POWER CONTROL FOR A SPREAD SPECTRUM CELLULAR MOBILE RADIO SYSTEM

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ABSTRACT

In two earlier papers (ICC'80 [3] and GLOBECOM'82 [6]) two power control schemes for spread spectrum cellular land mobile radio have been described, one for the upstream (mobile to base) link and one for the downstream link. Here we compare the power control problem for the upstream and the downstream links and show that using simple algebra we can equalize the signal-to-interference ratio for each mobile in a given cell in both links and thereby increase the capacity by 30 to 100% compared with a system with no power control. We also show that the SIR values can be equalized system-wide for both link directions by means of a nontrivial eigenvalue problem, which results in a further capacity improvement of 10 to 15%. Denial statistics are also presented.

INTRODUCTION

Cellular spread-spectrum land-mobile radio schemes have been proposed and analyzed in the literature [1], [2]. Power control is generally thought to be essential for the efficient performance of such systems.

In the upstream links (mobile to base) a significant difficulty is the so-called "near-far" effect, which permits strong interferers in the vicinity of the base station to overwhelm weak signals from more distant mobiles. This effect is worse for direct-sequence type signalling than for frequency-hopping. But in all cases some improvement can be obtained by dynamically controlling the transmitted power for every mobile traansmitter so that the base station receives more-or-less the same power from each mobile. This is true whether or not the scheme uses a cellular layout.

In the downstream, noncellular case, if all signals are transmitted with the same power, every receiver suffers the same signal-to-interference ratio, and no power control is needed. But in the downstream, cellular case, there is a distinct need for power control. A mobile that is near its base station will be almost unaware that there is any interference from outside its cell; but a mobile that is near a cell corner will receive about three times the level of interference since it is about equidistant from its own and two interfering base stations. Without power control, some corner mobiles might be incapacitated during periods of relatively high traffic load.

In this paper we present schemes for balancing the signal-to-interference ratio of the mobile downstream and upstream links, for every mobile in a given cell and (optionally) for all mobiles in the entire system. Results are given at the receiver antenna so that the results are independent of the choice of spreading function, modulation method or coding scheme. Results are also compared for the upstream and downstream links.

ASSUMPTIONS

1. The service area consists of N cells. Here we show them as hexagonal cells, but our analysis is more general and does not depend on cell shapes.

2. The load of the i-th cell is L_i Erlangs. Although the general traffic model permits variations about this mean from time to time, we will use the simplifying assumption that precisely L_i users are linked to the i-th base station at a given time.

3. The i-th base station receives P^U_i Watts of power from any one mobile in the i-th cell. The power transmitted by the k-th mobile in the i-th cell is P^U_{ik}, $k = 1, 2, \ldots, L_i$. (The superscript U denotes upstream.)

4. Base station i transmits a total of Q watts, which we divide up two ways as follows; the average power per mobile, P^D_i; and the actual power for the k-th mobile, P^D_{ik}, $k = 1, 2, \ldots L_i$. (The superscript D denotes downstream.) Thus

$$Q_i = \sum_{k=1}^{L_i} P^D_{ik} = L_i P^D_i \tag{1}$$

5. Knowledge of the attenuation factor beween each base station and each mobile is required. For the present analysis we will assume that the service area has uniform propagation characteristics with an inverse -α law, and that the exact location of each mobile is known. The distance between the k-th mobile in the i-th cell and the base station of the j-th cell is denoted by d_{ikj} (see figure 1.) Thus the total power received by mobile k in cell i is given by

$$R^D_k = \sum_{j=1}^{N} \frac{L_j P^D_j}{d^{\alpha}_{ikj}} \tag{2}$$

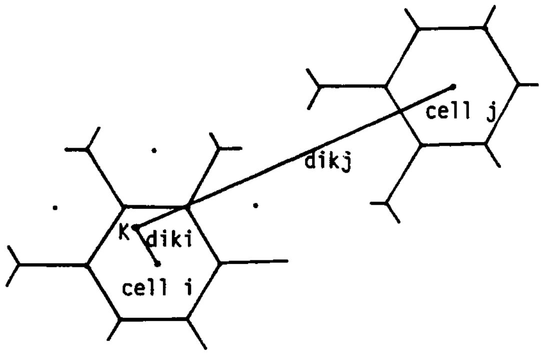

Fig. 1 Interference geometry.

We also have

$$P^D_{jk} = d^\alpha_{jkj} \, P^D_j \, . \tag{3}$$

In an actual implementation of such a scheme it would presumably be easier to acquire the attenuation information by direct measurement of signal strengths using a pilot signal radiated from each base station. However the present model is a convenient one for simulation tests of the method.

We have neglected the effects of shadow fading in this preliminary work, so our capacity results are somewhat optimistic.

6. The system is assigned a signal-to-interference lower limit S, determined from message-quality and service-grade requirements. This number is considerably less than unity because of the spread spectrum processing gain. Denial occurs when the admission of a mobile requesting service would result in a signal-to-interference ratio for the other users that is below the limit S.

POWER BALANCING

UPSTREAM.

The total power received by the base station expressed in (4) contains the desired signal with power P_i and the interference from the other mobiles. Thus the interference for signals received by the base station of the i-th cell can be expressed as

$$I^U_i = \sum_{j=1}^{N} P^U_j \sum_{k=1}^{L_j} \left[\frac{d_{jkj}}{d_{jki}} \right]^\alpha - P^U_i \tag{5}$$

The signal from the i-th mobile thus suffers the signal-to-interference ratio

$$S^U_i = \frac{P^U_i}{I^U_i}$$

Hence

$$\frac{1 + S^U_i}{S^U_i} P^U_i = \sum_{j=1}^{N} P^U_j \sum_{k=1}^{L_j} \left[\frac{d_{jkj}}{d_{jki}} \right]^\alpha \tag{7}$$

To balance the signal-to-interference ratios for each mobile in cell i, we set $S^U_i = S^U$ for each mobile in cell i, and solve for P^U_i for all i. This requires the solution of a straightforward linear algebraic equation. We refer to this operation as in-cell balancing since the equalization is done only within each cell, and different cells will in general have different SIR^U values.

To equalize the values of SIR^U for all cells, we let

$$\underline{P}^U = [P^U_1, P^U_2, \ldots, P^U_N]^T;$$

$$\underline{A}^U = [a^U_{ij}], \text{ where}$$

$$a^U_{ij} = \sum_{k=1}^{L_j} \left[\frac{d_{jkj}}{d_{jki}} \right]^\alpha ; \tag{8}$$

Then we have

$$\frac{1 + S^U}{S^U} \underline{P}^U = \underline{A}^U \underline{P}^U \tag{9}$$

This is a classic eigenvalue problem, where $\underline{P}^U$ is the eigenvector and the factor $(1 + S^U)/S^U$ is the eigenvalue.

DOWNSTREAM.

The total received power expressed in (2) has three components; the power or the desired signal, the interference from the user's own cell, and the interference from outside. The first term is given by;

$$P_{desired} = \frac{P^D_{ik}}{d^\alpha_{iki}} \tag{10}$$

Subtracting (10) from (2) we get an expression for the interference encountered by the mobile k in cell i;

$$I^D_{ik} = \sum_{j=1}^{N} \frac{P^D_j L_j}{d^\alpha_{ikj}} - \frac{P^D_{ik}}{d^\alpha_{iki}} \tag{11}$$

Thus this mobile suffers the signal - to - interference ratio

$$S_{ik} = \frac{P^D_{ik}}{I^D_{ik} \, d^\alpha_{iki}} \tag{12}$$

Combining (11) and (12) and solving for the transmitted power

$$P^D_{ik} = \frac{S^D_{ik}}{1 + S^D_{ik}} d^\alpha_{iki} \sum^{N} \frac{P^D_j L_j}{d^\alpha_{ikj}} \tag{13}$$

To balance the signal-to-interference ratios for each mobile in cell i, we set

$$S^D_{ik} = S^D_i \, , \; k = 1, 2, \ldots, L_i .$$

$$L_i P^D_i = \sum_{j=1}^{L_i} P^D_{ik} \, ,$$

$$= \frac{S_i^D}{1 + S_i^D} \sum_{k=1}^{L_i} d_{iki}^{\alpha} \sum_{j=1}^{N} \frac{P_j^D L_j}{d_{ikj}^{\alpha}} \tag{14}$$

Solving for S_i^D, we get an expression in terms terms of the set of P_i^D;

$$S_i^D = \frac{L_i P_i^D}{\sum_{k=1}^{L_i} d_{iki}^{\alpha} \sum_{j=1}^{N} \frac{P_j^D L_j}{d_{ikj}^{\alpha}} - L_i P_i^D} \tag{15}$$

And observing that (13) must be true for each k in i,

$$P_{ik}^D = \frac{S_i^D}{1 + S_i^D} d_{iki}^{\alpha} \sum_{j=1}^{N} \frac{P_j^D L_j}{d_{ikj}^{\alpha}} \tag{16}$$

Equations (15) and (16) are simply solved algebraically for the transmitted powers, thereby balancing the downstream SIR values for all mobiles in a given cell. As in the upstream case, in general these values will be different from cell to cell, and within a given cell the SIR values will be different for the upstream and downstream links.

To balance the values of SIR^D for each cell, we construct an eigenvalue equation similar to (9). Setting all the S_i^D in (16) to S^D, we have

$$Q_i = \frac{S^D}{1 + S^D} \sum_{j=1}^{L_i} Q_j \sum_{k=1}^{N} \left[\frac{d_{iki}}{d_{ikj}} \right]^{\alpha} \tag{17}$$

We now define

$$\underline{Q} = [Q_1, Q_2, \ldots, Q_n]^T; \text{ and}$$

$$\underline{A}^D = [a_{ij}^D], \text{ where}$$

$$a_{ij}^D = \sum_{k=1}^{L_j} \left[\frac{d_{iki}}{d_{ikj}} \right]^{\alpha} \tag{18}$$

The eigenvalue problem then becomes

$$\frac{1 + S^D}{S^D} \underline{Q} = \underline{A}^D \underline{Q} \tag{19}$$

where $\underline{Q}$ is the eigenvector and the factor $(1 + S^D)/S^D$ is the eigenvalue.

The existence of unique, positive eigenvalue solutions to both (9) and (19), together with corresponding all-positive eigenvectors, is guaranteed by the Perron-Frobenius theory of stochastic matrices [5]. Comparison of the defining equations (8) and (18) reveal that

$$\underline{A}^U = [\underline{A}^D]^T, \tag{20}$$

so that the eigenvalue solutions to (9) and (19), and hence SIR^U and SIR^D, are identical. However, the corresponding eigenvectors $\underline{P}^U$ and $\underline{Q}$, which determine the set of upstream and downstream transmitted powers, would in general be different.

RESULTS

To evaluate the above approach, a simulation study has been done using a "minimal nontrival service area"; namely, nineteen cells, each of equal size, arranged in three concentric rings; and an inverse-α law of propagation, uniform throughout the system. We give results here for α = 3 and 4, which represent the extremes of the range of values commonly observed [4].

To simulate the random positions of the mobile units, two spatial distributions were used. In the first, the mobiles were distributed randomly with uniform distribution so that the mean number of units in each cell was the same. In the second case, a bivariate Gaussian distribution was used, with mode at the center of the system and the variance adjusted to give mean numbers of units per cell in the ratio 10 for the center cell, 5 for the first ring of cells and 2 for the second (outer) ring. Results were generated for each set of mobile locations with no power balancing, for in-cell balancing only and for cell-to-cell balancing. The value of SIR criterion S used in the simulation was -20dB, which corresponds to a signalling system with a processing gain of 30-35dB with typical coding schemes. The capacity of a single-cell system with this SIR criterion would be $1/S$ = 100 users.

Figure 2 shows the denial-probability values versus mean load per cell for both the upstream and downstream cases, where the traffic distribution was uniform and no power control was used. Typically acceptable values of blocking in a radiotelephone system are in the 1% to 2% range, so the probability of denial in the no-balancing case are quite unacceptable except at trivially low traffic loads. The problem is more severe for the upstream case because the "near-far" effect is significant whenever two or more users are accessing the system, whereas the "corner effect" is less severe and requires relatively high traffic levels to become noticeable. We note also that when no balancing is used, the system has higher capacity for α = 4 than for α = 3 in the downstream case, and vice versa in the upstream case. This is because of the role played by the attenuation-versus-distance relationship in the two mechanisms, near-far effect and corner effect. A more rapid attenuation law creates greater near-far signal power ratios, whereas the same condition tends to shrink the size of the region near cell corners where the corner effect is manifested.

Figure 3 shows the loads at which the probability of denial is at the 2% level, for the uniform traffic distribution case, with both in-cell balancing only and cell-to-cell balancing. Upstream and downstream results are indistinguishable for this traffic distribution. The vertical range of values shown correspond to the range α = 3 (lower limit) and α = 4 (upper limit.)

The results of the two types of balancing are barely distinguishable at all levels of denial, particularly when $\alpha = 3$, so that in the uniform-distribution case there appears to be little advantage in terms of system capacity in implementing the cell-to-cell balancing algorithm. However, with in-cell balancing only there is still some small range of SIR values over the system. The increase in system capacity over the non-balanced case is very significant, though difficult to quantify due to the low levels of statistical significance attatched to our non-balanced results at low traffic levels. The range of improvement ratios we encountered were 30 to 100% in the downstream case, and much greater in the upstream case.

Figure 4 shows the corresponding set of results for the Gaussian traffic distribution. Here the upstream and downstream results are different with in-cell balancing only, but of course become identical with cell-to-cell balancing added. Our results show improvement ratios over the nonbalanced case of around 100% with in-cell balancing only, and a further 15% when cell-to-cell balancing is added. This latter improvement is due to the "matching" effect of the cell-to-cell balancing upon the individual cell capacities; with in-cell balancing the outer cells are using only a small part of their actual capacity, so this capacity can be sacrificed in the cell-to-cell balancing algorithm in order to increase the capacity of the heavily-loaded cells.

Figure 5 shows the decline of SIR in a cell-to-cell balanced system as the system traffic load grows. Results are given for both the uniform and the Gaussian distributions.

In each of these figures the absence of sensitivity to the propagation parameter α is very striking. The variation in capacity as α ranges from 3 to 4 is not nore that 15%, depending on the mobile distribution and the traffic load.

CONCLUSIONS

In this paper we have reported on the results of applying power balancing to both the upstream and downstream links of a spread spectrum cellular mobile radio system. The critical part of the technique is to balance the powers transmitted to each of the mobiles and the powers transmitted by each mobile to its base station so that the near-far effect in the upstream case and the corner effect in the downstream case are ameliorated. For a fixed probability of denial, the resultant traffic capacity is increased by more than 100%. Probability of denial due to excessive interference can be eliminated altogether for a large range of traffic loads using this technique, and when denial begins it does so in a graceful manner compared to blocking in the conventional sense. Thus one might set the hardware limit on the number of channels somewhere just above the onset of denial, so that the two curves- denial and blocking- coincide at the required service grade.

In addition, an eigenvalue method has been described that permits all the SIR values to be equalized system-wide, and made identical for both the upstream and downstream links. The resultant improvement in system capacity is 10 - 15% depending on mobile distribution and propagation constant.

ACKNOWLEDGEMENT

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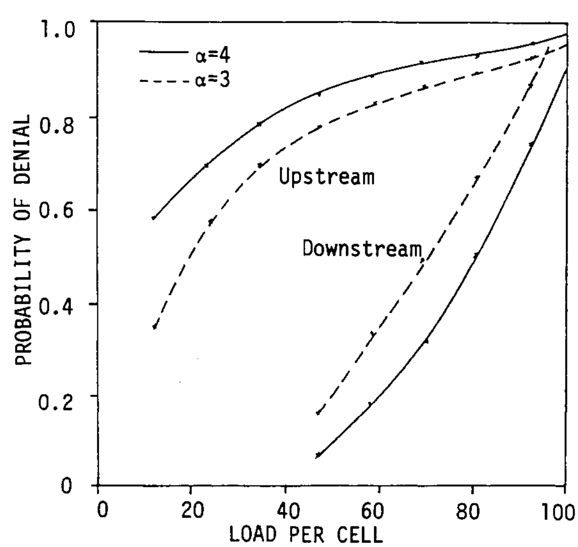

Figure 2. Probability of denial for uniform load distribution, no power control

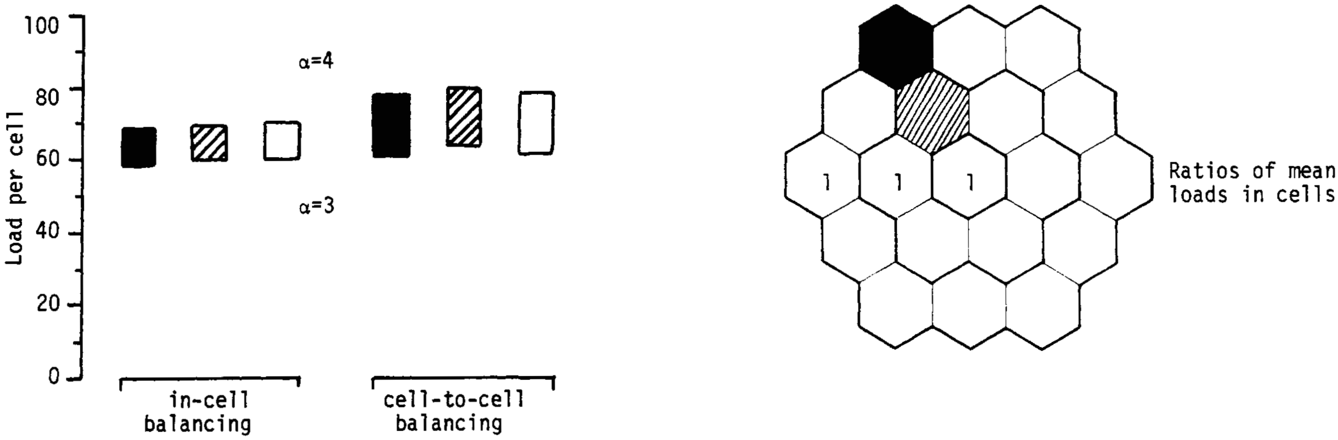

Figure 3. Traffic capacity for uniform load, P[denial]=0.02, upstream and downstream links.

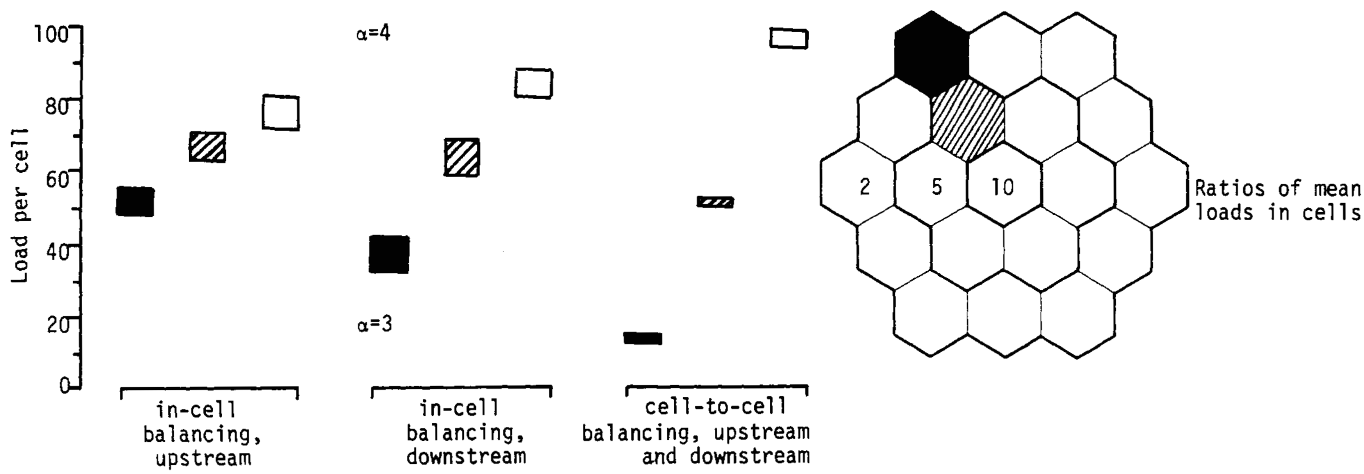

Figure 4. Traffic capacity for Gaussian load, P[denial]=0.02.

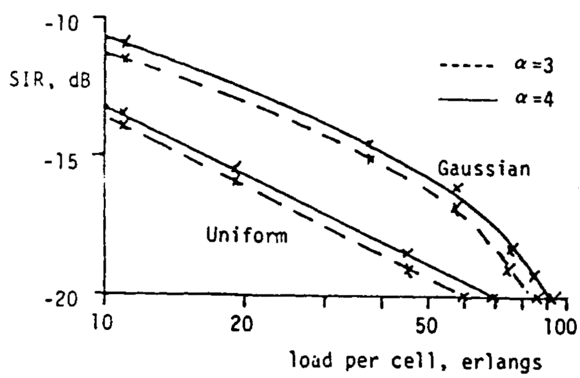

Figure 5. Signal to Interference Ratios with Fully Balanced System vs. Load in Center Cell.