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Delay Process Analysis for Integrated Voice/Data Transmission * in Slotted CDMA Wireless Communication Networks

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Abstract

Recently, multiple access techniques based on code division multiple access (CDMA) with other protocols and techniques have been positively applied for use in mobile radio and wireless personal communications. In this paper, we present an exact delay process analysis for integrated voice/data transmission in random access slotted CDMA wireless communication networks to numerically evaluate the system performance.

1 System Model

The system model consists of a finite number of users N and each user can be a source of both real-time bursty traffic (such as voice or video) and data traffic. The time axis is slotted. All users are synchronized and all packet transmissions are started only at the beginning of a time slot. We assume that the system supports N users making use of a set of codes M with unique spread-spectrum code sequence, where in general, $N > M$. Users with data packets can use the codes allocated to voice sources for transmission if the voice sources are in silent periods. In case there is no code available in a time slot, the packet is assumed to be cleared from the system without retransmission if it is a voice packet, while the packet is assumed to be blocked and retransmitted in the next time slot if it is a data packet. The allocation of codes to voice sources is given priority over that to data packets while an admission control, which restricts the maximum number of codes M_v available to voice sources, is considered for voice traffic not to monopolize the resource. The model is assumed to have four operational modes for each of N identical, independently operating users: idle mode (I), data transmission mode (D), talkspurt mode (T), and silent mode (S). A user can only be in one mode at a time.

2 Stationary Distribution of the System

We observe the system state at the end of slots and let $x(t) = \mathbf{I} = [i_d, i_t, i_s]$ denote the system state that there are i_d, i_t and i_s users in the data transmission, talkspurt and silent modes at the end of slot t, respectively. The total number S of system states is $S = (M_v^2 + 3M_v + 2)(N - M + 1)/2$.

Given that there are i_d, i_t and i_s users at the end of the t-th slot, the following events must occur to be j_d, j_t and j_s users in the data transmission, talkspurt and silent modes, respectively, at the end of the $(t+1)$-st slot, where $t \to \infty$.

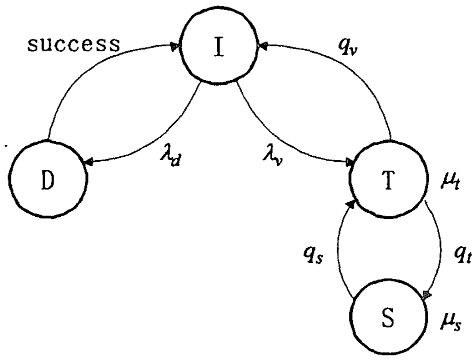

Figure 1: The state transition diagram.

(1) At the beginning of the slot, n_d and n_v users in the idle mode enter the data transmission mode and the talkspurt mode by generating new data and voice packets with probability λ_d and λ_v.

(2) At the beginning of the slot, k_t (k_s) users out of i_t (i_s) users in the talkspurt (silent) mode, transmit voice packets with probability μ_t and μ_s.

(3) Just before the end of the slot, $i_t + i_s - j_t - j_s + \min(M_v - i_t - i_s, n_v)$ users and l users in the talkspurt mode transit to the idle mode and to the silent mode, and $l + i_s - j_s$ users in the silent mode transit to the talkspurt mode, respectively, with parameters q_v, q_t and q_s, so that there would be j_t users in the talkspurt mode and j_s users in the silent mode at the end of the slot.

(4) As the number of data packets successfully transmitted in the slot becomes $\min(M - k_t - k_s - \min(M_v - i_t - i_s, n_v), i_d + n_d)$, j_d must be equal to $i_d + n_d - \min(M - k_t - k_s - \min(M_v - i_t - i_s, n_v), i_d + n_d)$.

Considering the above events, we can obtain the conditional transition probability $P_{\mathbf{IJ}}(\mathrm{n}, \mathrm{k})$ in the following.

$$P_{\mathbf{IJ}}(\mathrm{n},\mathrm{k}) = \binom{N - i_d - i_t - i_s}{n_d}\binom{N - i_d - i_t - i_s - n_d}{n_v}\lambda_d^{n_d}\lambda_v^{n_v}$$
$$\cdot(1-\lambda_d-\lambda_v)^{N-i_d-i_t-i_s-n_d-n_v}\binom{i_t}{k_t}\mu_t^{k_t}(1-\mu_t)^{i_t-k_t}$$
$$\cdot\binom{i_s}{k_s}\mu_s^{k_s}(1-\mu_s)^{i_s-k_s}\sum_{l=\max(0,j_s-i_s)}^{\min(j_s,j_t+j_s-i_s)}$$

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$$\binom{i_t+\min(M_v-i_t-i_s,n_v)}{i_t+i_s-j_t-j_s+\min(M_v-i_t-i_s,n_v)} \cdot \binom{j_t+j_s-i_s}{l} q_v^{i_t+i_s-j_t-j_s+\min(M_v-i_t-i_s,n_v)} q_t^{l}(1-q_v$$
$$-q_t)^{j_t+j_s-i_s-l}\binom{i_s}{l+i_s-j_s} q_s^{l+i_s-j_s}(1-q_s)^{j_s-l}$$
$$\cdot \delta_{j_d \quad i_d+n_d-\min(M-k_t-k_s-\min(M_v-i_t-i_s,n_v),i_d+n_d)} \qquad (1)$$

where δ is Dirac's delta.

Using $P_{\mathbf{IJ}}(\mathbf{n},\mathbf{k})$ we can write the transition probability $P_{\mathbf{IJ}}$ for the system as follows:

$$P_{\mathbf{IJ}} = \sum_{n_d=0}^{N-i_d-i_t-i_s} \sum_{n_v=0}^{N-i_d-i_t-i_s-n_d} \sum_{k_t=0}^{i_t} \sum_{k_s=0}^{i_s} P_{\mathbf{IJ}}(\mathbf{n},\mathbf{k})$$
$$\left(\begin{array}{l} 0 \le i_d \le N-M,\ 0 \le i_t \le M_v,\ 0 \le i_s \le M_v - i_t, \\ 0 \le j_d \le N-M,\ 0 \le j_t \le M_v,\ 0 \le j_s \le M_v - j_t \end{array} \right). \qquad (2)$$

Let $\mathbf{\Pi} = [\Pi_0, \Pi_1, ..., \Pi_{S-1}]$ denote the S-dimensional row vector of the stationary distribution. $\mathbf{\Pi}$ can be determined by solving $P_{\mathbf{IJ}}$ as $\mathbf{\Pi} = \mathbf{\Pi}\mathbf{P}$, $\sum_{i=0}^{S-1}\Pi_i = 1$, where $\mathbf{P}$ is an $S \times S$ matrix of $P_{\mathbf{IJ}}$.

3 Analysis of Delay Process

We first define a probability $[\mathbf{A}_i]_{\mathbf{IJ}}$ of successful transmissions of the data packets as follows:

$$[\mathbf{A}_i]_{\mathbf{IJ}} = \sum_{\mathbf{n},\mathbf{k} \in \mathbf{\Psi}(\mathbf{I})} P_{\mathbf{IJ}}(\mathbf{n},\mathbf{k}) \cdot \delta_{i \quad \min(M-k_t-k_s-\min(M_v-i_t-i_s,n_v),i_d+n_d)} \qquad (3)$$

where $0 \le i \le N-M-1$. Let $[\mathbf{D}_i^*(z)]_{\mathbf{I}}$ represent the mgf of the delay that a tagged data packet sees i packets before it, given $x(t) = \mathbf{I}$. We have

$$[\mathbf{D}_j^*(z)]_{\mathbf{I}} = \sum_{i=j+1}^{\min(N-M,M)} \sum_{\mathbf{J}} z[\mathbf{A}_i]_{\mathbf{IJ}} + z\sum_{i=0}^{j} \cdot \sum_{\mathbf{J}} [\mathbf{A}_i]_{\mathbf{IJ}} [\mathbf{D}_{j-i}^*(z)]_{\mathbf{J}}. \qquad (4)$$

Let $\tilde{\pi}_0$ represent the probability of a data packet being successfully transmitted in the first slot upon its arrival, and let $[\tilde{\mathbf{\Pi}}_i]_{\mathbf{J}}$ represent the probabilities that the data packet is not transmitted successfully in the first slot upon its arrival and is found among j_d users in the data transmission mode at the end of the $(t+1)$-st slot. They are:

$$\tilde{\pi}_0 = K \sum_{\substack{\mathbf{I},\mathbf{J},\mathbf{n},\mathbf{k} \\ n_d \ge 1}} [\mathbf{\Pi}]_{\mathbf{I}} P_{\mathbf{IJ}}(\mathbf{n},\mathbf{k}) \max\{0, \min(M-k_t -k_s - \min(M_v - i_t - i_s, n_v), i_d + n_d) - i_d\}. \qquad (5)$$

$$[\tilde{\mathbf{\Pi}}_i]_{\mathbf{J}} = K \sum_{\substack{\mathbf{I},\mathbf{n},\mathbf{k} \\ j_d \ge 1, n_d \ge 1}} [\mathbf{\Pi}]_{\mathbf{I}} P_{\mathbf{IJ}}(\mathbf{n},\mathbf{k}) \qquad (6)$$

by conditions that if $\min(M-k_t-k_s-\min[M_v-i_t-i_s,n_v],i_d+n_d) \ge i_d$ and $0 \le i \le j_d - 1$, or if $\min(M-k_t-k_s-\min[M_v-i_t-i_s,n_v],i_d+n_d) < i_d$ and $i_d - \min(M-k_t-k_s-\min[M_v-i_t-i_s,n_v],i_d+n_d) \le i \le j_d - 1$. K is a normalizing constant.

Finally we can obtain the mgf $D^*(z)$ of data packet delay as follows:

$$D^*(z) = \tilde{\pi}_0 z + \sum_{i=0}^{N-M-1} z\tilde{\mathbf{\Pi}}_i \mathbf{D}_i^*(z) \qquad (7)$$

where $\tilde{\mathbf{\Pi}}_i$ and $\mathbf{D}_i^*(z)$ are matrix forms of $[\tilde{\mathbf{\Pi}}_i]_{\mathbf{J}}$ and $[\mathbf{D}_i^*(z)]_{\mathbf{I}}$. Let $D^{(m)}$ represent the m-th derivative of $D^*(z)$ as $D^{(m)} = d^m D^*(z)/dz^m \mid_{z=1}$. We have

$$D^{(m)} = \begin{cases} \tilde{\pi}_0 + \sum_{i=0}^{N-M-1} \tilde{\mathbf{\Pi}}_i \left[\mathbf{D}_i^*(1) + \mathbf{D}_i^{(1)}\right], & m = 1, \\ \sum_{i=0}^{N-M-1} \tilde{\mathbf{\Pi}}_i \left[m\mathbf{D}_i^{(m-1)} + \mathbf{D}_i^{(m)}\right], & m > 1 \end{cases} \qquad (8)$$

where $\mathbf{D}_i^{(m)} = d^m \mathbf{D}_i^*(z)/dz^m|_{z=1}$. $\mathbf{D}_j^*(1) = (\mathbf{I} - \mathbf{A}_0)^{-1}\left[\sum_{i=j+1}^{\min(N-M,M)} \mathbf{A}_i \mathbf{e} + \sum_{i=1}^{j} \mathbf{A}_i \mathbf{D}_{j-i}^*(1)\right]$, where $\sum_{i=a}^{b} x_i = 0$ when $a > b$.

4 Numerical Results

From Eq.(7), we can obtain the coefficient of variation of the data packet delay $C_D = \sqrt{Var[D]}/E[D] = \sqrt{D^{(2)} + D^{(1)} - \{D^{(1)}\}^2}/D^{(1)}$. In Fig. 2, the coefficient C_D versus the offered data rate λ_d with different M_v is shown for $M = 10$, $N = 30$. As an example case we give $\mu_t = 1.0$, $\mu_s = 0.0$, $\lambda_v = 0.0006$, $q_t = 0.06$, $q_s = 0.04$ and $q_v = 0.002$, which are determined by referring to [1]. It should be noted that M_v has a significant effect on the coefficients C_d.

References

[1] D.J.Goodman, R.A.Valenzuela, K.T.Gayliard, and B.Ramamurthi, *IEEE Trans. on Commun.*, Vol.37, No.8, pp.885-890, 1989.

[2] M. Yin and Victor O. K. Li, *IEEE J. Select. Areas in Commun.*, Vol.8, No.4, pp.529-541, 1990.

[3] W.Yue and Y.Matsumoto, *IEEE GLOBECOM'98*, pp.445-451, 1998.

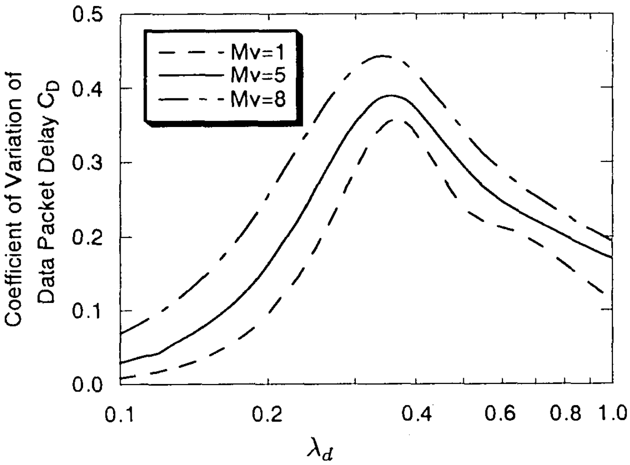

Figure 2: Coefficient C_D versus λ_d for $M_v = 1, 4, 8$.