Throughput Enhancement of Direct-Sequence Spread-Spectrum Packet Radio Networks by Adaptive Power Control

Asrar Sheikh, Yu-Dong Yao and Shixin Cheng

Abstract—**This paper investigates the performance of direct-sequence spread-spectrum packet radio networks in the presence of the near/far problem. It is found that the maximum throughput of the network suffers degradation due to the near/far problem. However, analysis also shows that, under high traffic conditions, a network with the near/far problem delivers higher throughput than another without the near/far problem. This suggests that the direct-sequence spread-spectrum packet radio network with the near/far problem retains stability for heavier traffic conditions. Following these findings, a new adaptive power control scheme is suggested to enhance network throughput under both low and heavy traffic conditions. The mean and variance of the packet delay are derived and network stability and deadlock avoidance issues are discussed. The impact of channel fading on the network behavior is also studied in this paper.**

I. Introduction

IN direct-sequence (DS) spread-spectrum (SS) systems, the transmitter of a desired signal may be located at a greater distance from the receiver while other interfering transmitters may be situated relatively closer to it and could swamp the desired signal if all the transmitters are radiating equal power. In this situation, signal-to-interference ratio at the receiver is severely degraded and an increase in the error probability is observed. This phenomenon is known as the near/far problem or interference. Under certain circumstances, the near/far interference could become so severe that DS signalling cannot be used [1]. In order to achieve an acceptable performance, it is arranged through implementation of power control that all the signals arrive at the receiver with the same average power [2,3]. With all the signals arriving at the receiver with the same average power level, the near/far problem in DS systems is eliminated.

In this paper we study a packet radio network (PRNet) with DS SS signal transmission; in particular, the near/far effect on the DS SS PRNet is investigated. Our major concern is to compare the throughput of the network in the absence and presence of the near/far problem. Answers to two questions are sought. First, does the near/far problem decrease the throughput of the DS SS PRNets? Second, what benefits can we derive through implementing power control in a DS SS PRNet? In order to evaluate the stability of the network, we will also study the delay performance. The near/far effect on narrowband (non- SS) PRNets has been investigated recently [4-7]. In this paper, we consider a wideband SS PRNet and also evaluate the different impacts of the near/far problem on the performance of narrowband and wideband PRNets.

This paper is organized as follows. Section II gives a description of the PRNet under consideration. The throughput of the DS SS PRNet in the presence of near/far problems is derived in Section III, both steady and fading channels are considered. The delay performance of DS SS PRNets and network stability issues are studied in Section IV. Conclusions are drawn in Section V.

II. Packet Radio Networks

A PRNet consists of geographically dispersed users. They communicate with each other via radio links and a central base station may exist but is not necessary. ALOHA access has been used in such networks [4-8] but SS signalling is also considered to be a good choice because of several reasons. For example, SS is a flexible form of multiple access by allowing users to use the channel simultaneously since each user has unique pseudorandom sequence and therefore does not suffer from the classical collision problem of ALOHA. Antijam and anti-interference properties of SS are also valuable particularly in military PRNets. Spread spectrum techniques for PRNets have been studied in several papers [9-14]. The study reported in this paper differs from others in the consideration of the near/far and power control effects. We shall evaluate the throughput of the DS SS PRNet in the presence of near/far problems and compare it with the case when the near/far problem is absent. We then discuss the merits and demerits of implementing power control to mitigate the near/far effect in a DS SS PRNet. An adaptive power control strategy is proposed and analyzed for throughput and delay performance.

We consider an SS PRNet, in which packets are transmitted from one user to another via a central station. Only uplink communications (from users to the central station) is studied in this work. Infinite number of potential users generating Poisson distributed data traffic is assumed. All users transmit packets of equal length in slots, but the transmissions are not synchronized. It is assumed that the distance from each user to the base station is different and is an independent random variable; each with an identical distribution. In [15], it is considered that the distance possesses unimodal probability density function (p.d.f.) and a bell-shaped p.d.f. could be chosen for the distance. For mathematical convenience, as in [4,6,15], we choose

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the p.d.f. of r (the distance) in the form of

$$p_r(r) = \frac{5r_o^4}{r^5} exp\left(-\frac{5r_0^4}{4r^4}\right), \quad r > 0 \tag{1}$$

where r_0 is the mode of r.

The PRNet efficiency is measured in terms of channel throughput, S, which is defined as the average number of packets successfully transmitted in time equal to the duration of a packet slot. Because of the spectrum spreading of SS signalling, we will consider normalized throughput in the studies. If the number of packets generated in the network is Poisson distributed with mean channel traffic G_{tra}, the probability of an arbitrary concerned packet being overlapped by i other packets is [6]

$$p(i) = G_{tra}{}^i exp(-G_{tra})/i!, i = 1, 2, \ldots \tag{2}$$

Denoting P_{suc} as the probability that a packet is successfully transmitted, the channel throughput is given by

$$S = G_{tra} P_{suc} \tag{3}$$

The probability P_{suc} can be expressed as

$$\begin{aligned} P_{suc} &= p(0) P_{pac}(0) + p(1) P_{pac}(1) + p(2) P_{pac}(2) + \ldots \\ &= exp(-G_{tra}) \sum_{i=0}^{\infty} G_{tra}^i (P_{pac}(i)/i!) \end{aligned} \tag{4}$$

where $P_{pac}(i)$ is the probability that the packet concerned is received correctly when there are i interfering packets.

III. Throughput Performance of the DS SS PRNet

DS users send packets to the base station by using their own spreading sequences, which is usually referred as transmitter-oriented transmission [16]. Spreading sequences may be assumed to be random sequences. All users transmit signals at the same power level, but the signals arrive at the base station with different power levels because of different propagation distances, thus creating the near/far problem. Inverse fourth power propagation model is considered in this paper.

A. Signal-to-Interference Ratio

Consider a packet slot with i+1 active users. Each active user transmits packets with the same power level, P. The desired packet arrives at the receiver with power bP/y^4, where b is a constant considered to be identical for all users and y is the distance between the source of the desired packet and the base station. Other i packets from i active users create interference and arrive at the base station with power bP/y_j^4 (j=1, 2, ..., i), where y_j is the distance of j-th user to the base station. Considering that the SS system operates with processing gain G_{pro}, we can write the signal-to-interference ratio at the output of the receiver [14,17] as

$$SIR(i) = (bP/y^4) / \left((2/(3G_{pro})) \sum_{j=1}^{i} bP/y_j^4\right) \tag{5}$$

We consider that multi-user interference is the primary cause of failed reception of packets while Gaussian noise is negligible. In (5), y and y_j's are assumed to remain constant over one packet slot but may vary from slot to slot. Therefore, $SIR(i)$ is a random variable even for a fixed i. The probability distribution of $SIR(i)$ is derived as follows.

$$\text{Prob}[SIR(i) < x] = \text{Prob}\left\{y > \left[3G_{pro}/\left(2x\sum_{j=1}^{i}\frac{1}{y_j^4}\right)\right]^{\frac{1}{4}}\right\} \tag{6}$$

Let

$$a = \left[(3G_{pro})/\left(2x\sum_{j=1}^{i}\frac{1}{y_j^4}\right)\right]^{\frac{1}{4}} \tag{7}$$

Equation (6) is found to be

$$\begin{aligned} \text{Prob}[SIR(i) < x] &= \text{Prob}(y > a) \\ &= \int_0^{\infty} \ldots \int_0^{\infty}\int_a^{\infty} p_y(y)\, dy \left(\prod_{j=1}^{i} p_{yj}(y_j)\right) dy_1 \ldots dy_i \\ &= 1 - (1 + 2x/3G_{pro})^{-i} \end{aligned} \tag{8}$$

An interesting as well as important topic in DS SS-related studies is the "Gaussian approximation," i.e., the despread multi-user interference is approximated as a Gaussian random variable. This approximation is usually used in evaluating the bit error probabilities in a DS SS system [2,18]. According to [19], while the Gaussian assumption is often used, this is not strictly necessary to establish the signal-to-interference ratio expression. That is to say, (5) can be obtained without a strict requirement of the Gaussian assumption. Nonetheless, the Gaussian assumption is quite reasonable when the DS SS processing gain and the number of interfering users are large [17,18]. The accuracy of the Gaussian approximation is investigated in [13,20,21]. As shown in [13], for G_{pro}=31, the approximation is reasonably accurate when the number of interfering users is 9 or more. For the ratio of the number of users to processing gain, this is equivalent to a value of about 0.3 or larger. As will be seen later, this is the range of traffic loads of interest in this paper.

B. Evaluation of Throughput

As shown in (3) and (4), the throughput of a PRNet can be derived given $P_{pac}(i)$, the packet success probability in the presence of i interfering packets. We can accurately derive an expression for the probability, $P_{pac}(i)$, by considering the length of the packet, the modulation scheme chosen, and coding used, but as explained below the knowledge of these parameters is not necessary. We may assume that a packet can be received correctly when the signal-to-interference ratio exceeds a given threshold as the studies in [4-7,14]. This approach is acceptable since selection of any combination of modulation and coding schemes results in a certain signal-to-interference ratio necessary to obtain certain performance. In this paper, our main concern is the near/far effect on PRNets rather than the effects of packet length, modulation or coding; the reason why this approach to evaluate $P_{pac}(i)$ is used.

Assuming that the threshold of signal-to-interference ratio to achieve successful reception of the desired packet is T_{SIR}, we have

$$P_{pac}(i) = \text{Prob}[SIR(i) > T_{SIR}] = (1 + 2T_{SIR}/(3G_{pro}))^{-i} \tag{9}$$

Using (9) and (3) and (4), we can find the channel throughput. The throughput is then normalized to the operating bandwidth. We define "normalized throughput" S_{nor} as the ratio of throughput S to bandwidth expansion G_{pro} (processing gain), i.e., $S_{nor}=S/G_{pro}$, which is the throughput per "unit" of bandwidth [12]. Finally, we get

$$S_{nor} = (G_{tra}/G_{pro})\, exp\,(-G_{tra}) \sum_{i=0}^{\infty} G_{tra}^{i} \frac{\left(1+\frac{2T_{SIR}}{3G_{pro}}\right)^{-i}}{i!} = G_{nor} exp\left(-2\,(T_{SIR}G_{nor}) / \left(\frac{2T_{SIR}}{G_{pro}}+3\right)\right) \quad (10)$$

where $G_{nor}=G_{tra}/G_{pro}$ is "normalized channel traffic."

The normalized throughput of a DS SS PRNet in the presence of the near/far problem is shown in Fig.1, with T_{SIR} as a parameter. G_{pro} is assumed to be 31 in this example. It is seen that smaller T_{SIR} results in higher throughput. The curve with T_{SIR}=1 (i.e., 0 dB) is an ideal case, which gives a theoretical performance limit. The choice of T_{SIR} depends on the type of receiver, modulation and detection scheme used. For example, a receiver with good capture characteristics can tolerate higher interference levels and consequently a lower value of T_{SIR} may be acceptable for adequate performance. For a receiver with ideal capture T_{SIR}=1 can be used. Practical receivers depart considerably from ideal ones and require higher T_{SIR} to operate satisfactorily. For these receivers T_{SIR} in excess of 5 dB is usually deemed reasonable.

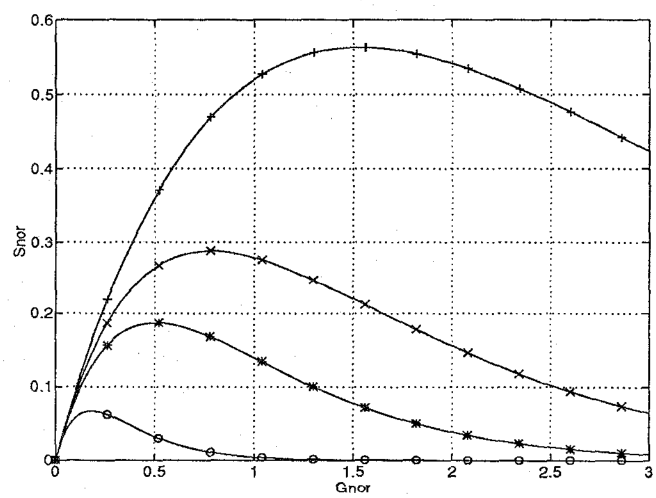

Fig. 1 Normalized throughput of a DS PRNet in the presence of the near/far problem; (G_{pro} = 31; T_{SIR} = 0 dB (+), 3 dB (x), 5 dB (*), and 10 dB (o))

C. Comparison with the Case without the Near/Far Problem

When power control is used in the DS SS PRNet, all packets (the desired and the interfering packets) arrive at the base station with the same power level, which eliminates the near/far problem. Under this condition, referring to (5), the signal-to-interference ratio in a slot with i+1 active users can be written as

$$SIR(i) = 3G_{pro}/(2i) \quad (11)$$

The probability $P_{pac}(i)$ is thus found to be

$$P_{pac}(i) = \text{Prob}\,[SIR(i) > T_{SIR}] = \begin{cases} 1 & ;\ 1 \le \text{INT}\left(\frac{3G_{pro}}{2T_{SIR}}\right) \\ 0 & ;\ \text{else} \end{cases} \quad (12)$$

where INT(.) indicates the largest integer smaller than or equal to the argument.

Inserting (12) into (4), the network throughput can be evaluated. In Fig.2, the normalized throughput of DS SS PRNets with and without the near/far problem are compared. It is observed that the maximum throughput of the network without the near/far problem (i.e., with power control) is higher than that of the one with the near/far problem (i.e., without power control). As shown in the curves with T_{SIR}=5 dB, the maximum throughput of the former (without the near/far problem) is 0.3032 while that of the latter (with the near/far problem) is only 0.1863. However, under high traffic conditions, the case with the near/far problem provides higher throughput. In the same example, the throughput of the network with the near/far problem is 0.1757 when G_{nor} is 0.7. Under the same conditions, the throughput of the network without the near/far problem is as low as 0.0378. Also note that the traffic range of G_{nor}≥.3 is of greater interest and importance in the comparison.

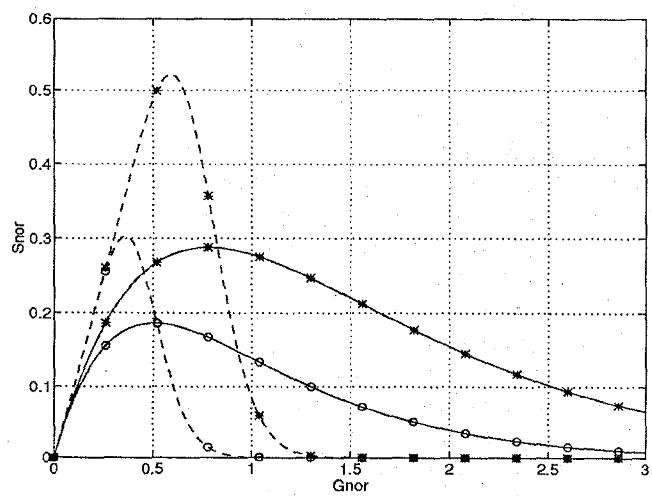

Fig. 2 Comparison of DS PRNets with and without the near/far problem; (G_{pro} = 31; T_{SIR} = 3 dB (*) and 5 dB (o); —: with the near/far problem, ---: without the near/far problem)

Figure 2 points out an interesting finding that the DS SS PRNet with the near/far problem (without power control) retains high throughput under heavy traffic conditions (i.e., seems to be more stable than the case with power control). This suggests that power control should not be implemented under heavy traffic conditions. However, under low traffic conditions, we must use power control in order to achieve higher throughput. An adaptive power control strategy is thus proposed where power control is in effect at low traffic and is switched off at high traffic conditions. The throughput curve of a DS SS PRNet with G_p=31 and T_{SIR}=5 dB using the proposed power control scheme is shown in Fig.3. In the proposed adaptive power control scheme, it is important to determine the traffic load at which deployment or suspension of power control takes place. Theoretically speaking, this is given by the traffic at which the throughput curves for systems with and without power control cross over.

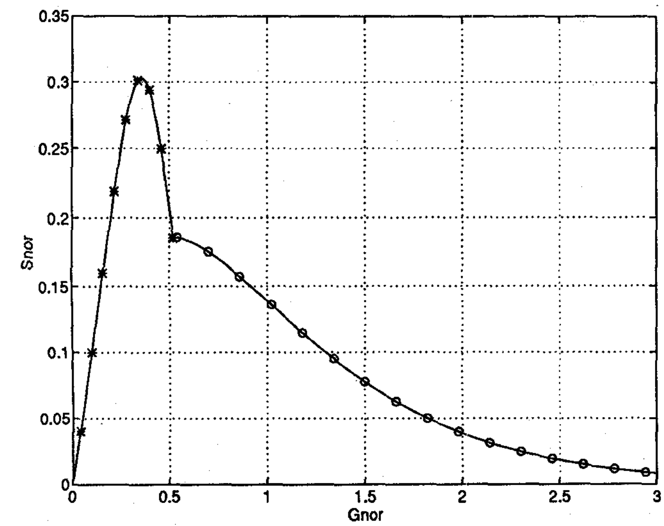

Fig. 3 Enhancement of throughput using adaptive power control; (G_{pro} = 31; T_{SIR} = 5 dB; *: deploying power control, o: suspending power control)

It is worth noting that the network stability issue can not be answered by using throughput curves alone. Therefore, a comparison about the stability of networks with and without power control can not be achieved using Fig.2. A better approach to evaluate network stability is to look into delay performance, which is given in Section IV.

Referring to [4-7], we find that the near/far problem has different effects on narrowband PRNets and wideband SS PRNets. Figure 4 shows the general tendency (we are not interested in the absolute value) of throughput curves of a narrowband ALOHA network and a wideband DS SS PRNet with and without power control. Figure 4(a) can be obtained using [7]. In the narrowband ALOHA network, the near/far problem increases channel throughput under both low and high traffic conditions and therefore power control is not recommended [4-7]. In a DS SS PRNet, as shown in this paper, an adaptive deployment/suspension power control scheme is desirable because the near/far problem degrades throughput at lower offered traffic, but has beneficial effects at higher offered traffic.

D. Presence of Fading

Signal fading is usually encountered in mobile PRNets. The exact form of fading depends on the nature of propagation conditions and the transmission bandwidth; flat Rayleigh fading [22] when signal bandwidth is narrower than the coherence bandwidth while frequency selective [22,23] when the transmission bandwidth exceeds it. Experiments [28] show that, in a mobile radio environment, the typical multipath delay spread varies from a low of 1/8 to a high of 16 μsec. In certain mountain areas delay spread figures up to 100 μsec. [29] have also been measured. Let us consider the multipath spread less than 1/2 μsec, a typical figure in the case of indoor or small cell land mobile radio. If the processing gain of the SS system is around 31 and message data rate is less than 25 kbps with PSK or DPSK modulation, the system can be considered to be operating in a flat fading (frequency non-selective) environment. This scenario is studied in this paper. If the system encounters larger multipath spread, considerations of frequency selective fading may be necessary [22,23]. In the case of the multipath channel where a discrete number of Rayleigh faded paths can be resolved, the network can be studied by considering that multipath propagation results in greater number of interference components. It is noted that a RAKE receiver [30] could be used under such circumstances to improve the system performance. In the case of multipath spread comparable to the chip duration of DS signals, severe intersymbol interference occurs. Both cases with frequency selective fading are not under consideration in this paper.

The expression of signal-to-interference ratio shown in (5) are generalized to include frequency non-selective fading by considering that all packets are affected by signal fading. We have

$$SIR(i) = \left(\frac{BbP}{y^4}\right) / \left(\frac{2}{3G_{pro}} \sum_{j=1}^{i} \frac{B_j bP}{y_j^4}\right) \quad (13)$$

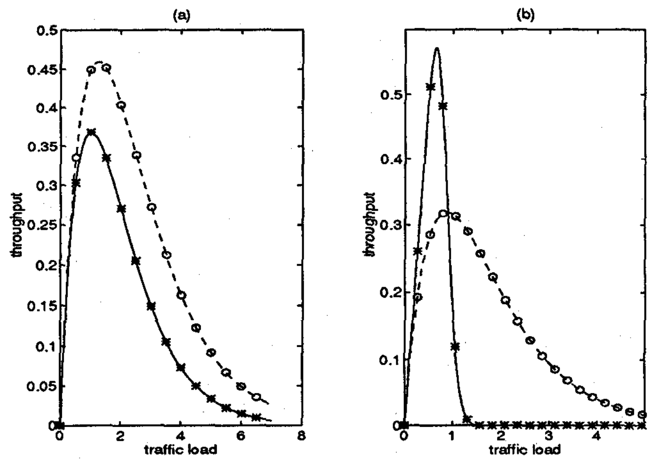

Fig. 4 Comparison of narrowband and wideband PRNets, effects of power control; (a) a narrowband ALOHA network (b) a wideband DS SS PRNet (*:with power control, o: without power control)

For a Rayleigh faded envelope, the corresponding instantaneous power is exponentially distributed. In (13), B and B_j's are independent random variables with an identical distribution expressed as

$$p_B(B) = \frac{1}{E(B)} exp\left(-\frac{B}{E(B)}\right) \quad (14)$$

for B>0. E(B) is the mean of B and E(B_j) =E(B) for all j. Let

$$z_j = B_j/B \quad (15)$$

the p.d.f. of z_j (j=1, 2,..., i) is derived as

$$p_{z_j}(z_j) = \frac{1}{z_j^2}\int_0^{\infty} p_{B_j}(B_j)\, p_{B_j}(B_j | z_j)\, B_j dB_j = \frac{1}{(1+z_j)^2} \quad (16)$$

for $z_j > 0$. Following the derivation in (8), we have

$$\text{Prob}\,[SIR(i) < x] = \int_0^\infty\int_0^\infty \cdots \int_0^\infty\int_0^\infty \cdots \int_0^\infty \left[1 - exp - \frac{5r_o^4 x}{6G_{pro}} \sum_{j=1}^{i} \frac{z_j}{y_j^4}\right] \left[\prod_{j=1}^{i} p_{yj}(y_j)\right] \left[\prod_{j=1}^{i} p_{zj}(z_j)\right] dy_1 \ldots dy_i dz_1 \ldots dz_i$$
$$= 1 - \left\{ \left(1 - \frac{2x}{3G_{pro}}\right)^{-1} \left[1 - \left(\frac{3G_{pro}}{2x} - 1\right)^{-1} \ln \frac{3G_{pro}}{2x}\right] \right\}^i \quad (17)$$

and then

$$P_{pac}(i) = \left\{ \left(1 - \frac{2T_{SIR}}{3G_{pro}}\right)^{-1} \left[1 - \left(\frac{3G_{pro}}{2T_{SIR}} - 1\right)^{-1} \ln \frac{3G_{pro}}{2T_{SIR}}\right] \right\}^i \quad (18)$$

Network throughput in the presence of fading as well as the near/far problem is shown in Fig.5. Degradation in throughput is observed when compared with that for the case without fading. In (13), (17) and (18), slow fading is implicitly assumed. Consequently, the power level of a signal (desired or undesired) remains constant over one packet duration, which results in that *SIR(i)* is constant throughout a packet. Under fast fading conditions, however, the signal level changes within a packet duration. In an extreme case (vary fast fading), adjacent bits in a packet are considered to be faded independently [7,24]. The very fast fading effect on ALOHA networks has been studied in [7] and we will not consider this effect in the present paper. Another channel impairment, log-normal shadowing [7], which usually occurs in a mobile radio environment, is not considered in this paper.

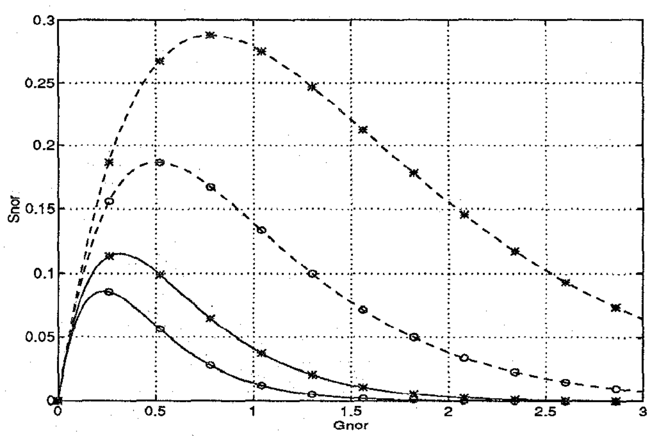

Fig. 5 Fading effects on a DS PRNet with the near/far problem ($G_{pro} = 31$; $T_{SIR} = 3$ dB (*) and 5 dB (o); —: with fading, ---: without fading)

IV. Delay Performance And Network Stability

A. Mean and Variance of Delay

The mean packet delay is another performance criterion of a PRNet. Assuming that the propagation delay is negligible, in a DS SS PRNet, the packet delay consists of the initial waiting time, the service time (packet transmission time), and the retransmission delay. Since packets are transmitted within well defined slots, a newly arrived packet must await the beginning of a slot to be transmitted. Given that a packet arrival occurring in a slot is uniformly distributed over one slot period, the average waiting time is simply half a slot. The service time is one slot since the packet length is of a slot. An average retransmission delay of 0.5(K+1) slots results whenever a retransmission is attempted [25] where a randomized retransmission strategy is used, in which the random time delay introduced is uniformly distributed over 1 to K slots. Denoting the number of total transmissions (transmission plus retransmissions) required to succeed in a packet transmission as m, we have the mean packet delay in slots

$$E\{d\} = 1.5 + E\{m-1\}\,[0.5\,(k+K)] \quad (19)$$

The p.d.f. of m is written as

$$p_m(m) = (1 - P_{suc})^{m-1} P_{suc};\; m = 1, 2, 3, \ldots \quad (20)$$

since an m-transmission event means that the first m-1 attempts fail and the m-th attempt succeeds. Equation (20) is a geometric p.d.f. [26] with mean P_{suc}^{-1} and variance $P_{suc}^{-2} - P_{suc}^{-1}$. Therefore we get the mean packet delay

$$E\{d\} = 1.5 + 0.5\,(K+1)\left(\frac{1}{P_{suc}} - 1\right) \quad (21)$$

and the variance of the packet delay

$$Var\{d\} = [0.5\,(K+1)]^2 \left(\frac{1}{P_{suc}^2} - \frac{1}{P_{suc}}\right) \quad (22)$$

Figure 6 shows the mean packet delay in a DS SS PRNet with

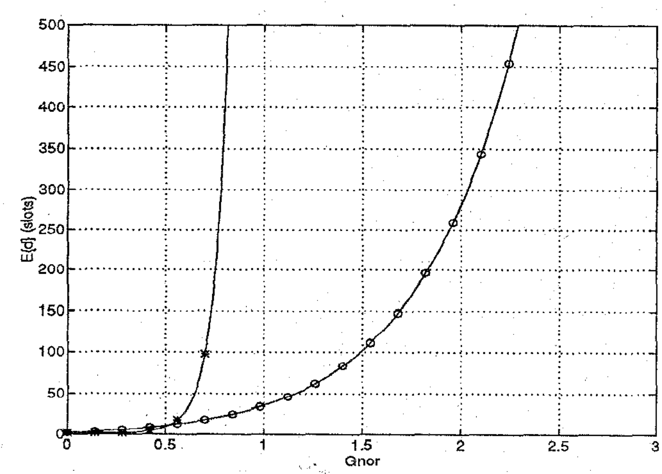

Fig. 6 Mean packet delay in DS PRNets with and without power control; ($G_{pro} = 31$; $T_{SIR} = 5$ dB; *: with power control, o: without power control)

or without power control. It is assumed that T_{SIR}=5 dB and K=10 (as in [25]). When the channel traffic is low (say, G_{nor}<0.5 in the example), smaller delay is experienced in a network with power control. Under high traffic conditions, the network without power control results in smaller delay. Also, when G_{nor}>0.5, the mean packet delay in a network without power control increases gradually with the increase of traffic load, while the delay in a power-controlled network increases dramatically (an unstable behavior). The variance of the packet delay is shown in Fig,7, which indicates the stability characteristics of the network. This is discussed in the following subsection.

B. Network Stability and Deadlock Avoidance

Network stability characteristics are usually investigated by considering the difference between the expected input traffic (new arrival) and the expected output traffic (successful transmission/retransmission) [12,27] or by considering the mean number of retransmissions [27]. The mean number of retransmissions is closely related to the mean packet delay as shown in (19). The variance of the packet delay, given in (22) and numerically in Fig.7, also characterizes the network stability. Under normal traffic conditions (low or medium traffic load, for example, G_{nor}<0.5), the network operates well (i.e., being in a good condition; reasonable throughput and delay). An increase in traffic load results in a larger delay. If the delay variance is relatively small, the delay fluctuation would be small and the network would keep in the good condition or return to the good condition after the traffic load returns to normal. However, if the delay variance is relatively large, the delay increase could be dramatic and the network may depart from the good condition and not be able to return to it after the traffic load is reduced. It is therefore concluded that a smaller delay variance is very important for maintaining network stability. In the example of Fig.7, smaller delay variance is achieved in a power-controlled PRNet when G_{nor}<0.5. In the event of G_{nor}>0.5, a critical traffic range regarding to network stability, the network without power control results in much smaller delay variance than the power-controlled network.

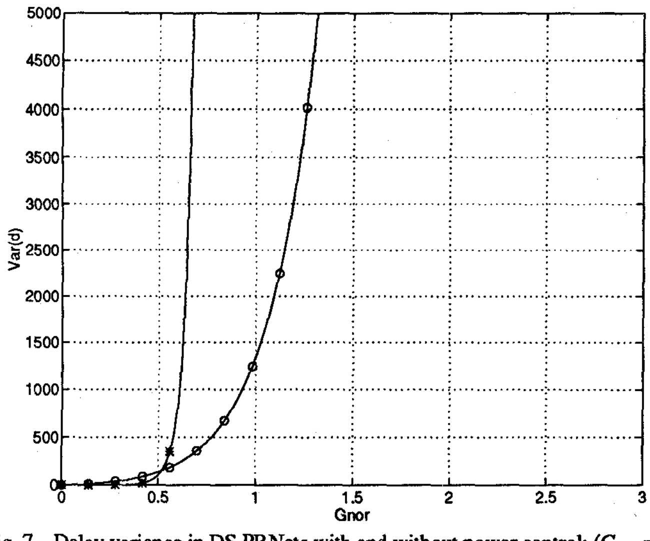

Fig. 7 Delay variance in DS PRNets with and without power control; (G_{pro} = 31; T_{SIR} = 5 dB; *: with power control, o: without power control)

Deadlock [26], an issue related to the network instability, is a phenomenon which occurs when the network is heavily loaded resulting in zero throughput. That is to say, no packet can be transmitted successfully. As shown in Fig.2, for the case with T_{SIR}=5 dB, deadlock occurs when $G_{nor} \approx 1$ in a power-controlled DS SS PRNet. In a DS SS PRNet without power control, deadlock may also occur but under extremely heavy traffic conditions and as shown in Fig.2, deadlock is virtually avoided. Therefore, the suspension of power control can be used as a means to avoid deadlock. The dynamic power control method given in Section III is thus used to stabilize the network. Under normal traffic conditions (say, G_{nor}<0.5 as in the example of Fig.3), power control should be deployed to achieve higher throughput. In a busy period, G_{nor}>0.5, the power-controlled network would turn to deadlock. Instead, using the dynamic power control method, the power control is suspended during the busy period and the deadlock is thus avoided as shown in Fig.3. After the busy period, the traffic load returns to normal and the power control is deployed again.

The reason to be able to achieve deadlock avoidance is explained as follows. Under high traffic conditions, the network is over loaded and the traffic exceeds the network capacity. With power control, all transmitting packets arrive at the receiver (base station) with the same power level. Not a single packet can be received successfully and the network throughput drops to zero (deadlock). With suspending power control, packets arrive at the receiver with different power levels and those packets with higher power levels have better chances to be received successfully resulting in non-zero network throughput. The is actually due to capture effects (high-power packets capture the receiver) [4-7].

A similar statement can be made to explain Fig.2, i.e., the comparison of DS SS PRNets with and without power control. Under low and medium traffic conditions, the number of interfering packets is usually smaller than INT[$3G_{pro}/(2T_{SIR})$] (see(12)) and every packet can be received successfully in a power-controlled PRNet. However, in the network without power control, those packets with lower power levels may not be received correctly. Therefore, power control is required to achieve higher throughput in this traffic region. If the traffic is very high, successful packet reception is still possible in a PRNet without power control because of the capture effects while this is not the case for a power- controlled PRNet. This explains why power control should not be used in case of very high traffic.

V. Conclusions

Several observations are made in this paper. First, the maximum throughput of DS SS PRNets decreases due to the existence of the near/far problem. Second, because of the near/far effect, the throughput of the DS SS PRNet increases comparing with that of the network without the near/far problem under high traffic conditions. The results obtained in this paper indicate that the implementation of power control is helpful only when channel traffic is low. Therefore, we may use power control under low traffic conditions and suspend the power control in case of high channel traffic. This is the adaptive power control scheme suggested in this paper to enhance the throughput of DS SS PRNets under both low and high traffic conditions. The network stability issue is studied through the evaluation of the mean and variance of the packet delay. It is also observed that network deadlock is virtually avoided using the adaptive power control strategy.

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