Research Note

Comparison of CDMA and TDMA in AWGN Channels

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In this paper, two multiple access methods in time and code domains are compared for Additive White Gaussian Noise (AWGN) channels. Time Division Multiple Access (TDMA) has been used for many years and its features are well-known. Characteristics of Code Division Multiple Access (CDMA) and its advantages over TDMA are studied in this paper. The burstiness nature of voice traffic and unequal bit transmission time in TDMA and CDMA are used to compare the performance of the two techniques. Delay, throughput and packet loss, as performance parameters, are evaluated and computed for data and voice traffics. Capability of CDMA in accommodating sources with different bit rates is also considered. The results represent a noticeable improvement in the performance of CDMA over TDMA when features of the spread spectrum techniques are taken into consideration.

INTRODUCTION

After successful utilization of Code Division Multiple Access (CDMA) technique in military communications, it is now being used in many commercial applications such as satellite communication, cellular mobile communication and factory automation. The most important feature of CDMA is the protection against multipath fading, an unavoidable aspect of wireless channels. Some other desirable features of CDMA such as inherent security, graceful performance degradation, flexibility in accommodating multimedia (voice/data) traffic with variable data rate, use of silent times of voice traffic, etc., make it a potential candidate for Local Area Networks (LANs) and many other applications. New services in LANs that permit file or image transfer among computers require a high bit rate. ATM increases the cost of network due to star connection, and token ring limits the bit rate when the number of active users is small. In this paper, the CDMA is applied as an alternative multiple access method for LANs.

Some parts of LANs in the newly emerging indoor

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communications are wireless in which usage of the CDMA methods seems to be evident. Application of CDMA in the wired backbone of a wireless LAN increases the compatibility between the two divisions and reduces the interface overhead.

Various aspects of Spread Spectrum methods especially Direct Sequence (DS/SS), such as admission policies for voice and data traffic [1], performance analysis of CDMA over optical fiber channels [2,3], multiuser detection [4] and error probability for CDMA systems [5,6], have been investigated in the literature. Also, comparison between code and non-code division multiple access methods has been performed, especially for fading channels. The advantages of CDMA over other multiple access methods in Rayleigh and Rician fading channels have been reported in [7]. Unfortunately, in [7] some inherent aspects of CDMA were not considered resulting in a poor performance of CDMA in Additive White Gaussian Noise (AWGN) channels. The bursty nature of voice traffic and unequal time duration of bit transmission in CDMA and other multiple access methods are some of these aspects.

Throughout this paper, a similar approach as in [7] has been used to derive the probability of error, packet loss, throughput and delay. To keep the consistency, the same notations as given in [7] are also used. The results of [7] are generalized for AWGN channels with variable SNR, bursty sources and different user bit rates. In particular, three systems: TDMA, CDMA and a hybrid system called CDMA/TDMA are compared. The performance parameters for these systems

in an AWGN channel are computed and compared. The results represent a better throughput, delay and packet loss for CDMA when compared to TDMA for low SNR and bursty sources. This shows that CDMA methods are suitable not only for fading channels but also for AWGN channels. This is not in agreement with [7], where results are only applicable to very high SNR and non-bursty sources. The inferior performance of CDMA for non-fading channels in [7] is a consequence of certain constraints. Here, these constraints are further explored and the performance measures are derived in their absence.

In the next section, the three mentioned systems are described. Then, the performance parameters, i.e., delay, throughput and packet loss are computed for both voice and data traffic. The effects of different bit rates of users on bit error probability are considered. The numerical results and comparisons among systems are presented and, finally, conclusions are given.

DESCRIPTION OF SYSTEMS

The performance of each system is determined by delay, throughput and packet loss. Prior to describing the systems and computing these important parameters, a glossary of parameters used in this paper is provided:

- U: number of users,

- L: number of bits per packet,

- T_c: chip period,

- Λ: message arrival rate per user (in messages per unit time),

- $\overline{E}$: average number of packets per message,

- $\overline{E^2}$: mean square message length,

- λ_i: total user arrival rate in packets per user per frame (for system i),

- μ_i: service rate in packets per user per frame (for system i),

- T_S: slot time,

- T_F: frame time,

- S: network throughput,

- ρ: traffic intensity (utilization factor) for system i,

- P_c: the probability of correct detection for a packet.

To compare TDMA, CDMA and CDMA/TDMA, it is assumed that the input parameters, i.e., Λ, L, $\overline{E}$, $\overline{E^2}$ and U are the same. The time axis is divided into frames with length T_F and only one packet is transmitted in each frame.

TDMA

In TDMA, the frame time is divided into U slots. One slot is assigned to each user for transmitting a packet. Each packet includes L bits. The user packet arrival rate is given by:

$$\lambda_1 + \Lambda T_F \overline{E}. \tag{1}$$

The subscript "1" in λ_1 indicates TDMA. Since each user transmits only one packet in each frame, the service rate is equal to $1 (\mu_1 = 1)$. Therefore, the traffic intensity or utilization factor is:

$$\rho_1 = \lambda_1/\mu_1 = \Lambda T_F \overline{E} = \rho. \tag{2}$$

Bits in error might be received due to noise and other channel imperfections. If a packet is received in error, it will be retransmitted until it is correctly received. Retransmission is incorporated in the analysis by increasing the average number of packets per message from $\overline{E}$ to $\overline{E'}$. If the probability of correct detection of a packet is $P_c^{(1)}$, where the superscript (1) indicates the first method, i.e., TDMA, it is obtained that:

$$\overline{E_1'} = \overline{E}/P_c^{(1)}. \tag{3}$$

In fact, $P_c^{(1)}$ is the ratio of correctly received packets to total transmitted packets. Therefore, the useful throughput per user is:

$$\rho_1' = \rho P_c^{(1)}. \tag{4}$$

Correspondingly, the mean square message length is [2]:

$$(\overline{E_1^2})' = \frac{2 - P_c^{(1)}}{[P_c^{(1)}]^2} \overline{E^2}. \tag{5}$$

CDMA

In CDMA, all active users transmit their packets in the whole frame time. Again it is assumed that each user transmits one packet in each frame. Thus,

$$T_S^{(2)} = T_F, \tag{6}$$

where the superscript (2) represents the second method, i.e., CDMA. Similar to all spread spectrum direct sequence systems, in CDMA, the source data bits are multiplied by the code sequences generated by shift registers. There are different kinds of codes used in DS/SS, however, Gold sequences are more suitable for CDMA applications [8,9]. The chip period of the Gold sequences, T_c, is selected such that the bandwidth

of the coded signal is equal to the channel bandwidth. The spread spectrum processing gain is defined as:

$$PG^{(2)} = \frac{T_F/L}{T_c^{(2)}} = 2^n - 1 \approx U, \tag{7}$$

where n is the length of a shift register generating the Gold sequences. For TDMA, the processing gain is given by:

$$PG^{(1)} = 1. \tag{8}$$

Using an approach similar to TDMA, the parameters for CDMA are:

$$\lambda_2 = \Lambda T_F \overline{E} \tag{9}$$

$$\rho_2 = \lambda_2/\mu_2 = \Lambda T_F \overline{E} = \rho, \tag{10}$$

$$\rho_2' = \rho P_c^{(2)}, \tag{11}$$

$$(\overline{E_2^2})' = \frac{2 - P_c^{(2)}}{[P_c^{(2)}]^2} \overline{E^2}. \tag{12}$$

The number of overlapping users in a slot is equal to:

$$M_2 = [\rho U], \tag{13}$$

where $[x]$ denotes the smallest integer greater than or equal to x.

CDMA/TDMA

The hybrid CDMA/TDMA is a trade-off between the TDMA and CDMA systems. A new parameter N is defined that takes values between 1 and U. The frame time is divided into N slots. Each slot is shared by U/N users. The hybrid CDMA/TDMA system is identical to TDMA for $N = U$ and to CDMA for $N = 1$. Such as before:

$$PG^{(3)} = U/N, \tag{14}$$

$$T_S^{(3)} = T_F/N, \tag{15}$$

$$\rho_3 = \lambda_3/\mu_3 = \Lambda T_F \overline{E} = \rho, \tag{16}$$

$$\rho_3' = \rho P_c^{(3)}, \tag{17}$$

$$(\overline{E_3^2})' = \frac{2 - P_c^{(3)}}{[P_c^{(3)}]^2} \overline{E^2}, \tag{18}$$

$$M_3 = \left\lceil \frac{\rho U}{N} \right\rceil. \tag{19}$$

If the bit errors are assumed to be independent, $P_c^{(i)}$ is related to the bit error probability $P_b^{(i)}$ by:

$$P_c^{(i)} = [1 - P_b^{(i)}]^L, \quad i = 1, 2, 3. \tag{20}$$

Bit error probability will be evaluated shortly in a direct sequence PSK modulation system in a fading-free AWGN channel.

PERFORMANCE ANALYSIS

Although the above three cases are different, in all of them the same frame structure is used. Thus, TDMA is used as a reference model to evaluate the packet delays. The total message transfer delay for TDMA is given by:

$$T = T_a + T_b, \tag{21}$$

where T_a is the mean waiting time in an $M/G/1$ queue and T_b is the packet transmission delay. In the sequel, a closed form is derived for the delay. Using Pollaczek-Khinchin formula [10],

$$T_a = \frac{\Lambda \overline{X^2}}{2(1 - \rho)}, \tag{22}$$

where X, the service time of each message, is:

$$X = K T_F, \tag{23}$$

where K is the random variable representing the number of packets in each message with an average of $\overline{E}$. Then,

$$\overline{X^2} = T_F^2 \overline{E^2}. \tag{24}$$

Substituting Equation 24 in Equation 22 and using $\lambda_i = \Lambda T_F \overline{E}$,

$$T_a = \frac{\lambda_i T_F \overline{E^2}}{2(1 - \rho)\overline{E}}. \tag{25}$$

As shown in Figure 1, if a message with length $\overline{E}$ arrives at time t_0, its total transmission delay is given by:

$$T_b = \overline{Y} + T_S + (\overline{E} - 1)T_F, \tag{26}$$

where $\overline{Y}$ is the average of a random variable Y with values between 0 and T_F. Assuming a uniform distribution for Y,

$$\overline{Y} = T_F/2. \tag{27}$$

Hence,

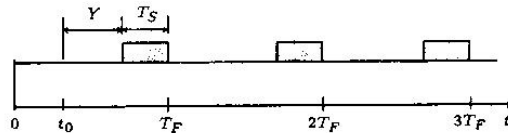$$T_b = T_F/2 + T_S + (\overline{E} - 1)T_F = \frac{2\overline{E} - 1}{2}T_F + T_S. \tag{28}$$

Figure 1. A framing scheme in a slotted digital communication system.

To apply this equation in all three systems, two changes are to be made. The first is to replace $\overline{E}$ and $\overline{E^2}$ by $\overline{E'}$ and $(\overline{E^2})'$, respectively, due to erroneous packet transmission. The second is to use the corresponding parameters for each system. Therefore, the total message transfer delay is given by [2]:

$$T_i = \frac{\rho_i T_F}{2(1-\rho_i)} \frac{(\overline{E_i^2})'}{\overline{E_i'}} + \frac{2\overline{E_i'}-1}{2}T_F + T_S^{(i)}. \tag{29}$$

Using Equations 2 to 5 for TDMA, Equations 6, 10 and 12 for CDMA and Equations 15 to 18 for CDMA/TDMA in the above relation results in:

$$T_1^d = \frac{\rho T_F(2-P_c^{(1)})}{2(1-\rho)P_c^{(1)}} \frac{\overline{E^2}}{\overline{E}} + \frac{2\overline{E}-P_c^{(1)}}{2P_c^{(1)}}T_F + \frac{T_F}{U}, \tag{30}$$

$$T_2^d = \frac{\rho T_F(2-P_c^{(2)})}{2(1-\rho)P_c^{(2)}} \frac{\overline{E^2}}{\overline{E}} + \frac{2\overline{E}-P_c^{(2)}}{2P_c^{(2)}}T_F + T_F, \tag{31}$$

$$T_3^d = \frac{\rho T_F(2-P_c^{(3)})}{2(1-\rho)P_c^{(3)}} \frac{\overline{E^2}}{\overline{E}} + \frac{2\overline{E}-P_c^{(3)}}{2P_c^{(3)}}T_F + \frac{T_F}{N}. \tag{32}$$

In these equations, the superscript "d" represents data traffic.

In transmission of voice traffic, the amount of acceptable delay is limited. Therefore, retransmission of packets is meaningless. This can be considered through replacing $P_c^{(i)}$ by 1 in Equation 30,

$$T_1^v = \frac{\rho T_F \overline{E^2}}{2(1-\rho)\overline{E}} + (\overline{E}-1/2)T_F + \frac{T_F}{U}. \tag{33}$$

In addition, the CDMA related systems have more useful features obtained from their structures. For fair comparison of the multiple access methods, these features must be considered. Unfortunately, these features have not been accommodated in [7] resulting in a poor performance for CDMA.

As explained in the previous section, due to the bursty nature of traffic, an activity ratio α is defined which is about 0.3 to 0.6 depending on the modulation and the techniques used for bandwidth compression. It represents the ratio of useful channel utilization by each user. $\rho_r = \alpha\rho$ is substituted in Equations 31 and 32 and the following is obtained:

$$T_2^v = \frac{\alpha\rho T_F \overline{E^2}}{2(1-\alpha\rho)\overline{E}} + (\overline{E}-1/2)T_F + T_F, \tag{34}$$

$$T_3^v = \frac{\alpha\rho T_F \overline{E^2}}{2(1-\alpha\rho)\overline{E}} + (\overline{E}-1/2)T_F + \frac{T_F}{N}. \tag{35}$$

In Equations 33 to 35, the superscript "v" indicates voice traffic. It is evident that in transmission of the voice traffic, some packets might be lost. The packet loss is estimated as:

$$P_{loss}^{(i)} = \rho(1-P_c^{(i)}), \quad i = 1, 2, 3. \tag{36}$$

The network throughput for all three systems is given by:

$$S^{(i)} = \rho P_c^{(i)}, \quad i = 1, 2, 3. \tag{37}$$

Now, delay, throughput and packet loss for voice and data traffic are computed. First, $P_c^{(i)}$, or equivalently $P_b^{(i)}$, is evaluated which are related to each other by Equation 20. Figure 2 shows the direct sequence multiple access system model. In this model, a channel simply adds a white Gaussian noise. At the receiver input,

$$r(t) = \sum_{k=1}^{M} \sqrt{2p}a_k(t-\tau_k)b_k(t-\tau_k)\cos(\omega_c t + \varphi_k)$$
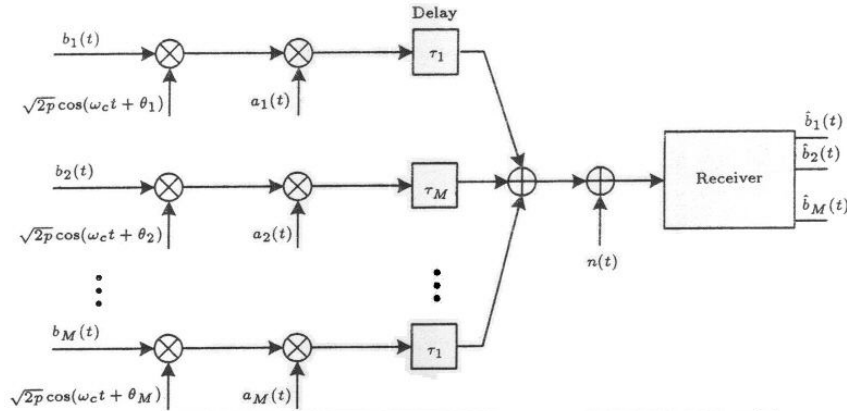$$+ n(t), \tag{38}$$

Figure 2. The phase-coded spread spectrum multiple access system model.

where $n(t)$ is AWGN with density $N_0/2$, $a_k(t)$ is the code used by the kth user, $b_k(t)$ is the kth user data sequence, τ_k is the delay and M is the number of active users. At the output of the ith matched filter in the receiver,

$$Z_i = \int_0^{T_F} r(t)a_i(t)\cos(\omega_c t)dt. \qquad (39)$$

The signal to noise ratio is $PT^2/2$ divided by the variance of Z_i, which is evaluated by Pursley [5] as:

$$Var\{Z_i\} = \frac{PT_F^2}{12N_S^3}\sum_{\substack{k=1 \\ k \neq i}}^{M_i} r_{k,i} + \frac{N_0 T_F}{4}, \qquad (40)$$

where N_S is the sequence length and:

$$r_{k,i} = \sum_{l=0}^{N_S-1} \{C_{k,i}^2(l-N_S)+C_{k,i}(l-N_S)C_{k,i}(l-N_S+1)$$

$$+ C_{k,i}^2(l-N_S+1) + C_{k,i}^2(l) + C_{k,i}(l)C_{k,i}(l+1)$$

$$+ C_{k,i}^2(l+1)\}, \qquad (41)$$

with $C_{k,i}(l)$ being the discrete aperiodic cross correlation function for sequences $a_j^{(k)}$ and $a_j^{(i)}$, defined as:

$$C_{k,i}(l) = \begin{cases} \sum_{j=0}^{N_S-1-l} a_j^{(k)}a_{j+l}^{(i)}, & 0 \leq l \leq N_S - 1 \\ \sum_{j=0}^{N_S-1+l} a_{j-l}^{(k)}a_j^{(i)}, & l-N_S \leq l < 0 \\ 0, & |l| \geq N_S \end{cases} \qquad (42)$$

For each specified code sequence, $Var\{Z_i\}$ could be computed from Equation 40 by evaluation of the Expressions 41 and 42. Using the very good approximation of [5],

$$\frac{1}{6N_S^3}\sum_{\substack{k=1 \\ k \neq i}}^{M_i} r_{k,i} \approx \frac{M_i - 1}{3N_S}, \qquad (43)$$

it is obtained that:

$$SNR_i \approx \left\{ \frac{N_0}{2E_b} + \frac{M_i - 1}{3PG_i} \right\}^{-1} \qquad (44)$$

In [5], it is shown that Expression 43 is an exact expression when random sequences are employed. The bit error probability is related to SNR_i by:

$$P_b^{(i)} = \frac{1}{2}erfc(\sqrt{SNR_i}), \qquad (45)$$

where $erfc(.)$ is the complementary error function defined as:

$$erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty e^{-x^2}dx. \qquad (46)$$

In Expression 44, the first term is the signal to noise ratio and the second shows the interference from other users. This term diminishes for TDMA since there is no overlapping user ($M_1 = 1$).

According to Expression 44, the bit energy E_b is the same for the TDMA, the CDMA and the CDMA/TDMA systems. However, the duration of transmission of a bit in these three cases is different. Therefore, to keep E_b the same, a CDMA or CDMA/TDMA user exerts much smaller peak power than a TDMA user. Assuming equal maximum power for all three systems, Expression 44 changes to:

$$SNR_i \approx \left\{ \frac{N_0}{2E_b}\frac{T_b^{(1)}}{T_b^{(i)}} + \frac{M_i - 1}{3PG_i} \right\}^{-1} \qquad (47)$$

where $T_b^{(i)}$ is the duration of bit transmission in the ith system and is given by:

$$T_b^{(1)} = \frac{T_F}{UL}, \qquad (48)$$

$$T_b^{(2)} = \frac{T_F}{L}, \qquad (49)$$

$$T_b^{(3)} = \frac{T_F}{NL}. \qquad (50)$$

USERS WITH DIFFERENT BIT RATES

Another advantage of CDMA is the flexibility in accommodating different bit rate traffic. To explain it, consider a scenario in which the bit rate of some of the users is half the others'. In TDMA, T_F is determined according to the higher bit rate and the users with a smaller bit rate send their traffic in alternative frames leaving some slots empty in the other frames. This reduces the overall utilization factor of the system.

In CDMA, T_F is the same as TDMA, with each user utilizing the whole frame time. Thus, there will be U users in half the frames and K users in the others, with $1 \leq K \leq U$ representing the number of full-rate users. This tends to reduce the probability of error in the frames with a smaller number of users.

Let $P_b(e|U)$ be the bit error probability in the CDMA technique when U users are active in a given frame. Then, the overall bit error probability for this scenario is given by:

$$P_b = \frac{1}{2}[P_b(e|U) + P_b(e|K)]. \qquad (51)$$

Note that since $K \leq U$, $P_b \leq P_b(e|U)$. Thus, it can be concluded that CDMA performs better when the sources have different bit rates.

NUMERICAL RESULTS

For all three systems, it is assumed that: $U = 256$, $L = 256$, $\overline{E} = \overline{E^2} = 1$ and $T_F = 1$. The signal to noise ratio ($SNR_b = 2E_b/N_0$) was left to be variable and the performances of the systems were obtained for different values of SNR_b.

The division factor in the CDMA/TDMA is assumed to be $N = 8$. The delay for voice traffic in packets is shown in Figure 3. In this figure, the corresponding curves for the CDMA and CDMA/TDMA systems, with the activity ratio $\alpha = 1$, are also shown.

It is noticed that if the activity ratio of the voice traffic is not considered, TDMA outperforms the two other systems. However, only the CDMA-related systems can efficiently use the burstiness of voice to reduce the total delay. Surprisingly, the delay is almost invariant to traffic variation. Similar results are obtained for various values of α as illustrated in Figure 4. The figure shows that the results are correct for a wide range of α.

Figure 5 illustrates the packet loss for a voice traffic with $SNR_b = 3$. This figure shows that the equal bit power assumption for the three systems causes the CDMA to outperform the other two systems. The CDMA/TDMA technique also has a very close performance. Up to $\rho \leq 0.4$, packet loss is nearly zero for the CDMA and CDMA/TDMA techniques, whereas packet loss increases linearly with traffic in TDMA.

Corresponding curves for data traffic are shown in Figures 6 and 7. The delay for data traffic is relatively large. This is due to a small SNR_b. In this case, similar to Figure 5, assuming equal bit power causes a better performance in CDMA. Figure 7 shows the throughput for data traffic. The maximum throughput in TDMA is about 0.16 which is largely due to a small SNR_b.
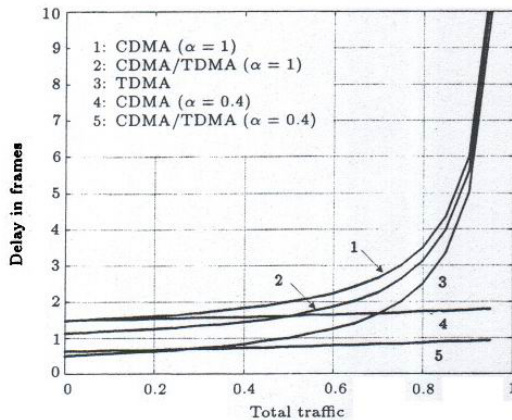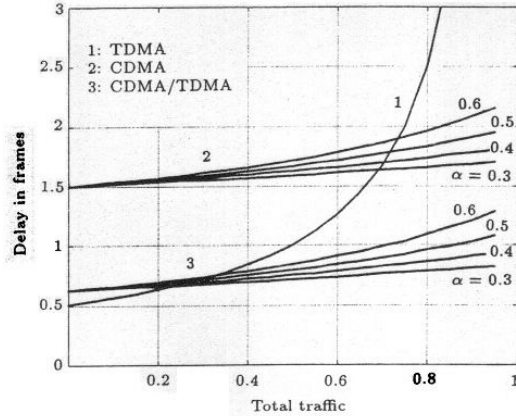

Figure 4. Delay for various values of α.
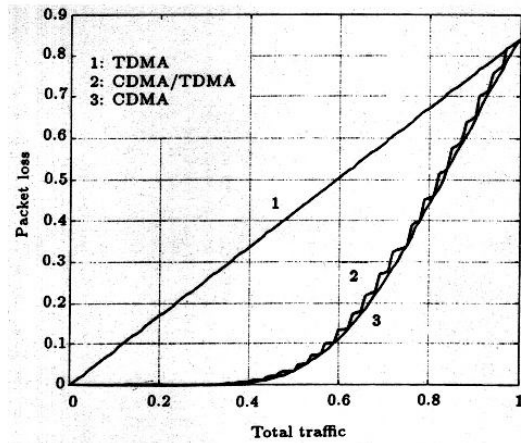
Figure 5. Packet loss for voice traffic.

Figure 3. Delay for voice traffic.
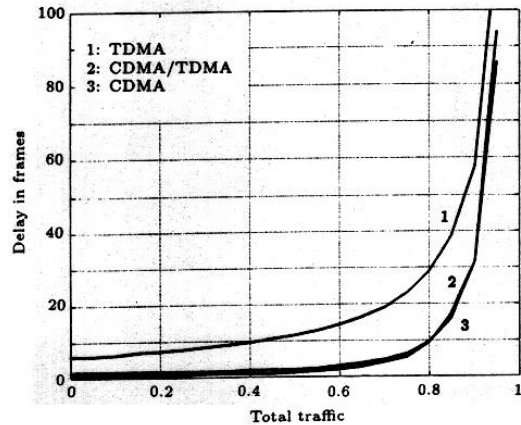
Figure 6. Delay for data traffic.

Figure 7. Throughput for data traffic.

Figure 9. Packet loss versus total traffic and SNR_b for voice traffic.
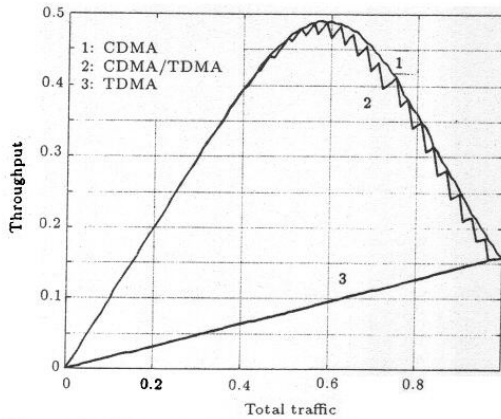
However, the CDMA and CDMA/TDMA systems have a much better throughput with a maximum of about 0.49. Note that the spread spectrum based systems represent low bit error probability for small values of SNR_b. This is achieved by increasing the bandwidth.

To see the effect of variation of SNR_b in the performance of these systems, the throughput for data traffic and the packet loss for voice traffic are computed and sketched for SNR_b in the range of 0.01 to 10. The results for the TDMA and CDMA systems are presented in Figures 8 and 9. The throughput of TDMA varies rapidly when SNR_b increases from 2 to 6, whereas in CDMA it remains almost constant for all values of SNR_b. Therefore, the performance of CDMA is not very sensitive to noise power. On the other hand, for small values of SNR_b, the packet loss of voice traffic for TDMA is more than that for the CDMA (Figure 9). However, by increasing SNR_b, TDMA shows a small packet loss as compared to CDMA. The packet loss for the CDMA system remains constant in a wide range of SNR_b. In addition to this, for traffic below 0.5, the packet loss is negligible in CDMA.

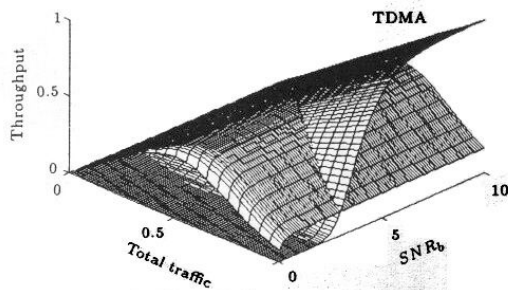The bit error probability versus normalized K is plotted in Figure 10. This figure shows that bit
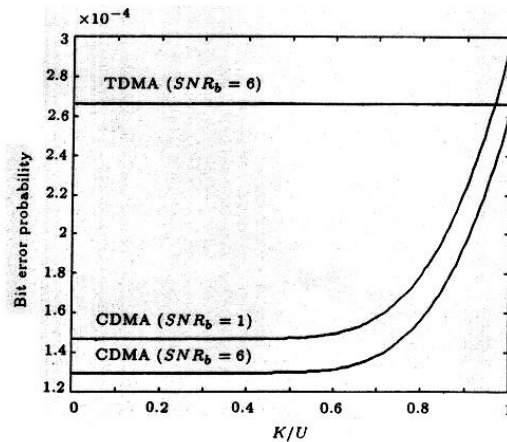

Figure 10. Bit error probability versus normalized K.

error probability in CDMA decreases with decreasing K, whereas it remains constant in TDMA. Hence, the smaller bit rate of some sources in CDMA improves the performance of the system in terms of the bit error probability; however, they do not have any impact on the bit error probability in TDMA.

CONCLUSION

The delay, bit error probability, throughput and packet loss of the TDMA, CDMA and CDMA/TDMA techniques for voice and data traffic in AWGN channels were studied. Some special capabilities of CDMA such as the activity ratio of voice traffic and the bit energy were taken into consideration. It was shown that the CDMA-related systems can efficiently use the burstiness factor of voice to reduce the total delay in packet transmission. For CDMA and CDMA/TDMA techniques, up to $\rho \approx 0.4$, packet loss was nearly zero whereas it increased linearly with traffic in TDMA.

Figure 8. Throughput versus total traffic and SNR_b for data traffic.

The inherent capability of CDMA in using the activity ratio of the voice traffic causes a nearly constant delay for a wide range of traffic. Spread-spectrum based systems represent better performance for small signal to noise ratios. Therefore, they are more appropriate for the power-limited channels or where the noise power changes rapidly, since they are not very sensitive to noise power.

In this paper, the inherent features of CDMA have been discussed and how these factors affect the performance of CDMA in comparison with TDMA is explained. In addition, it is illustrated that when the sources in the system have different bit rates, the bit error probability for CDMA is even smaller than that for the other multiple access systems. It is evident that the conditions of each channel and the characteristics of the traffic sources determine which method is more appropriate.

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