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Analysis of throughput and stability for ACK-ALOHA-CDMA channel

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Abstract: A new acknowledgment-type slotted-ALOHA code division multiple access (ACK-ALOHA-CDMA) channel which can be used in the inbound channels of very small aperture terminal (VSAT) networks is proposed in order to simplify the synchronization equipment of networks in the slotted-ALOHA-CDMA systems. By dividing all VSAT stations into M subsystems and sending out periodic inquiry signals from the Hub station to the VSAT station, the channel model is established. By the means of deriving multi-access interference (MAI) and packet detecting probability, steady-state throughput is calculated. By applying diffusion process theory to the analysis of the stability of the ACK-ALOHA-CDMA channel, the drift parameter $a(r)$, the diffusion parameter $b(r)$ and the steady transition probability density $p(r)$ are investigated. Simulation results indicate that significant performance improvement and high-bandwidth efficiency can be gained and one or two steady equilibrium points can be obtained by using this channel. Consequently, the ACK-ALOHA-CDMA channel is very suitable for cutting down on the expense of satellite VSAT systems and distributed packet radio networks.

Key words: throughput; stability; ACK-ALOHA-CDMA

The ALOHA system is widely used in satellite VSAT systems[1], distributed packet radio networks and military communication networks. It is known that the method of the CDMA spread spectrum and the slotted-ALOHA can improve the throughput of systems[2]. Much work has been done for the slotted-ALOHA[3-8]. In order to simplify the synchronization equipment of networks in the slotted-ALOHA-CDMA systems, a new kind of acknowledgment-type slotted-ALOHA-CDMA channel for a multiple code spread spectrum, which is called the ACK-ALOHA-CDMA channel, is studied in this paper. Simulation results show that significant performance improvement and high-bandwidth efficiency can be gained by using this channel. Consequently, the ACK-ALOHA-CDMA is very suitable for the uplink channels of VSAT stations in satellite VSAT systems. It can not only improve the performance, but also simplify the synchronization equipment and reduce the costs of VSAT systems.

1 Model of ACK-ALOHA-CDMA Channel

The slotted-ALOHA system which transmits packets in time slots can improve the throughput, but the synchronization equipment will increase the costs of the system. It is known that the spread spectrum ALOHA system, which applies spread spectrum modulation techniques to the pure ALOHA system, can improve the performance of systems. In order to simplify the synchronization equipment of the system in the slotted-ALOHA-CDMA channel, a new kind of acknowledgment-type-ALOHA-CDMA channel which can be used in satellite VSAT systems is proposed as follows.

The VSAT system's hub station sends out inquiry signals (i. e. synchronous pulses) to the VSAT station. The inquiry signal is equal to the time synchronous signal in the slotted ALOHA-CDMA channel. The controlling element of the VSAT station receivers act in step with the inquiry pulse signal which is transmitted by the hub station. Since the distances from the VSAT station to the hub station are different, the transmitting action from the VSAT station's receivers does not synchronize for an identical inquiry signal. As a result, the channel can be regarded as a kind of acknowledgment-type-ALOHA-CDMA channel, which is called an ACK-ALOHA-CDMA channel. Fig. 1 gives the model of the ACK-ALOHA-CDMA channel. In Fig. 1, λ_0 is the transmitting probability of the VSAT station for an identical inquiry signal, and λ_r is the re-transmitting probability of the VSAT station due to no response from the hub station.

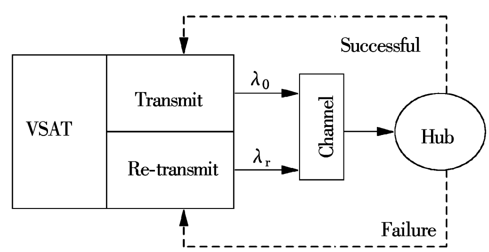

Fig. 1 The model of ACK-ALOHA-CDMA channel

Set a synchronic signal which is sent by the hub station as the starting point of time. The arrival time which is from the VSAT station to the hub station by the satellite is written as TOA. So it has maximal difference time of arrival $D = \max(\mathrm{TOA}) - \min(\mathrm{TOA})$.

Because of the large number of users, all the users are divided into M subsystems and a spread spectrum code is used by a subsystem. The amount of service for each subsystem is independent and equal. It is said that in a given time, the number of packets transmitted by users in each subsystem is the same.

2 Throughput Analysis of ACK-ALOHA-CDMA Channel

2.1 Throughput

The number of packets which are transmitted by each

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subsystem's user in period T obeys the Poisson distribution whose intensity is $\lambda_i T_0$, i. e.,

$$\text{Prob}[n_i = k] = \frac{(\lambda_i T)^k}{k!}\exp(-\lambda_i T)$$
$$K = 0, 1, 2, \ldots; i = 1, 2, \ldots, M \quad (1)$$

Let all the VSAT stations be divided into M subsystems in a VSAT system and a spread spectrum code is used by a subsystem. The PN code $C^{(i)}$ is

$$C^{(i)} = \{C_1^{(i)}, C_2^{(i)}, C_3^{(i)}, \ldots, C_N^{(i)}\} \qquad i = 1, 2, \ldots, M \quad (2)$$

where N is the length of the PN code. Let

$$\left.\begin{aligned} R_{1i}(\tau) &= \int_{\tau}^{T_d} C^{(1)}(t)C^{(i)}(t-\tau)\,dt \qquad 0 < \tau < T_d \\ \hat{R}_{1i}(\tau) &= \int_0^{\tau} C^{(1)}(t)C^{(i)}(t-\tau)\,dt \qquad 0 < \tau < T_d \end{aligned}\right\} \quad (3)$$

where $R_{1i}(\tau)$ and $\hat{R}_{1i}(\tau)$ are the autocorrelations for PN codes $C^{(1)}$ and $C^{(i)}$, respectively; T_d is the data code width.

In all subsystems, the same spread spectrum pattern is used. Assume that the duration of packets is T_0 and the conflict block is αT_0 (It is usually not more than 2 chips of spread spectrum code.), where α is the capture ratio. It can be proved that the multi-access interference (MAI) of the acknowledgment-type-ALOHA-CDMA channel is[9]

$$I_{\text{MAI}} = \frac{1}{4}S\sum_{i=1}^{M}\lambda_i T_0(\overline{R_{1i}^2} + \overline{\hat{R}_{1i}^2}) \leqslant \frac{1}{4}SG\max_{1\leqslant i,j\leqslant M}(\overline{R_{ji}^2} + \overline{\hat{R}_{ji}^2}) \quad (4)$$

where S is the power of signal; $G = M\lambda_i T_0$, and it is a mean value of the packets concerning the whole system within the packet duration T_0. So the BER P_e can be estimated as

$$P_e = Q\left[\left(\frac{2}{\frac{1}{3N^3}G\max\limits_{1\leqslant i,k\leqslant M}(2\mu_{ki}(0) + \mu_{ki}(1)) + \text{SNR}_0^{-1}}\right)^{\frac{1}{2}}\right] \quad (5)$$

where $\text{SNR}_0 = 2E_b/N_0$, $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{1}{2}t^2}dt$.

Usually, $2\mu_{ki}(0) + \mu_{ki}(1) = N^2$ for the Gold code, we have

$$P_e = Q\left[\left(\frac{2}{\frac{1}{3N}G + \text{SNR}_0^{-1}}\right)^{\frac{1}{2}}\right] \quad (6)$$

In the ACK-ALOHA-CDMA channel, the length of packets is T_0, and the period of the inquiry signal is T. So the BER P_e can be amended as

$$P_e = Q\left[\left(\frac{2}{\frac{1}{3N}G\frac{T_0}{D} + \text{SNR}_0^{-1}}\right)^{\frac{1}{2}}\right] \quad (7)$$

If the code can correct e-bit errors, then the detecting probability of the packets is

$$P_W(G) = \sum_{i=0}^{e}\binom{L}{i}P_e^i(1-P_e)^{L-i} \quad (8)$$

Fig. 2 gives the arrival time to the hub station for the same frame. The differential of the arrival time obeys the distribution[10].

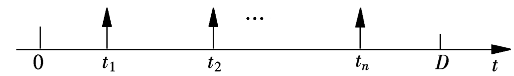

Fig. 2 Arrival time for the same frame

$$\text{Prob}[\Delta t_k > x] = \left(1 - \frac{x}{T}\right)^n \qquad k = 1, 2, \ldots, n; 0 < x < T \quad (9)$$

For $T/T_0 < 1$, only the first packet may be received successfully. The probability is

$$P = \text{Prob}[\Delta t_2 > \alpha T_0] = \left(1 - \frac{\alpha T_0}{T}\right)^n \quad (10)$$

For $T/T_0 > 1$, there are other packets which are received successfully. The probability is

$$P(n) = \sum_{k=1}^{n} p_k q_k \quad (11)$$

where p_k is the successful probability of the k-th packet, and q_k is the successful probability of the k-th arrival for a packet. Then

$$\left.\begin{aligned} q_k &= \frac{1}{n} \qquad k = 1, 2, \ldots, n \\ p_k &= \text{Prob}[\Delta t_k > T_0, \Delta t_{k+1} > \alpha T_0] \approx \\ &\quad \text{Prob}[\Delta t_k > T_0]\text{Prob}[\Delta t_{k+1} > \alpha T_0] = \\ &\quad \left[\left(1 - \alpha\frac{T_0}{T}\right)\left(1 - \frac{T_0}{T}\right)\right]^n \qquad k = 1, 2, \ldots, n \end{aligned}\right\} \quad (12)$$

From Eqs. (11) and (12), we have

$$P(n) = \frac{n-2}{n}\left[\left(1 - \alpha\frac{T_0}{T}\right)\left(1 - \frac{T_0}{T}\right)\right]^n + \frac{1}{n}\left(1 - \alpha\frac{T_0}{T}\right)^n + \frac{1}{n}\left(1 - \frac{T_0}{T}\right)^n \qquad n \geqslant 2 \quad (13)$$

From Eqs. (1), (7) and (13), the throughput of the ACK-ALOHA-CDMA channel $S(G)$ is

$$S(G) = MP_W(G)\sum_{k=1}^{\infty}[kP(k)\text{Prob}[n_i = k]] = P_W(G)Me^{-G/M}\left[e^{\beta_1 G/M} + e^{\beta_2 G/M} + \frac{\beta_3 G}{M}e^{\beta_3 G/M} - \frac{\beta_1 + \beta_2 - \beta_3 - 1}{M}G - 2e^{\beta_3 G/M}\right] \quad (14)$$

where $\beta_1 = 1 - \alpha T_0/T, \beta_2 = 1 - T_0/T, \beta_3 = \beta_1\beta_2$.

2.2 Analysis of simulation results

Considering the geographical distribution of VSAT stations and the duration of packets, we assume that $T_0/D = 5$, and the duration of packets $L = 100$; the capture ratio $\alpha = 0.05$. Fig. 3 shows the relationship between throughput $S(G)$ and G when spread spectrum processing gain $N = 31$, 63 and 511, respectively, in which the number of subsystems $M = 30$, the number of error corrections $e = 2$, and the input signal-to-noise ratio of the receiver is 6 dB. When $N > 511$, the throughput $S(G)$ does not improve greatly.

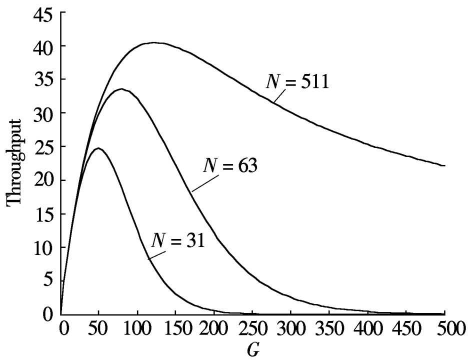

Fig. 3 Throughput for $N = 31, 63, 511$

3 Stability of ACK-ALOHA-CDMA Channels

3.1 Diffusion process

Let n be the division frame number of the inquiry signal. In the n-th division frame, the backlog of the channel is $B(n)$. The number of users which are in the waiting state is $W(n)$. If the propagation time is zero, i. e., $W(n) = 0$, then the channel state $B(n)$ can be described by a simple one-dimensional Markov process. According to the model in Fig. 1, $B(n+1)$ is decided by $B(n)$. So the channel state $B(n)$ is a Markov chain. Let

$$r(nT) = \frac{B(n)}{N} \qquad n = 0, 1, 2, \dots \tag{15}$$

where N is the number of users. Obviously, $0 \leqslant r(nT) \leqslant 1$, $r(nT)$ is discrete in time and the value is quantized. When $N \to \infty$, we have $r(nT) - r((n-1)T) \to 0$. So when N is very large, $r(nT)$ can be approximated as a continuous function, where $r(t)\,(t > 0)$ is a diffusion process.

The diffusion process is equal to the ratio of the channel's backlog to the number of users. Let $r(s) = r_0$, then the transition probability density of channel state, $p(s, r_0; t, r)$, $0 \leqslant r_0, r \leqslant 1$, satisfies the Chapman-Kolmgorov forward function, i. e.,

$$\frac{\partial}{\partial t} p(s, x; t, u) = -\frac{\partial}{\partial u}[a(t, u) p(s, x; t, u)] + \frac{1}{2}\frac{\partial^2}{\partial u^2}[b(t, u) p(s, x; t, u)] \tag{16}$$

where $a(t, u)$ is the drift parameter; $b(t, u)$ is the diffusion parameter and it is not negative.

3.2 Drift parameter and diffusion parameter

In this paper, N, λ_0, λ_r and propagation delay R are the parameters of the ACK-ALOHA-CDMA channel. They are written as $(N, \lambda_0, \lambda_r, R)$. In Fig. 1, the channel parameter is $(N, \lambda_0, \lambda_r, 0)$. So we can write the drift parameter as $a(r)$ and the diffusion parameter as $b(r)$. If the time increment is an inquiry signal's period T, then

$$\left.\begin{aligned} a(r) &= \frac{1}{TN} E\left[\Delta B(n+1) \,\middle|\, \frac{B(n)}{N} = r\right] \\ b(r) &= \frac{1}{TN^2} E\left\{[\Delta B(n+1)]^2 \,\middle|\, \frac{B(n)}{N} = r\right\} \end{aligned}\right\} \tag{17}$$

Let $\Lambda_0 = N\lambda_0$, $\Lambda_r = N\lambda_r$. When the number of users is very large and λ_0 and λ_r are small, the number of users which are in the re-transmitting state $X_r(n)$ and the number of users who are in the primitive state $X_0(n)$ obey the Poisson distribution,

$$\left.\begin{aligned} \text{Prob}\left[X_r(n) = k \,\middle|\, \frac{B(n)}{N} = r\right] &= \frac{(r\Lambda_r)^k}{k!}\exp(-r\Lambda_r) \\ \text{Prob}\left[X_0(n) = k \,\middle|\, \frac{B(n)}{N} = r\right] &= \frac{(r\Lambda_0)^k}{k!}\exp(-r\Lambda_0) \end{aligned}\right\} \tag{18}$$

and $X_r(n)$ and $X_0(n)$ are independent. For an inquiry signal, if the number of responding users is k and k packets are transmitted, the number of packets which are transmitted successfully is written as $S(k)$, then

$$\Delta B(n+1) = X_0(n) - S[X_0(n) + X_r(n)] \tag{19}$$

According to Eq. (18), we have

$$\left.\begin{aligned} &E\left[X_0(n) \,\middle|\, \frac{B(n)}{N} = r\right] = (1-r)\Lambda_0 \\ &E\left\{S[X_0(n) + X_r(n)] \,\middle|\, \frac{B(n)}{N} = r\right\} = \mathrm{e}^{-G}(\mathrm{e}^{\beta_1 G} + \mathrm{e}^{\beta_2 G} + \\ &\quad \beta_3 G\mathrm{e}^{\beta_3 G} - \beta_1 G - \beta_2 G + \beta_3 G + G - 2\mathrm{e}^{\beta_3 G}) \end{aligned}\right\} \tag{20}$$

where $G = (1-r)\Lambda_0 + r\Lambda_r$. Therefore, we can obtain the drift parameter,

$$a(r) = \frac{1}{TN}[(1-r)\Lambda_0 - \mathrm{e}^{-G}(\mathrm{e}^{\beta_1 G} + \mathrm{e}^{\beta_2 G} + \beta_3 G\mathrm{e}^{\beta_3 G} - \beta_1 G - \beta_2 G + \beta_3 G + G - 2\mathrm{e}^{\beta_3 G})] \tag{21}$$

According to Eq. (19), we have

$$\begin{aligned} E\left\{[\Delta B(n+1)]^2 \,\middle|\, \frac{B(n)}{N} = r\right\} = {} & E\left[X_0^2(n) \,\middle|\, \frac{B(n)}{N} = r\right] - \\ & 2E\left\{X_0(n) S[X_0(n) + X_r(n)] \,\middle|\, \frac{B(n)}{N} = r\right\} + \\ & E\left\{S^2[X_0(n) + X_r(n)] \,\middle|\, \frac{B(n)}{N} = r\right\} \end{aligned} \tag{22}$$

From Eq. (18), we have

$$E\left[X_0^2(n) \,\middle|\, \frac{B(n)}{N} = r\right] = [(1-r)\Lambda_0]^2 + (1-r)\Lambda_0 \tag{23}$$

The second item in Eq. (22) is

$$\begin{aligned} & E\left\{X_0(n) S[X_0(n) + X_r(n)] \,\middle|\, \frac{B(n)}{N} = r\right\} = \\ & (1 - \beta_1 - \beta_2 + \beta_3 + \beta_1 \mathrm{e}^{r\beta_1\Lambda_r} + \beta_2 \mathrm{e}^{r\beta_2\Lambda_r} + \\ & r\beta_3^2\,\Lambda_r \mathrm{e}^{r\beta_3\Lambda_r} - \beta_3\,\Lambda_r \mathrm{e}^{r\beta_3\Lambda_r})(1-r)\Lambda_0 \mathrm{e}^{-G} + \\ & \beta_1(1-r)\Lambda_0 \mathrm{e}^{-(1-\beta_1)r\Lambda_r}\mathrm{e}^{-(1-r)\Lambda_0}[\mathrm{e}^{\beta_1(1-r)\Lambda_0} - 1] + \\ & \beta_2(1-r)\Lambda_0 \mathrm{e}^{-(1-\beta_2)r\Lambda_r}\mathrm{e}^{-(1-r)\Lambda_0}[\mathrm{e}^{\beta_2(1-r)\Lambda_0} - 1] + \\ & [\beta_3(1-r)\Lambda_0 \mathrm{e}^{\beta_3(1-r)\Lambda_r} - 2\mathrm{e}^{\beta_3(1-r)\Lambda_r} + \\ & 2\beta_3(1-r)\Lambda_0 + 2]\, r\Lambda_r\beta_3 \mathrm{e}^{\beta_3 r\Lambda_r}\mathrm{e}^{-G} \end{aligned} \tag{24}$$

It is difficult to demonstrate a strict analysis expression from the third item in Eq. (22). But according to the circumstances which are discussed in this paper, we have

$$\left.\begin{aligned} &E[S^2(k)] \approx E^2[S(k)] = [(k-2)\beta_3^k + \beta_1^k + \beta_2^k]^2 \quad k \geqslant 2 \\ &E[S^2(1)] = 1 \end{aligned}\right\} \tag{25}$$

Therefore, the third item in Eq. (22) is

$$\begin{aligned} E\left\{S^2[X_0(n) + X_r(n)] \;\middle|\; \frac{B(n)}{N} = r\right\} = {} & e^{-G}[e^{\beta_1^2 G} + e^{\beta_2^2 G} + 2e^{\beta_3 G} + \\ & 4e^{\beta_3^2 G} - 4e^{\beta_1\beta_3 G} - 4e^{\beta_2\beta_3 G} - G(\beta_1 + \beta_2 - 2\beta_3)^2 + 1] + \\ & (\beta_3^2 G)^2 e^{(\beta_3^2 - 1)G} - 3\beta_3^2 G e^{-G}(e^{\beta_3^2 G} - 1) + \\ & 2\beta_1\beta_3 G e^{-G}(e^{\beta_1\beta_3 G} - 1) + 2\beta_2\beta_3 G e^{-G}(e^{\beta_2\beta_3 G} - 1) \end{aligned} \tag{26}$$

We can obtain diffusion parameter $b(r)$ by adding Eqs. (23), (24) and (26) together.

According to the Chapman-Kolmgorov forward function, Eq. (16), we have

$$\begin{aligned} \frac{\partial}{\partial t} p(s, r_0; t, r) = {} & -\frac{\partial}{\partial r}[a(r) p(s, r_0; t, r)] + \\ & \frac{1}{2} \frac{\partial^2}{\partial r^2}[b(r) p(s, r_0; t, r)] \end{aligned} \tag{27}$$

Let $p(r) = \lim\limits_{t \to \infty} p(0, 0; t, r)$, then

$$-\frac{\mathrm{d}}{\mathrm{d}r}[a(r)p(r)] + \frac{1}{2}\frac{\mathrm{d}^2}{\mathrm{d}r^2}[b(r)p(r)] = 0 \tag{28}$$

3.3 Analysis of simulation results

The point of crossing zero of the drift parameter is called the balance point of the channel. Fig. 4 and Fig. 5 show the driftage $A(r)$ ($A(r) = NTa(r)$) and transferring probability density $p(r)$ (normalized) of the ACK-ALOHA-CDMA channel for different parameters of the channel. Fig. 6 shows the driftage $A(r)$ ($A(r) = NTa(r)$) of the ACK-ALOHA-CDMA channel for $\lambda_0 = 0.000\,5$, 0.001, $0.001\,5$, 0.002, $0.002\,5$, 0.003, respectively. As an example, let $D/T_0 = 5.0$, $\alpha = 0.05$. We can see that the performance of the channel is poor when its parameter $(N, \lambda_0, \lambda_r, R) = (10^3, 0.003, 0.1, 0)$, because it only has a stable balance point in a high delay area. The channel will enter saturation sooner or later. The channel whose parameter is $(10^3, 0.002, 0.05, 0)$ has a balance point in a low delay area. But its throughput is too small and performance is not ideal. The throughput and delay are a pair of contradictions all the time to a random access channel and we should judge them by the demands of the system. As for a satellite VSAT system, if it is necessary to decrease the delay time from the VSAT station to the hub station, the throughput should be reduced. Fig. 6 indicates that the user's primitive transmitting probability is limited for a given channel. If the amount of service on the system is too large, the system will enter saturation.

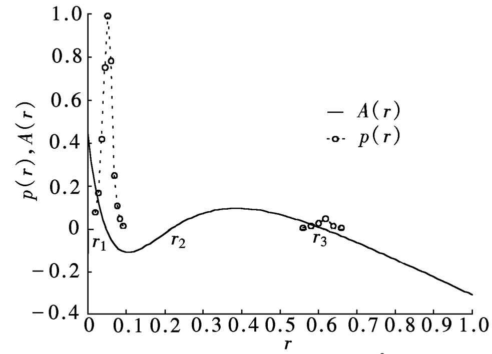

Fig. 5 $A(r)$ and $p(r)$ for parameter $(10^3, 0.002, 0.05, 0)$ ($N = 1\,000$, $D/T_0 = 5.0$, $\alpha = 0.05$, $\lambda_r = 0.05$, $\lambda_0 = 0.002$)

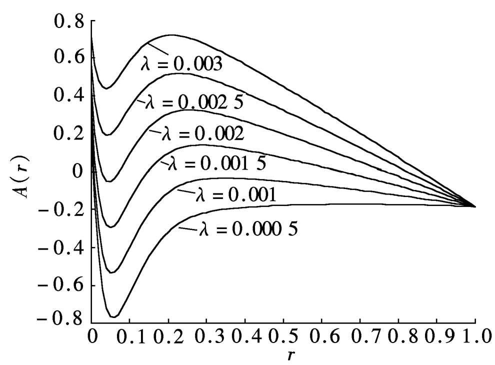

Fig. 6 Driftage $A(r)$ for different λ_0

4 Conclusion

This paper proposes a new kind of the ALOHA-CDMA channel based on a multiple-code spread spectrum, which is called the ACK-ALOHA-CDMA channel. A model of the channel is developed first. Then, the steady-state throughput of the channel is studied. Simulation results indicate that significant performance improvement and high-bandwidth efficiency can be gained by using this channel. Finally, the channel's diffusion and drift parameters with a diffusion process theory are inferred, and the stability of the channel is investigated. The results indicate that throughput and delay are a pair of contradictions to a random access channel and we should judge them by the demands of the system. The ACK-ALOHA-CDMA channel proposed in this paper can be widely used in satellite VSAT systems, distributed packet radio networks and military communication networks.

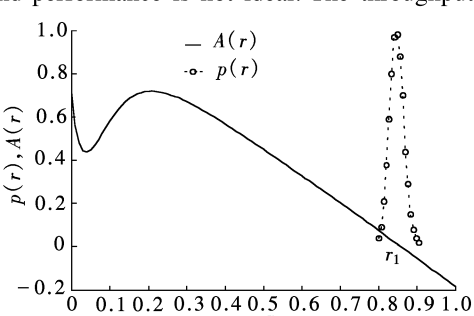

Fig. 4 $A(r)$ and $p(r)$ for parameter $(10^3, 0.003, 0.1, 0)$ ($N = 1\,000$, $D/T_0 = 5.0$, $\alpha = 0.05$, $\lambda_r = 0.1$, $\lambda_0 = 0.003$)

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应答式 ALOHA-CDMA 信道的吞吐量及稳定性分析

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摘要:为了简化时隙 ALOHA-CDMA 系统的时间同步设备,提出了一种可用于卫星 VSAT 网络内向信道的应答式时隙 ALOHA-CDMA 信道模型. 将端站分为 M 个子系统,利用主站发出周期性询问信号,建立了信道模型;通过扩频多址干扰(MAI)和分组检测概率的推导,计算出该信道的稳态吞吐量;并将扩散过程理论用于该信道的稳定性分析,得到扩散系数 $a(r)$、漂移系数 $b(r)$和信道平稳分布 $p(r)$. 仿真结果表明,该系统可以显著提高信道吞吐性能和信道利用率,且存在 1 ~ 2 个稳定平衡点. 应答式时隙 ALOHA-CDMA 信道可以降低卫星 VSAT 系统及分组无线网络系统的组网成本.

关键词:吞吐量;稳定性;应答式时隙 ALOHA-CDMA
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