Admission Control for Maximal Throughput in CDMA Systems

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***Abstract*— Power control is a fundamental component of CDMA networks because of the interference that users cause to one another. Consequently, too many users in the system may lead to an overload whereas too few would generate an inefficient use of resources. Previous work by the authors has highlighted some fundamental properties of a CDMA system pertaining to the required power distribution when a particular terminal has reached its power limit. These properties have formed the basis for an admission control scheme which leads to an efficient use of system resources. This paper expands on this scheme and shows that optimal throughput with a fixed number of users can be achieved for a range of received power values and that this range of values is affected by the geometry of the users' location relative to the base station. Further, we determine the conditions under which both the analytical solutions and physical simulations agree.**

I. Introduction

Code division multiple access (CDMA) is a wireless communications standard well accepted by industry today. Much research has gone into optimizing the system for voice and data applications. Data applications in particular are very important due to the proliferation of the Internet and peer-to-peer communications. Early work on optimal CDMA resource allocation focused on power control for telephone communications and determined that to maximize the number of voice connections all signals should arrive at a base station with equal power [1]. When considering delay tolerant data communications one of the most practical measurements of system performance is the aggregate throughput of information that passes through the system per unit of time. There are various approaches to achieve maximum throughput in a wireless cellular system. The main controllable variables are data rate, transmit power, number of users simultaneously operating in the cell, and the scheduling of the transmissions.

The throughput may be optimized with respect to any individual resource or a combination of them. For example, initial studies of power control for data communications focused on maximizing the utility of each terminal, with utility measured as bits delivered per Joule of radiated energy [2], [3]. References [4]–[6] perform throughput maximization through joint rate and power control. A related strand of recent work [7]–[10] adjusts the power and rate of each terminal to maximize the aggregate weighted throughput of a base station.However, this analysis does not consider how or when users should be allowed into the system. Reference [11] maximizes the rate and considers the optimum number of users that the cell may support while minimizing the total transmit power. Our analysis is based on the fact that there is always a minimum received power from the set of users in the cell and find the optimal number of users in a cell using fundamental concepts.

Early analysis in cellular systems led to admission control strategies that optimized the system's Erlang Capacity [12] or the number of active connections per unit bandwidth. References [13]–[15] consider admission control subject to a specified minimum required received signal-to-interference plus noise ratio (SINR). Our analysis, by maximizing over the number of users in the system, gives us the precise value of the SINR to achieve maximum throughput.

Our previous work concentrated on maximizing the aggregate data throughput of a CDMA base station. Recent work reported in [16] dealt specifically with the case when noise and out-of-cell interference are negligible, and found that the transmitter power levels should be controlled to achieve power balancing. With power balancing, all signals arrive at the base station with equal power. In [17] we found that with additive noise (a) power balancing leads to sub-optimal performance and (b) that when one terminal has a maximum power constraint, the other terminals should aim for the same received power, which depends on the maximum SNR of the constrained terminal. The optimization performed is based on a function which reflects the quality-of-service (QoS) of a user. The function is a frame success function (FSF) that embodies various properties of the physical layer, such as receiver structure and coding techniques. Our goal is not only to attain the optimal power control scheme but also to decide on the optimal number of terminals the system may support given that they are power limited.

The main contribution of this paper is the demonstration that there is a key parameter: the interference noise-to-received power ratio, ρ, that controls the call admission mechanism. The parameter ρ also reflects the effects due to location of the individual terminals as well as their transmission capabilities. We find a range of ρ where the optimal number of users permitted in the system remains constant. The optimal number of users results in maximum throughput and this value tracks the analytical results well under certain conditions.

This paper is organized as follows. The next section presents an analytical system model that is used for the optimization and the algorithm which is used for admission control. Section III we present a physical system and apply our algorithm. We provide some numerical results and comment on the algorithms performance. Finally, Section IV discusses the implications of the results and points to future research directions.

II. System Model

A. Analytic Model

We consider a wireless CDMA system with N terminals. Each terminal generates a constant stream of information to transmit in packets. Each packet contains L information bits. A forward error correction (FER) code, if present, and a cyclic redundancy check (CRC) are added to each packet for a net packet length of M bits. These M bits are transmitted by user i at a rate of R_i bits/sec. A digital modulator then spreads the incoming sequence of bits into a bandwidth of W Hz which is a system constant. The processing gain is then defined as $G_i = W/R_i$. Finally, the spread sequence is RF modulated and transmitted with a power of P_i watts. The path gain from terminal i to the base station is h_i. The received signal power from user i is then $Q_i = P_i h_i$. There is also power received from the environment such as the inter-cell interference and receiver noise. Both components are treated together as additive white Gaussian noise (AWGN). The receiver AWGN, σ^2, is identical for all the users. For notational convenience we define the following:

$$
\begin{aligned}
s_i &= \frac{Q_i}{\sigma^2} \\
\rho_i &= \frac{1}{s_i}
\end{aligned}
$$

where s_i is the received signal-to-noise ratio and ρ_i is the noise-to-received signal ratio.

At the base station there is a demodulator, correlator, and CRC/FEC decoder. All of the details about the transmission system (RF modulation, CRC, etc.) are represented by a unitary function $f_i(\gamma_i) = f_{s_i}(\gamma_i) - f_{s_i}(0)$,where $f_s(x)$ is known as the frame success function (FSF), which is dependent on the received signal-to-interference-plus-noise ratio (SINR) ,γ_i defined as:

$$
\begin{aligned}
\gamma_i &= \frac{GP_i h_i}{\sum_{j\neq i} P_j h_j + \sigma^2} && (1)\\
&= \frac{GQ_i}{\sum_{j\neq i} Q_j + \sigma^2} && (2)\\
&= = \frac{Gs_i}{\sum_{j\neq i} s_j + 1} = G\alpha_i && (3)
\end{aligned}
$$

The FSF is the probability of receiving a frame of length M bits successfully and depends on the transmission system, packet size, modem configuration, channel coding, antennas, and radio propagation conditions. An important property of this function which we will be using is that it is a sigmoidal function [18], [19] and hence monotonically increasing in its argument.

The actual throughput of any particular user is therefore

$$T_i = \frac{RL}{M} f(\gamma_i) \tag{4}$$

The goal is to maximize the throughput of the base station defined as

$$U_N = \sum_i \beta_i T_i \tag{5}$$

We make some very basic assumptions in our analysis considering the above system model. First, all the terminals are operating at some fixed data rate, $R_i = R$ bits/sec, $\forall i \in N$. This then results in all users having a fixed processing gain $G_i = G$, $\forall i \in N$. We also assume that one terminal is transmitting at it's maximum power. This is a very practical consideration because this event may occur when the terminal is located in a very poor location which results in its received signal strength, whether on the down-link or the up-link, to be highly attenuated. The received power is small and the received SINR is even less.

The rationale behind assuming that one terminals transmits at maximum power can be easily verified. Given equation (4) let us assume that the users may scale their powers by some factor $\epsilon > 1$. The received SINR is then

$$\gamma_i = \frac{GP_i h_i \epsilon}{\sum_{j\neq i} P_j h_j \epsilon + \sigma^2}$$

while the equation for the throughput remains the same. Taking the derivative with respect to ϵ yields

$$\frac{\partial T_i}{\partial \epsilon} = \frac{RL}{M} f'(\gamma_i) \frac{\sigma^2 G P_i h_i}{\left(\sum_{j \neq i} P_j h_j \epsilon + \sigma^2\right)^2}$$

and given that $f'(x) > 0, \forall x > 0$, the throughput can increases when all the users increase their power. Practically, this can not go on forever because of the limited amount of power that batteries may deliver.

Each terminal has a maximum transmit power, $P_{i,max}$, and hence a maximum received signal strength, $Q_{i,max}$. We assume that there is a terminal which is power limited. By power limited we mean a terminal whose maximum *received* power is less than all the other terminals and label this as the N^{th} terminal. In our analysis we order the labels of the terminals such that $Q_{1,max} \geq Q_{2,max} \geq \cdots \geq Q_{N,max}$. We may rewrite the received SINR expression of (1) by dividing both the numerator and the denominator by $Q_{N,max}$ to get the following,

$$\gamma_i = \frac{G z_i}{\sum_{j \neq i} z_j + \frac{\sigma^2}{Q_{N,max}}} = \frac{G z_i}{\sum_{j \neq i} z_j + \rho + 1}, \forall i \neq N$$

$$\gamma_N = \frac{G}{\sum_{j \neq i} z_j + \frac{\sigma^2}{Q_{N,max}}} = \frac{G z_i}{\sum_{j \neq i} z_j + \rho}$$

where

$$z_i = \frac{Q_i}{Q_{N,max}}$$

B. Previous Results

To find the value of z_i, $i \neq N$ that leads to maximum throughput, we proceed by taking the first order derivatives with respect to every z_i. It was shown in [20], [21] that when one terminal is power limited the other terminals in the system must aim for an equal received power value that is strictly greater than that of the power limited terminal, i.e. $Q_i = Q_j \, \forall i, j \neq N$ and $Q_i/Q_N \triangleq z_i = z > 1$, $i \neq N$. In this case the received γ_i may be rewritten as:

$$\gamma_i = \gamma = \frac{Gz}{(N-2)z + 1 + \rho} \quad (6a)$$

$$\gamma_N = \frac{G}{(N-1)z + \rho} \quad (6b)$$

where $\rho = 1/s_N$.

Furthermore, [20] showed that the optimal $\gamma = \gamma^*$ is found by solving the following

$$\frac{f(\gamma)}{\gamma\left(1 + \frac{\gamma}{G}\right)} = f'(\gamma) \quad (7)$$

and the optimal $\gamma_N = \gamma_N^*$ is found by solving

$$(1+\rho) f'(\gamma^*) (G + \gamma^*)^2 = f'(\gamma_N) (G + \gamma_N)^2 \quad (8)$$

Since γ^* can be uniquely found from (7), (8) is simply a function of γ_N. We know from [22] that the RHS of (8) is upper bounded and the only unknown value that must be supplied is ρ. Hence, if ρ is too large, there may not be a solution to the problem. A plot of these two equations for $\rho = 1$ and $G = 128$ is shown in Figure 1. There are actually two possible solutions to (8). We take as the optimal γ_N^* the larger of the two because of our previous argument that the larger the received SINR the larger the throughput. Observe that both γ^* and γ_N^* are in terms of z and N and since we have two equations in two unknowns we may find the unique solution. For the particular FSF pertaining to non-coherent FSK the optimal ratio was found to be $z^* = Q_i/Q_N \approx 1.21$ and the corresponding optimal number of users is $N^* = 12.04 \approx 12$.

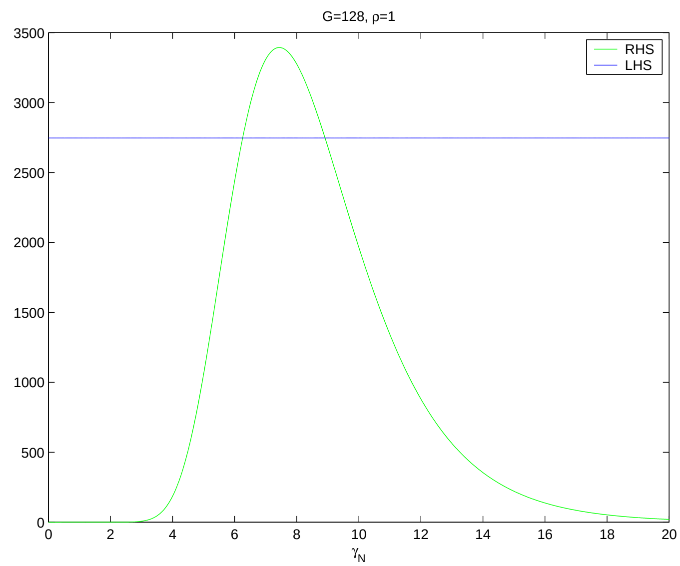


Fig. 1. Plot of equation (8)

To get a better understanding about the system we find the maximum number of terminals that may be allowed into the system. The resulting value of z necessary for maximizing the throughput is found by rearranging equation (6a) and solving for z to get

$$z = \frac{(1+\rho)}{\left(\frac{G}{\gamma^*} + 1\right) - (N-1)} \quad (9)$$

We may make several observations here. First, as the noise-to-received power ratio of the power limited terminal increases, so does the necessary received power of the other terminals. Also, the feasible number of users that the system may support must satisfy the positivity constraint of power, specifically

$$(N-1) < \left(\frac{G}{\gamma^*}+1\right) \Rightarrow N < \frac{G}{\gamma^*}+2 \qquad (10)$$

where the N^{th} user is power limited. If equation (10) is met with equality, then $z = \infty$. This implies that all of the other users must operate at a very high power to make the interference from the weak terminal negligible. As long as the number of users in the system is in the feasible range described by (10) we may find a valid value of z.

A sub-optimal solution is to use power-balancing (or equal received powers), $z = 1$. The optimal number of users that the system may support in this particular case is found from the following equation:

$$N^* = \frac{G}{\gamma^*} + 1 - \rho \qquad (11)$$

Note how noise acts as ρ interfering users. When $\rho = 1$, then $N^* = 11.69$. If we round to the nearest integer then we see that the optimal number of users is identical to that with the optimal power ratio. Hence, our presumption for using $z = 1$ is verified in this case.

Clearly our analysis is heavily dependent on the power received from the weakest terminal, the one with the highest noise power spectral density-to-received power ratio, $\rho_N = \sigma^2/Q_N$. This reflects how the system should behave as the N^{th} terminal gets weaker, or equivalently how the system behaves when a terminal begins to distance itself from the base station. Based on these results Algorithm 1 is proposed. Note that N is the *initial* number of users in the cell.

Algorithm 1 Finding Optimal N^*

1) Solve for γ^* from (7)
2) Measure all of the received powers Q_i and sort them.
3) Label the user according to $Q_{1,max} \geq Q_{2,max} \geq \cdots \geq Q_{N,max}$
4) For $j = N$ to 1
   a) Calculate $\rho_{j,max} = \sigma^2/Q_{j,max}$
   b) Calculate $\hat{j} = G/\gamma^* + 1 - \rho_{j,max}$.
5) Admit into the system the terminals $i < j$, $i, j \in N$, where j is closest to $\hat{j}$.

III. Numerical Analysis

Let us consider what the optimal number of users in the system would be for any particular value of ρ_{max}. The result is shown in Figure 2.

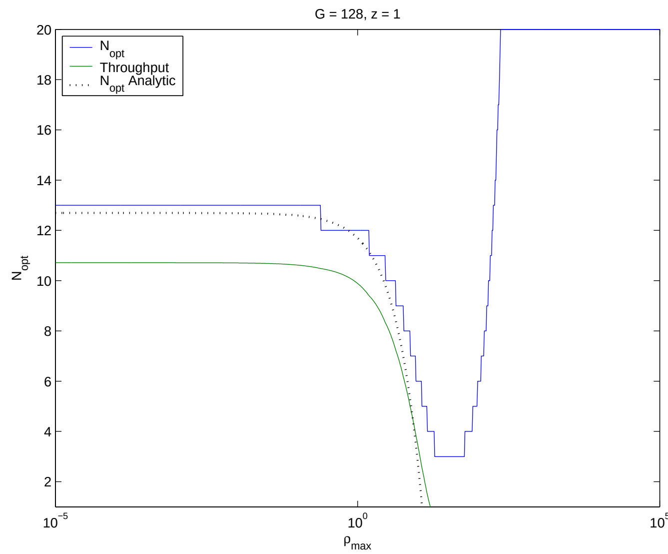


Fig. 2. Optimal number of users for the value of processing gain $G = 128$ and $z = 1$ over varying ρ_{max}. The dotted line is the analytic optimum number of users from (11).

Clearly we see that there is range on ρ_{max}. Notice that the optimal number of users follows very closely to our analytical result. It is interesting to note that as ρ_{max} increases, the optimal number of users approaches N_{init}. This may be explained as follows. The noise-to-received signal ratio is so large our received SINR is very small, but still some non-zero value. This results in negligible, but non-zero, throughput. We are better off allowing all the users to transmit simultaneously, since if there are fewer users then there are also fewer possible bits being received. This is equivalent to saying that the users are operating in a "serendipitous" mode [19]. In practical terms it is better to turn off all the terminals at this large value of ρ_{max}. This is also verified by our analytical results, because for values of $\rho_{max} > 11$ (Figures 4a and 2) we find that the optimal number of users $N_{opt} < 0$. Since this value is unrealistic, we may assume that in this case there are no active users which precisely follows our practical considerations. This case would make sense provided that all the users are experiencing the same ρ_{max}. In a practical environment, there may some users which are closer to the BS and experience a much lower ρ implying that the furthest terminal should be handed-off or dropped in order to increase the cell capacity.

Another interesting observation is that the optimal number of users is never less than 3. This, again, is due to the fact that the analysis is performed assuming that the users are always equidistant from the BS.

Now we consider a single CDMA cell of unit area 1 km^2 with N users in the system which can be seen in Figure 3. The users are uniformly distant from the base station (BS) located in the center of cell. Therefore, the distance of the i^{th} terminal from the BS is

$$d_i = \frac{i}{N\sqrt{\pi}}$$

There is distance based path loss which results in a path gain $h_i = Cd^{-\mu}$. Without loss of generality, this is equivalent to users being distributed along a line with the BS at one of the end points. Table I lists the parameters that we use for our numerical study and their values. Note how no two terminals are equidistant from the BS. This model is used for illustrative purposes. It is very simple to extend this model and perform a random distribution within the cell, but it would make very little difference since we organize all of the received signal strengths in order of their magnitude, as mentioned in Section II-A.

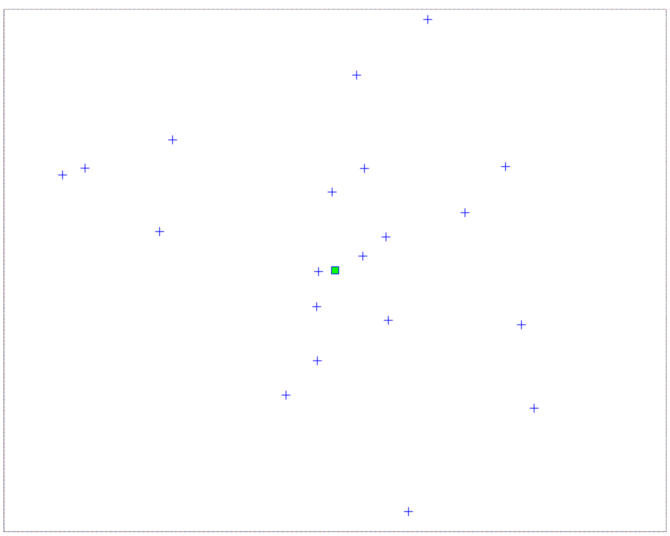


Fig. 3. User distribution within the cell. Note that no two terminals are equidistant from the BS.

We assume an initial number of users in the system $N_{init} \gg G/\gamma^* + 1$, where γ^* is the solution to (7). Every terminal has data to transmit, implying that each terminal has a desire to be always on. The received signal powers are then arranged in order from the strongest to the weakest. Since we consider only path loss, the terminal which is furthest from the BS encounters the largest signal attenuation and therefore transmits at the highest transmit power. Power balancing is used on the terminals so that the received power of every terminal is equal to that of the farthest one. After the throughput of the cell is calculated, we ignore the terminal with the weakest received signal power and perform that same analysis described previously on the remaining inner most terminals. The number of terminals that results in the largest throughput, N_{opt}, is considered the optimal number of users given their current location. Afterwards, we gradually increase the distance between the mobile terminals and the base station. The results may be seen in Figure 4. In Figure 4a the marked lines show the range over which ρ_{max}, the noise-to-signal ratio of the terminal farthest from the BS, is acceptable for a particular number of users when there is equal received power among the terminals $(z = 1)$ and when the optimal power is used $(z > 1)$. This received power value is limited to that of the furthest terminal. The solid line with the negative slope is a plot of the optimal number of users, N^*, versus ρ_{max} as obtained from (11). Figure 4b shows how the throughput is affected as ρ increases for the case when there are five terminals in the cell. This corresponds to the five *inner-most* terminals. The vertical lines indicate the valid range of ρ that correspond to Figure 4a.

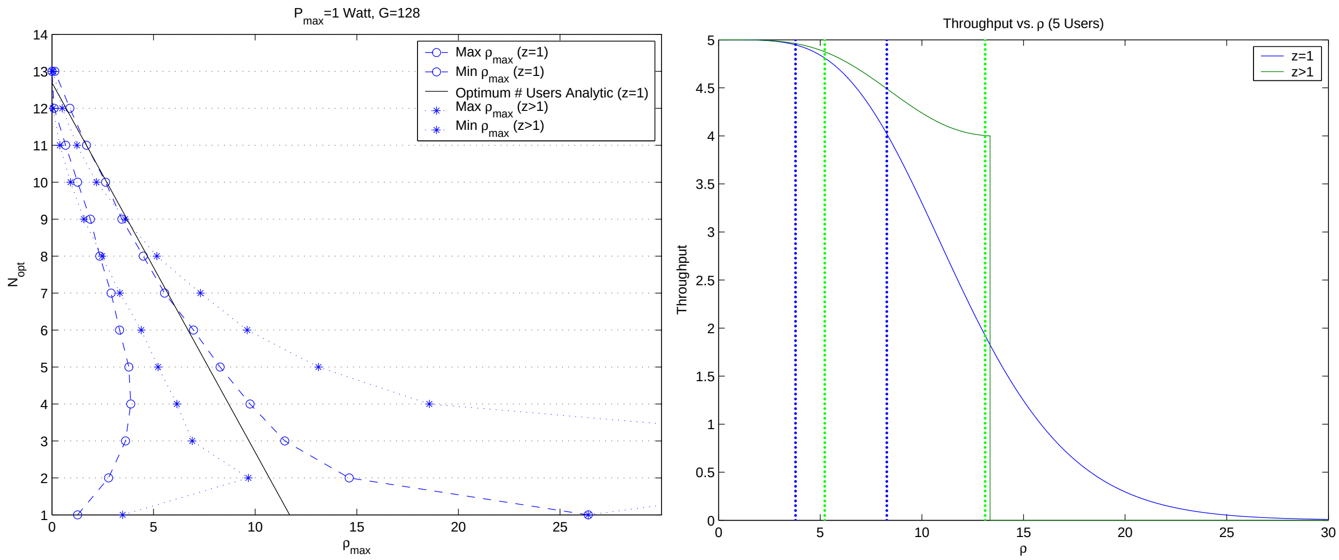
TABLE I

PARAMETERS FOR NUMERICAL ANALYSIS

Parameter	Value
AWGN, σ^2	$5x10^{-15}$ W
Processing Gain, G	$90, 150$
Path Loss Exponent, μ	3.6
Path Gain Coefficient, C	10^{-10}
Initial number of Users, N	20
Max. Tx. Power, P_{max}	1W

Several observations may be made from these figures.

1) The lower bound in the range of ρ_{max} for N_{opt} users is due to that fact that the furthest mobile is some finite distance away from the base station when the $(N_{opt} + 1)^{st}$ user is removed from the cell. Therefore, there still exists some finite value of ρ_{max}. Obviously, for $\rho_{max} = 0$ the system may support N_{opt} users since we are then considering the noiseless case. Henceforth, what we are interested in is the maximum value of ρ_{max}, i.e. $\bar{\rho}_n = \max \rho_n$, that can support a certain number of users.
2) Maximum throughput can be attained over a range of values of ρ_{max}. For example, with a processing



(a) Optimal Number of Users vs. ρ_{max}

(b) Throughput Behavior versus ρ_{max}

Fig. 4. (a) Optimal Number of Users for $G = 128$ over varying ρ_{max}. The marked lines represent the range of values of ρ_{max} where maximum throughput is achieved for $z = 1$ or $z > 1$. The solid slanted line is the analytic optimum number of users from (11). The points marked 'x' represent the optimum number of users with a search for the optimum z>1. (b) Throughput versus ρ_{max}. The vertical lines show the corresponding allowable range of ρ_{max} from (a) .

gain $G = 128$, $N = 5$, and $z = 1$ throughput is maximized when $\rho_5 \in (0, \overline{\rho}_5)$, where $\overline{\rho}_5 = 8.2$, provided there are only 5 mobiles in the cell. For $\rho_{5,max} < \overline{\rho}_5$ we may actually admit more users in the cell. If the fifth terminal achieves ρ_5 in the allotted range, then throughput is maximum. However, if ρ_5 exceeds this range, then it becomes necessary to hand-off the terminal to a neighboring cell or drop it in order to ensure maximum throughput. When $z > 1$ we see that we can tolerate a much larger value of ρ_5 before hand-off is necessary, since $z_{opt} = \infty$.

3) The range of allowable values of ρ_{max} which guarantees maximum throughput decreases as the number of terminals in the system grows. This occurs because the amount of noise that can be tolerated falls as the system approaches its limit. As such, when there are more mobile terminals in the system, then the point at which the weakest user should be dropped/handed off gets smaller. Hence, the location of the terminal greatly affects the performance of the system.
4) We examined the difference in terms of the range of valid ρ between the sub-optimal case $z = 1$ and the optimal situation of $1 < z < \infty$. We found that when there are $N = 9$ users in the system, the results were identical. When $N > 9$, the optimal $z > 1$ resulted in a smaller range of allowable ρ while for $N < 9$ it resulted in a larger range of ρ. The difference in the allowable ρ was up to ± 4 dB. However, for $z > 1$ we see that we are able to have a higher throughput across all ρ as Figure 4b shows.
5) The analytic result in equation (11) with equal received power represents a good approximation for finding the optimal number of users in the system which guarantees maximum throughput, but only when there are many users in the system $(N > 5)$. When $N \leq 5$, the correspondence between the tangent line and the curve begins to diverge and the equal received power assumption no longer leads to close to optimal results. In any case, the analytical result tells us the maximum allowable value of ρ_{max} at which the weakest terminal may operate at.

IV. Summary and Conclusions

In this paper we have shown how equal received power leads to near-optimal performance. This result provides a practical mechanism for admission control. Also, as the number of users in the system increases, our analytical results are satisfied within reasonable bounds. We demonstrated how given a certain cell geometry there is an allowable range of signal-to-background noise ratios at which maximum throughput is achieved. The smaller this value, the smaller the net throughput, though it is still maximum. The allowable range of noise-to-signal ratio for optimal throughput decreases as the number of users increases. When we approach the maximum allowable number of users in the system, we approach the noiseless case and therefore require perfect equal received power.

This work provides a basis for admission control in the wireless data system. By finding the optimal and suboptimal power allocations we are able to realize what the best strategy is in terms of the number of users in the system. When a terminal decides to enter the system from any particular location, all that is required is the value of the received signal strength. Since we assumed the AWGN remains fairly constant within our single cell system, Algorithm 4a may be simply implemented at the base station. Note, that the solution to (11)is actually an upper bound. We aim for this value to utilize the system resources in the best possible manner. But if the number of users in the system is less than N^* for a particular value of ρ_{max}, then we find that we have a choice between the throughput and the power, as shown in Figure 4b. Therefore, it is better if the system has some mechanism to attract more users into it's area of coverage. One such mechanism is a pricing scheme [23] which is the subject of future research.

Future work would also consider a heterogeneous system where terminals may operate at various different data rates and different frame success functions. Also, it would be advantageous to consider the behavior of the system in a multicellular environment and to consider the priority of the users and the QoS in terms of hand-off/dropping rate.

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