Distributed Dynamic Channel Resource Allocation in Wireless Communication Systems

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Abstract

We consider the problem of allocation of bits and power among N channels in a multi-user cellular system. We suppose that no users within the same cell interfere with each other, and that the N channels assigned to the users are randomized such that any given interferer is encountered in only one of the channels. We present distributed algorithms to allocate power and bits so as to maximize a cost function including as elements the bit rate actually achieved and the likelihood of dropping calls already in progress. Procedures for rapidly estimating the likelihood of achieving target bit rates in the channel are also presented.

I. Introduction

To maximize the capacity of next generation wireless systems, such as personal communication services (PCS) and wireless LANs, multiple bit rates must be supported. In these systems, users within close proximity of a base station will be able to achieve higher overall transmission rates than users who are located near a cell boundary. Loading of the network will also affect the bit rate, since increased interference will limit the maximum signal-to-interference ratio (SIR) available to each user. Load level and limited transmitter power can also affect the ability of active users to stay in the network if new users are allowed to move in and interfere with active users or if propagation conditions change.

Previous work has focussed on techniques for admitting new users to a given channel while maintaining the link quality of existing users on that channel [1]. We expand this technique to include multiple channels and rapid estimation of the ability to gain access to a channel. Specifically, we examine the problem of a user wishing to select which M out of N channels to access. An algorithm is presented to estimate which M channels can be successfully allocated. We then explore ways in which this algorithm can be used to balance the network goals of high capacity, fairness in admitting new users, and a low probability of dropping active users.

II. Dynamic resource allocation

We assume a hexagonal cellular network with base stations at the center of each cell. The power allocations on the uplink channels (from user to base station) are analyzed as follows. For a set of K users sharing a radio channel, we define an KxK matrix H with elements:

$$H_{ij} = \begin{cases} G_{ii} & i = j \\ -\gamma_j G_{ij} & i \neq j \end{cases} \tag{1}$$

where G_{ij} is the gain from user j to base station i. Each user is assigned a power level P_j and SIR γ_j. The given choice of power levels and SIRs are feasible if positive solution vectors exists for the matrix equation:

$$H\vec{P} \geq N\vec{\gamma} \tag{2}$$

where N is the noise power [1].

In a cellular network, power can be allocated to individual users in a centralized fashion by solving the set of equations in (2) for a fixed γ whenever a new user wishes to be admitted. If the solution yields a positive power vector the new user is allowed access, otherwise he is blocked.

When multiple channels are used, the access problem becomes more complicated. We are interested in frequency hopped code division multiple access systems (FH-CDMA) because systems of this type can help mitigate the effects of Rayleigh fading and achieve high capacity by reducing intracell interference [2]. In our FH-CDMA system, a user's hopping pattern is determined using orthogonal latin squares. If N is prime, the latin square for each cell can be computed by:

$$\{a\}_{ij} \equiv ai + j \qquad (\text{mod } N) \tag{3}$$

where $a \in \{1, 2, ...N\text{-}1\}$ is the cell number, and $i, j \in \{0, 1, ...N\text{-}1\}$ are the row and column indices for the square. An element $\{a\}_{ij}$ indicates which user assigned to base station a will transmit on channel i at time j. With latin square hopping patterns, each user will receive interference from no other user in its own cell, and at most one other user from each other cell in the network. Furthermore, on each hop the user will see a different set of interferers. The goal is to efficiently allocate M out of N hops to maximize capacity.

III. Distributed algorithms

A distributed algorithm for determining feasible solutions to equation (2) is given in [1]. In this algorithm, users update their powers at iteration k using the update equation:

$$P^k = P^{k-1} f\left(\frac{\gamma_d}{\gamma_m}\right) \qquad (4)$$

where γ_m is the measured SIR at time k-1 and γ_d is the desired SIR. The update depends upon whether the desired SIR has been achieved. That is, whether or not the ratio of the SIRs is greater than one. If the update function is defined as:

$$f(x) = \begin{matrix} x\delta & x < 1 \\ \delta & x > 1 \end{matrix} \qquad (5)$$

active users in the network will maintain an SIR between γ_d and $\delta\gamma_d$ while new users will increase their power in steps of δ. If a feasible power vector exists for the new user, its received SIR will increase to the desired level and it is admitted. If a feasible power vector does not exist, its received SIR will level out at some value less than the desired level and the user will not be admitted.

This algorithm has many properties that make it suitable for large networks. Central control is not required since each user is responsible for maintaining its own SIR. In addition, explicit communication between users is not required since only received power and interference measurements are used in the update equations. Both of these features help to minimize network complexity.

In practice, however, the distributed algorithm exhibits several problems. New users can temporarily push admitted users below their desired SIR level. One remedy for this problem is to have new users increase their power in smaller steps than admitted users. However, this slows down the admission process because it takes longer for a new user to achieve his desired SIR. Furthermore, if the admitted users have limited transmitter power, they may eventually reach a point where they cannot increase their power to prevent a new, infeasible user from being admitted. In this case, instead of the new user being blocked the old user is dropped. This is undesirable in most networks.

To improve the access algorithm we add a channel probing test to the admissions process. The goal of the channel probing is for new users to be able to rapidly estimate whether or not it is feasible to enter a new channel.

IV. Channel probing

In a high SNR system, we can make an assumption that the interference a user measures will be dominated by one other user. This tends to occur because feasible solutions will only exist if the users are spaced far apart. When combined with the attenuation in the radio channel proportional to R^{-4}, the sparse density of users will generate one user with considerably more effect on the admission of a new user than any other. This fact can be exploited to generate a threshold test as follows.

If user 0 attempts to access base station 0 on the same channel as user 1, the following condition must be satisfied for a feasible solution:

$$G_{00} > \frac{\gamma_0 \gamma_1 G_{01} G_{10}}{G_{11}} \qquad (6)$$

We assume user 1 has been admitted to the network and user 0 is trying to gain access by increasing his power. Both users operate according to the power control algorithm described by equation (5). User 0 will then measure the change in interference between steps k and k+1:

$$i_0^{k+1} - i_0^k = \frac{\gamma_0 G_{10} G_{01}}{G_{11}} (P_0^{k+1} - P_0^k) \qquad (7)$$

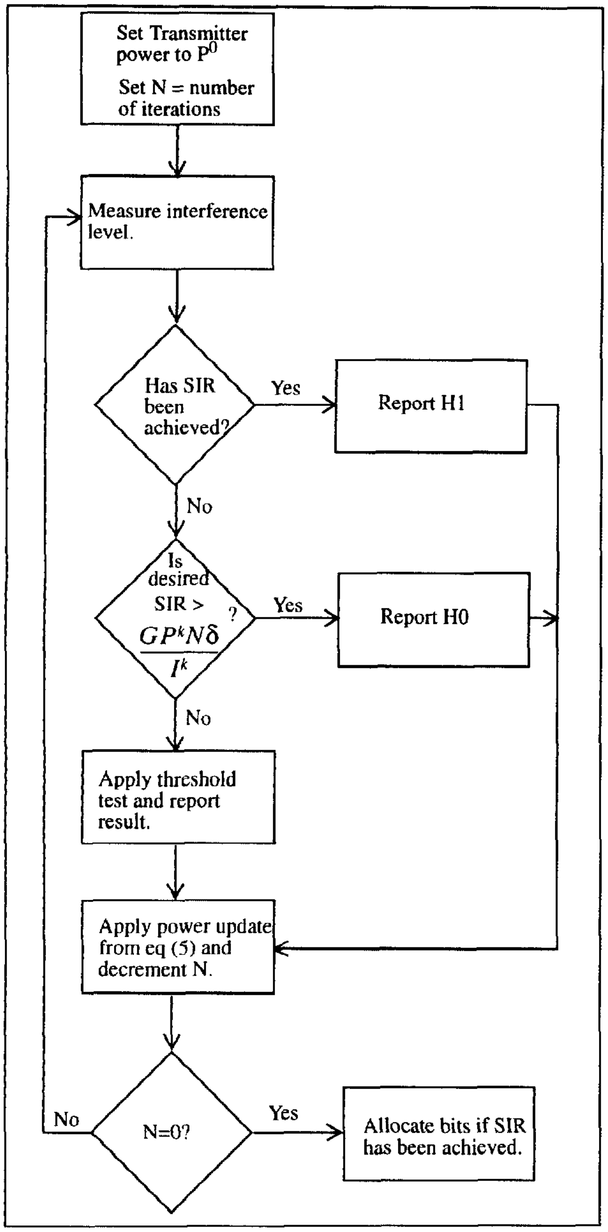
At step k+1, user 0 can then predict if γ_0 is feasible from the expression:

$$G_{00} > \gamma_0 \frac{(i_0^{k+1} - i_0^k)}{(P_0^{k+1} - P_0^k)} \qquad (8)$$

If the inequality holds, the algorithm reports hypothesis H_1, the desired SIR is feasible. If the inequality does not hold, then the algorithm reports the opposite, hypothesis H_0.

By itself, this threshold test suffers from errors during the probing process. Two simple improvements, however, increase its accuracy significantly in simulations. These are first checking to see if the desired SIR has been achieved and then checking to see if, given the current level of interference, there are enough power increase steps to reach the desired SIR. The complete probing algorithm is given in flowchart 1.

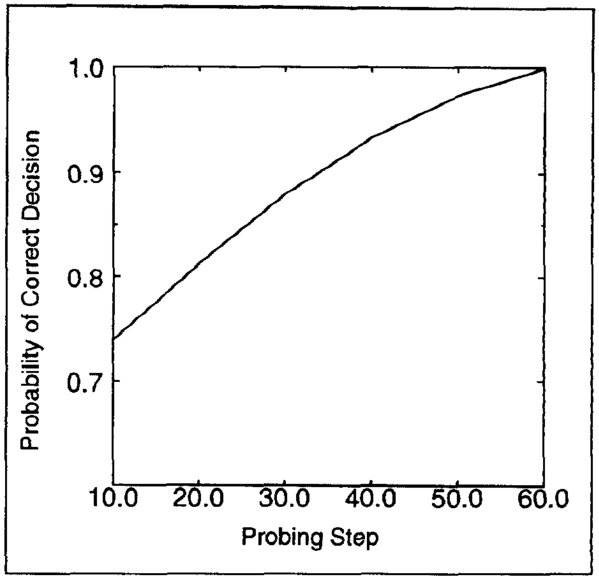
Flowchart 1. Channel Probing Algorithm



A simulation program has been developed to test the channel probing algorithm under dynamic conditions. In this simulation we use latin squares frequency hopping over at set of N=23 channels. New users increase their power in 1.4 dB steps for 60 iterations where each iteration is a cycle through all 23 channels. Every 10 iterations, a threshold test is made. If, after 60 iterations, the new user has a feasible power on any of the channels, it is admitted. After admission, the user no longer transmits on any of the infeasible channels.

The arrival of new users is modeled as a Poisson process and the hold times of users are exponentially distributed. The arrivals are uniformly distributed in space over the network of 19 cells. The load of the network is adjusted to provide a blocking probability of 1%. Statistics are gathered for the center cell in the network. A plot of the probability of a correct decision by the channel probing algorithm is given below.

Fig. 1. Channel Probing Algorithm Results



A number of factors affect the accuracy of the probing algorithm, including the load on the system, the required SIR, and the number of steps before the threshold test is made. To be useful, the algorithm must be able to make accurate decisions before a user has reached his desired SIR, otherwise probing has no advantage over the original admission algorithm given in equation (5). In the simulation plotted above the median user gain to its base station was -71.8 dB and the initial power was +40 dB. The median interference level was +24.7 dB. With these values, a slot reaches the desired SIR level (10 dB) at step 47. However, the probing algorithm is able to determine the probability of achieving the desired SIR with 88% accuracy at step 30, some 42 dB below the peak probing power. If a channel returns H0 at step 30, it can be powered down immediately. This will prevent interference to active users on the channel.

V. Admission algorithm

A complete admission algorithm has been designed to take advantage of the channel probing algorithm (see flowchart 2). This algorithm decides whether to admit or block users based on whether or not feasible power solutions can be found for at least M out of N hops. The threshold test is used to eliminate channels that are unlikely to be allocated. Unfortunately, since the threshold test is not completely accurate, the algorithm must allow some leeway for errors. A trade-off then results between allowing a new user to continue to probe a channel that is unlikely to be accessible versus decreasing the set of possible channel choices.

This algorithm takes advantage of the threshold test to determine if a user is likely to allocate at least M_l hops. If at least M_l hops seem likely, the unlikely hops are powered down and the algorithm then continues to probe those slots that will most likely be allocated. The strategy here is to help new users to acquire channels, but only to those that are required for admission. If M_l is chosen to be N, the algorithm becomes greedy, probing all channels until it either gets what it wants or runs out of probing steps.

For some networks, it may be desirable to make the access algorithm less greedy, if doing so will prevent active users from being dropped. This can happen when transmitters have limited dynamic range. Another option is to permit re-probing the network to prevent dropping. This could potentially increase network capacity, if active users were able to find feasible power solutions. We have implemented a simulation program that includes both the probing and re-probing features.

VI. Simulation results

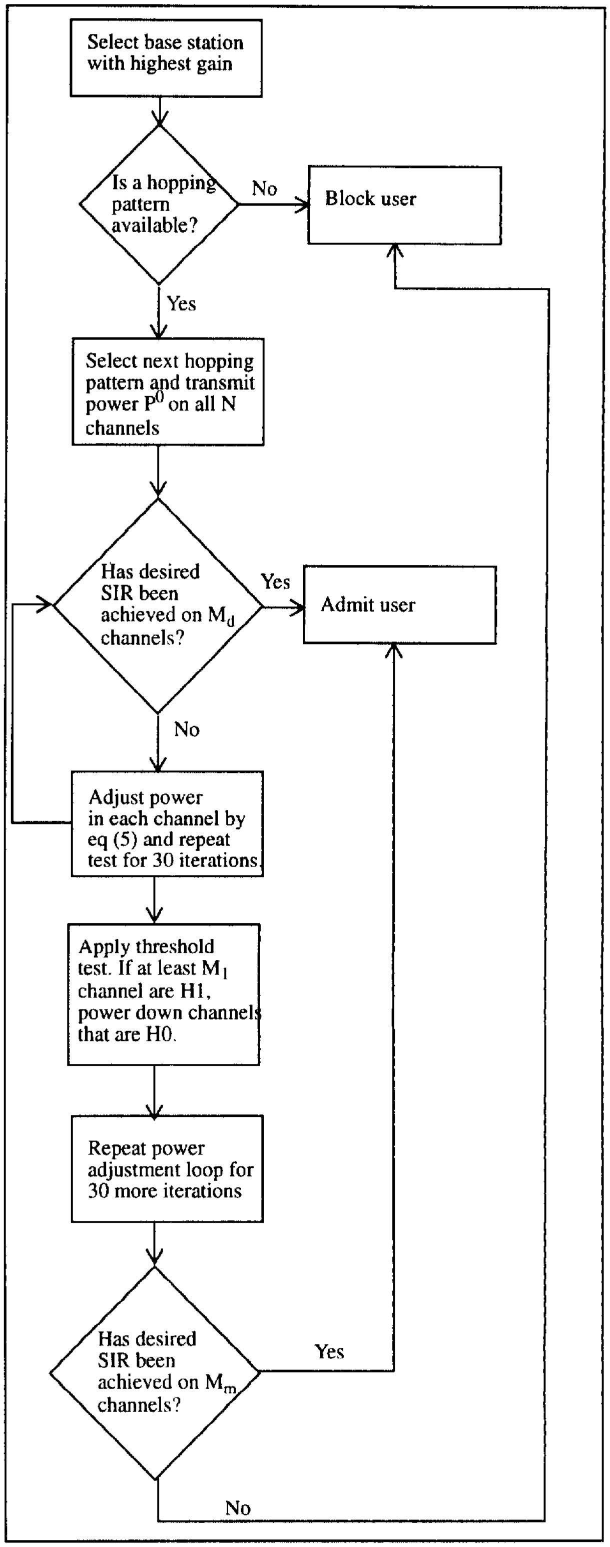
We present a case in which the value of M_l is adjusted to help lower the dropping probability of a network while maintaining a high throughput. This type of network behavior is required for PCS networks where call dropping will cause customer dissatisfaction. As a network becomes loaded users should first have a gradual lowering of voice quality (bit rate) and then new users should be blocked. Call dropping should occur rarely, if ever.

The simulated network consists of 19 hexagonal cells with base stations at the center of each cell. R^{-4} propagation loss and lognormal shadowing are included. Users frequency hop using latin square patterns as described above. Each user wishes to access up to M_d=15 slots but will accept a minimum of M_m=9 slots before being blocked.

Once admitted, a user must maintain the required SIR (10 dB) in all active slots. If it is unable to do so, it may re-probe up to three times before being dropped. Transmitter dynamic range is limited to 84 dB for probing users and 100 dB for admitted users, so dropping can occur if a congested channel is probed too long and an admitted user can no longer increase its power. User arrivals follow a Poisson distribution in time and are uniformly distributed in space on a circle that encompasses the network. User hold times are exponentially distributed.

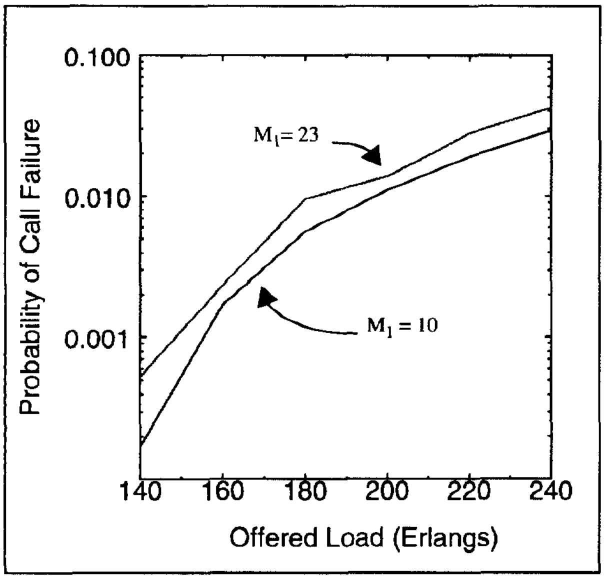
Interestingly, the throughput of the network, in terms of total hops allocated, does not vary much with the value of M_l. This indicates that the algorithm is able to effectively limit the number of slots allocated to new users such that the goals of high capacity and low dropping probability

Flowchart 2. Channel Admission Algorithm



are maintained.

Fig. 2. Admission Algorithm Comparison



VII. Summary

Future wireless networks will need to work with multiple bit rates to satisfy the demands of multimedia and high speed computing with limited bandwidth. With multiple bits rates the problems of network access and resource allocation become more complicated because users may wish to know what rates are available before they choose to access the network.

We have examined a distributed algorithm for rapidly estimating the number of hops that are accessible to a new user in a FH-CDMA system. We have also shown how the estimation algorithm can be used to optimize the network for balanced blocking and dropping probabilities while maintaining high throughput.

In the future we plan to expand the probing algorithm to handle multiple constellations per hop. Instead of giving a yes/no answer on the feasibility of a given hop, the algorithm will instead return the maximum possible constellation size that can be used on that particular slot. This algorithm will be implemented in hardware in a prototype high speed, adaptive wireless transceiver under development at UCLA.

Acknowledgments

This work was supported in part by grants from the University of California MICRO Program, the Motorola University Partners in Research Program, Rockwell, and ARPA.

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