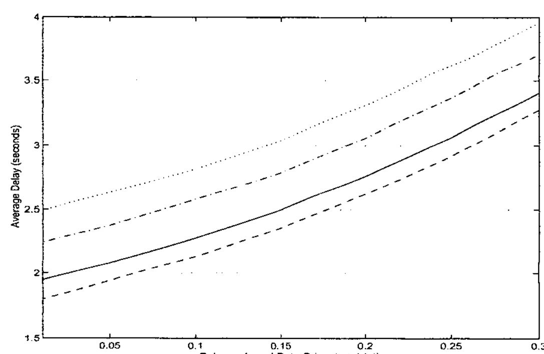

Fig. 1. Average delay versus the Poisson arrival rate of access packets for a broadband communications system using the proposed algorithm. The dashed line is for $(P_0, \Delta P) = (0, 1)$ in dB, where P_0 is the user terminal initial power bias and ΔP is the power adjustment step size. The solid line is for $(P_0, \Delta P) = (-0.2, 1)$ in dB. The dash-dotted line is for $(P_0, \Delta P) = (0, 0.5)$ in dB. The dotted line is for $(P_0, \Delta P) = (-0.2, 0.5)$ in dB.

V. Numerical Results and Conclusions

The performance of the proposed algorithm is simulated for an example system with the following parameters. The position determination employed by each user terminal gives a

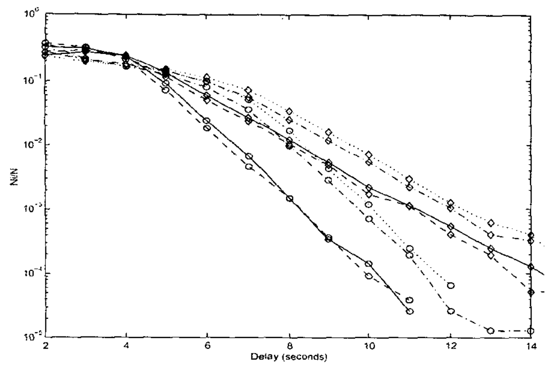

Fig. 2. Probability density of the delay in access process in a broadband communication network using the proposed algorithm. The circle lines are for the Poisson arrival rate $G = 0.1$ packet per slot and the diamond lines are for $G = 0.2$ packets per slot. The dashed line is for $(P_0, \Delta P) = (0, 1)$ in dB, where P_0 is the user terminal initial power bias and ΔP is the power adjustment step size. The solid line is for $(P_0, \Delta P) = (-0.2, 1)$ in dB. The dash-dotted line is for $(P_0, \Delta P) = (0, 0.5)$ in dB. The dotted line is for $(P_0, \Delta P) = (-0.2, 0.5)$ in dB.

Gaussian error with zero mean and the standard deviation of 2 kilometers. The user terminal initial timing error has a Gaussian distribution of zero mean and the standard deviation as $\sigma_t = 6.6$ microseconds. The probability density function of the user terminal initial power is given by (7) with $(A, B, \sigma_p) = (1.5, 1.0, 0.2)$ in dB and the initial power bias P_0 either as zero dB or -0.2 dB. The threshold power level P_T to close the link is zero dB. The power adjustment step size is either 0.5 dB or 1.0 dB per step. The slot time is $T_0 = 3.5$ milliseconds per time slot. The round trip delay is 0.5 second. 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 $I_0 = [-8, 8]$ micro-seconds. The registration failure probability caused by that 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 (3), or $3.0E - 17$ if we choose $J = 2$.

Fig. 1 plots the average delay versus the Poisson arrival rate G of access packets for the example system. The total number of success feedback received by each user terminal is $M = 2$ to have high confidence that the user terminal has successfully completed the access process. For each point $N = 10^5$ user terminals are simulated to complete access 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 access process is less than 4 seconds. In real slotted Aloha systems, it is well known that the packet arrival rate G should not be higher than 0.10. This is because the system will drift toward the instable state once the arrival rate is higher than some value and can not recover from the instable state [4]. For a real system with the access packet arrival as a Poisson process having $G \leq 0.10$, the average delay is less than 3 seconds. 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%. The effect of the initial power bias to the average delay is independent to the arrival rate G of user terminals accessing network, which agrees with intuition.

Fig. 2 shows the probability density of the delay in the access process. The abscissa is the delay t in seconds. The ordinate shows the number N_t/N, where N_t is the number of access processes completed in $(t - 1, t]$ seconds and N is the total number of access processes simulated. It can be seen that when the arrival rate G increases, the probability density function corresponding to the power adjustment step size $\Delta P = 1.0$ dB spreads out faster than that for $\Delta P = 0.5$ dB. This means the variance of the delay for $\Delta P = 1.0$ dB is larger than that 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 probability density. Therefore, it is preferable for the example system to adjust the power using the step size 0.5 dB and have the initial power bias as -0.2 dB.

The access algorithm proposed in this paper can achieve successful user access to broadband wireless and satellite networks within a reasonable delay. The algorithm can overcome the nonnegligible time uncertainty and power uncertainty associated with each user terminal in the access channel.

References

[1] S. Vaughn and R. Sorace, "Demonstration of the TDRS Ka-band transponder," *Proc. 2000 IEEE Military Commun. Conf.*, vol. 2, pp. 1055-1065, 22-25 Oct., 2000, Los Angeles, CA.

[2] J. Liu, "Performance of user terminal registration algorithm," *Hughes Network Systems Tech. Report,* August 2000.

[3] N. Abramson, "The throughput of packet broadcasting channels," *IEEE Trans. Comm.*, vol. COM-25, no. 1, pp. 117-128, Jan. 1977.

[4] D. Bertsekas and R. Gallager, *Data Networks*, Prentice Hall, 1992.

[5] N. Abramson, *Multiple Access Communications: Foundations for Emerging Technologies*, New York: IEEE Press, 1993.

[6] P. Mathys and P. Flajolet, "Q-ary collision resolution algorithms in random-access systems with free or blocked channel access," *IEEE Trans. Information Theory*, vol. IT-31, no. 2, pp. 217-243, March 1985.

[7] R. G. Gallager, "A perspective on multiaccess channels," *IEEE Trans. Information Theory*, vol. IT-31, no. 2, pp. 124-142, March 1985.

[8] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, New York, McGraw-Hill, 1991.