Interference Evaluation in CDMA Ad Hoc Networks

R. P. Ramos, M. Geandre Rêgo, Tarciana Lopes, R. Baldini Filho and C. de Almeida

***Abstract*— This work presents an expression for the mean value of the interference in wireless code division multiple access (CDMA) ad hoc networks. CDMA is an interesting alternative for ad hoc networks, due to its characteristics, such as, multiple transmissions and interference rejection. Multihop CDMA network models generally consider network interference as a random variable with known distribution. Unlike the proposed model, this work analyses the performance of the CDMA ad hoc network as a function of the number of interferers deriving an expression for the mean value of the interference.**

***Index Terms*— CDMA, ad hoc networks, performance, interference, mean value.**

I. Introduction

Mobile ad hoc networks have recently been the theme of several researches [1] [2]. The main feature of wireless ad hoc networks is its ability to allow a group of communications nodes to set up and maintain a network among themselves, without the support of a base station or a central controller. Many technological factors, such as cheaper hardware, smaller transceivers, and faster processors are increasing the interest in wireless ad hoc networks.

From the applications perspective, wireless ad hoc networks are useful for situations that require temporary networking capability, such as crisis response, conference meetings, sensor networks, military applications, home and offices networks, etc. One of the fundamental challenges in mobile ad hoc networks is to increase the overall network throughput. The low throughput is attributed to the hostile characteristics of the radio channel combined with the contention-based nature of medium access control (MAC) protocols commonly used in ad hoc networks [3].

In wireless CDMA ad hoc networks, differently from the network models used in the literature [1] [2], multiple simultaneous successful transmissions using all of the available spectrum are possible. CDMA is based on spread spectrum techniques, in which the user occupies the entire available bandwidth, through use of spreading codes [4]. In CDMA systems, multiple packets with different spreading codes can be correctly received simultaneously by different receivers in a time slot (i.e. the multiple access capability of CDMA systems). Other desirable features of CDMA systems include multipath resistance, inherent multipath time diversity and interference rejection. Therefore, it is not surprise that CDMA is being used in ad hoc networks.

The authors are with the Communications Department - DECOM, State University of Campinas - UNICAMP, C.P. 6101, CEP: 13083-852, Campinas-SP, Brazil. Emails: {rramos,geandre,tarciana,baldini,celso}@decom.fee.unicamp.br

The ability of wireless ad hoc networks to satisfy quality of service (QoS) requirements is still an open problem. Factors such as, the difficulty of sharing the channel medium with many neighbors, make difficult to solve the QoS challenges. CDMA ad hoc network models presented in the literature [5] [6] [7] consider the network interference as a random variable with known distribution. In this work, the performance of a multihop CDMA network is analysed based on a new expression for the mean value of the interference. The expression obtained is directly to the number of interfering users, which provides a more comprehensive measurement tool.

This paper is structured as follows. In Section II, the system model is described. Section III discusses the factors that affect the network capacity. The mean value of the interference is obtained and discussed in Section IV. Section V summarizes the key conclusions.

II. System Model

The system model consists of a direct-sequence CDMA ad hoc network under heavy traffic conditions with binary phase shift keying (BPSK) and rectangular chip pulse. The system is slotted and each terminal transmits independently of others with probability p. The traffic is assumed to be uniform. During each slot, a snapshot of the terminals is taken, that is, the network topology is constant over a packet transmission time, which is equivalent to have a constant interference level during this time interval [5]. The positions of terminals obey an area uniform distribution. The number of terminals in the network is modeled by a Poisson point process in a plane, with probability density function (PDF):

$$P[k\ terminals\ in\ R_a] = \frac{e^{-\lambda A_r}(\lambda A_r)^k}{k!}, \tag{1}$$

where the parameter λ is the average number of terminals per unit area and A_r is the area of a given region R_a in the plane.

Let's assume a wireless multihop network where the band-pass equivalent model of the transmitted signal in an environment with K terminals is given by:

$$s(t) = \sum_{k=1}^{K} s_k(t), \tag{2}$$

where

$$s_k(t) = A_m d_k(t-\tau_k) c_k(t-\tau_k) y_k e^{j\phi_k}, \tag{3}$$

where k represents the terminals index, A_m the transmitted signal amplitude, $d_k(t)$ is the k-th terminal information bit stream, τ_k the symbol delay, $c_k(t)$ is the k-th terminal spreading sequence, ϕ_k is the initial carrier-phase (without loss of generality its value is assumed to be 0) and y_k is the path-loss of the terminal k, that is given by:

$$y_k = \frac{1}{r_k^{\gamma/2}}, \tag{4}$$

where γ is the path-loss exponent and r_k is the distance between the k-th terminal and the receiver terminal.

The conventional detection of the CDMA systems, using matched filters, presents the following expression for signal-to-interference-plus-noise ratio per encoded bit, by considering that the transmitted power is the same in all terminals:

$$\gamma_{bc} = \frac{1}{\frac{1}{r_c}\left[\frac{2Y}{3G_pR^{-\gamma}} + \left(\frac{E_b}{N_0}\right)^{-1}\right]}, \tag{5}$$

where r_c is the code rate, G_p is the processing gain, E_b/N_0 is the signal-to-noise ratio, R is the distance from the desired transmitter to the target user and Y is a random variable that represents the total interference power at the receiver normalized by the transmitted power [5], given by:

$$Y = \sum_k y_k^2 \tag{6}$$

Reference [5] derived the distribution of the interference power Y at a receiver and the optimum transmission ranges in multihop DS-CDMA networks over AWGN channel. Its probability density function is given by:

$$p_Y(y) = \frac{\pi}{2}\lambda_t y^{\frac{-3}{2}} e^{\frac{-\pi^3\lambda_t^2}{4y}}, \tag{7}$$

where $\lambda_t = p\lambda$ is the average number of transmitting terminals per unit of area.

A new approach will be developed based on an approximating γ_{bc} by its mean value. This is equivalent to calculate the mean value of the variable Y defined in (6).

In order to calculate the mean value of the interference, it is considered a very large circle with radius A centered at the target terminal inside it, that contains K transmitting terminals, R being equals to the desired transmitter-target terminal separation distance and r_0 being a very small radius in such a way that the transmitted power is assumed to be constant within it. It is also assumed that the signal strength decays only after distance r_0 from the target terminal, $r_0 \ll R \ll A$. Figure 1 depicts the considered distances to estimate the interference value.

Considering that all terminals are simultaneously transmitting at the same transmitted power, the random variable that represents the interference power at the origin is given by:

$$I = \sum_{k\in D_A} P_t r_k^{-\gamma}, \tag{8}$$

where P_t is the transmitted power, r_k is the distance of the kth terminal to the target terminal and $D_A = \pi A^2$ is the area of the circle of radius A.

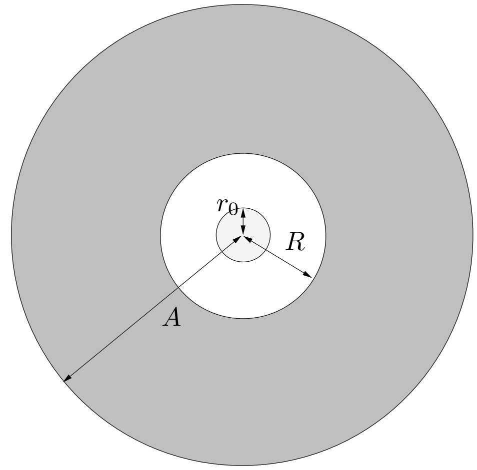

Fig. 1. Scenario considered to calculate mean value of the interference

The mean value of the interference normalized by the transmitted power is:

$$\begin{aligned}\overline{I} &= \sum_{k\in Da} E\{r_k^{-\gamma}\} \\ &= (K-1)E\{r^{-\gamma}\},\end{aligned} \tag{9}$$

where $(K-1)$ is the number of the transmitting terminals within the area D_A.

Since the terminal positions are uniformly distributed in the circular region of radius A, then the probability density function of r is:

$$p_r(r) = \begin{cases} \frac{2r}{A^2}, & r \leq A \\ 0, & otherwise \end{cases} \tag{10}$$

The mean value of r is given by:

$$E\{r^{-\gamma}\} = \int_{-\infty}^{\infty} r^{-\gamma} p_r(r)dr \tag{11}$$

Assuming a path loss exponent $\gamma = 4$ and substituting (10) into (11), results:

$$\begin{aligned}E\{r^{-\gamma}\} &= \int_0^A \frac{1}{r^4}\frac{2r}{A^2}dr \\ &= \int_0^{r_0} \frac{1}{r_0^4}\frac{2r}{A^2}dr + \int_{r_0}^{A} \frac{1}{r^3}\frac{2}{A^2}dr \\ &= \frac{1}{A^2}\left(\frac{2}{r_0^2} - \frac{1}{A^2}\right)\end{aligned} \tag{12}$$

Finally, substituting (12) in (9), the mean of the interference normalized by the transmitted power results to:

$$\overline{I} = (K-1)\frac{1}{A^2}\left(\frac{2}{r_0^2} - \frac{1}{A^2}\right), \tag{13}$$

The mean value of the signal-to-interference-plus-noise ratio per encoded bit is obtained as:

$$\overline{\gamma_{bc}} = \frac{1}{\frac{1}{r_c}\left[\frac{2\overline{I}}{3G_pR^{-\gamma}} + \left(\frac{E_b}{N_0}\right)^{-1}\right]} \tag{14}$$

Then, the mean encoded bit error probability can be written as [4]:

$$P_{bc} = Q(\sqrt{2\overline{\gamma_{bc}}}) \tag{15}$$

where $Q(.)$ is the area under the Gaussian tail and $\overline{\gamma_{bc}}$ is given by (14).

From (13) and (14), can be seen that the new expression obtained for $\overline{\gamma_{bc}}$ is directly related to the number of interfering users, which gives a more comprehensive measure for the mean interference value.

III. Network Capacity

Following the theoretical analysis derived in [5], we are going to state the network capacity. Before introducing this measurement tool, we are going to derive the nodal throughput of the network as a function of the transmission probability p and the probability of a packet success P_s.

The probability of a packet success is entirely dependent on the coding scheme. A linear block code of length n and error correction capability t, represented by (n, k, t) is considered [8]. Then, the probability of a packet success is given by:

$$P_s = \sum_{i=0}^{t} \binom{n}{i} (P_{bc})^i (1 - P_{bc})^{n-i} \tag{16}$$

where P_{bc} is the mean encoded bit error probability given by (15).

The nodal throughput is the rate at which a terminal successfully transmits a packet. Since it is assumed a uniform traffic and considering the routing to be "balanced", the nodal throughput will be the same for all terminals. Ref. [5] shows that the nodal throughput of a network with a very large number of potential transmitters is given by:

$$\xi = (1 - p)(1 - e^{-p})\, P_s \tag{17}$$

where $(1 - p)(1 - e^{-p})$ is defined as the tendency to pair up (per terminal), and P_s is the probability of a packet success. The tendency to pair up can be viewed of as a tendency to a given transmitter to establish a connection with the target receiver.

A. Expected Progress per Slot

The expected progress per slot has been used in previous works as the performance criterion in the analysis of ad hoc networks. It is a measure of network throughput, and it is defined as the product of the local terminal throughput to the distance between the transmitter and receiver (number of bit-meters per symbol period per terminal) [5]. It is a performance measure that increases with P_s and decreases as the number of hops increases. The expect progress per slot is given by [5]:

$$Z = \xi R \tag{18}$$

where ξ is the one-hop throughput of the transmitter, defined in (17).

IV. Results

In this section, some numerical results are presented for the expected progress per slot, using the results derived on the last two sections.

Figure 2 shows the expected progress per slot versus the distance between transmitter and receiver (R) for an AWGN channel, and different values of transmitting terminals (K). A BCH code (127,71,9) is used together the following system parameters: $G_p = 64$, $\frac{E_b}{N_0} = 10$ dB, $r_0 = 0.1$m and $A = 200$m.

In a multihop network, there is usually a trade off between the distance covered in one hop and the probability of a successful transmission. It is picted from Fig. 2 that there exists an optimum link distance for each corresponding value of K. Note that for 10 transmitting terminals inside the area A, the optimum link distance is approximately 3.7 m, while for $K = 60$, the optimum transmitter-receiver distance is almost 2 m. Therefore, an increase in the number of transmitting terminals, corresponding to an increase of interferers, decreases the optimum link distance.

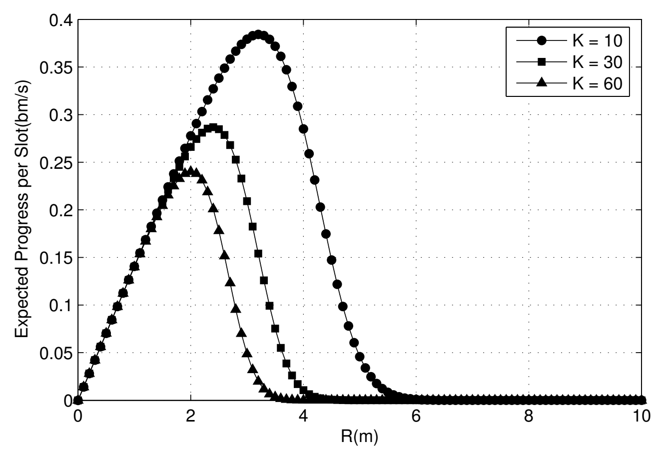

Fig. 2. Expected Progress per Slot versus R

A different view of the expected progress per slot is plotted in Figure 3. Now, it is parameterized in K, for different values of R. The same values attributed in the Fig. 2 are used in Fig. 3.

An increase on the interferers number, density of users in the area A, degrades considerably the network capacity. An interesting observation is that as shorter the link is more softly the expected progress per slot varies with the increase of the transmitting terminals. This can be explained by noting that a smaller radius means less interferers close to the transmitter in spite of the number of bigger hops.

V. Conclusions

In this work the performance of ad hoc CDMA networks has been evaluated through an expression for mean value of the interference. It concerns the analysis of the multiple access interference (MAI), addressing the near-far problem that undermines the throughput performance in CDMA ad hoc networks. This work also concluded that there exists an

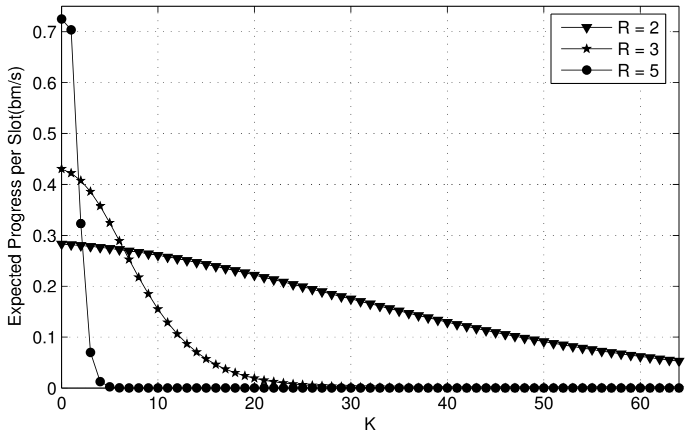

Fig. 3. Expected Progress per Slot versus K

optimum link distance depending on the number of transmitting terminals. Moreover, the expected progress per slot as a function of the transmitting terminals (interferers) is presented. These results can be useful to assess the behavior of the ad hoc CDMA networks under the system loading aspect.

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