

# Unified power control, error correction coding and scheduling for a CDMA downlink system\*

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Transmitting multimedia data over a CDMA channel presents a new set of challenges. Sometimes, data demands will exceed the system capacity, in which case the system must make the most efficient use of its limited resources. The resources we consider are: fixed bandwidth available for each user and the transmit power budget for each cell. In this paper, we present our approach for unifying power control, variable forward error correction (VFEC), and scheduling for a downlink system by allocating the system resources. Our objective is to maximize the overall system satisfaction, which we call "system utility". This objective is achieved by applying a distributed algorithm which divides the overall optimization problem into a hierarchy of three levels (system, cell and user). At each level, the system performs independent and parallel optimizations; the critical information is then passed to the higher level for further optimization. Finally, an iterative and distributed algorithm is applied at the system level to achieve the overall system optimization.

## 1. Introduction

This paper addresses design and control issues for multi-user, multimedia indoor wireless communication systems. While this work is motivated by the Berkeley Infopad project [1], the approach and the techniques are not limited to the Infopad system.

The Berkeley Infopad employs direct-sequence code-division multiple-access (DS CDMA) for downlink transmissions. The radio at each basestation transmits several data types ranging from low-data-rate and error sensitive control information, to high-data-rate but more error tolerant real-time video. In addition to this wide range of error tolerance and bandwidth requirements, multimedia data streams are bursty compared to traditional cellular voice data. Therefore, it is challenging to deliver the different data streams according to their required quality of service, and at the same time, avoid over-engineering.

Several techniques can be applied for reliable transmission over a time varying channel. Power control [2] (i.e., adjusting the transmit power level at the basestation) is used to control received signal to noise ratio (SNR). Forward error correction (FEC) introduces redundancy to combat transmission errors. Because bandwidth demands for multimedia applications vary greatly, prioritizing (i.e., scheduling) among data streams is needed when bandwidth demands exceed channel capacity. In this paper, we see these three techniques as three "control knobs" for adjusting the system performance, and we claim the system design is incomplete if we do not consider all of them jointly.

Many solutions are feasible by various combinations of these three techniques. Therefore, designers are left to choose what they want to optimize. For example, previous works aimed at maximizing the Erlang capacity which is defined as the number of active users [2], minimizing

transmit power while meeting a certain SNR requirements [3,4], or maximizing the Shannon capacity [5]. However, none of these design objectives consider the heterogeneities of multimedia data and users. This leads to many shortcomings. For example, it is difficult to prioritize one data type over others, or to prioritize users using these design metrics, or to distinguish various users' preferences.

A multiuser, multimedia system is designed to meet the needs of users, as a result, system performance should not be measured in terms of system-centric quantities like throughput or transmit power level. Instead, we believe system performance should be evaluated solely in terms of overall user satisfaction, which we call "utility". As shall be discussed later, we assume a user's satisfaction of an application depends on the delivered bandwidth and bit error rate (BER).

This paper is organized as follows. First, the system structure and its constraints are presented. Next, we discuss the qualitative properties of utility functions, and we argue that maximizing system utility should be the sole objective when designing a system. Lastly, we present the utility maximization algorithm.

## 2. System structure

### 2.1. System requirements

The Berkeley Infopad system employs DS CDMA for downlink transmission (i.e., basestation to portable). This system, shown in figure 1, is a multimedia communication system which simultaneously serves a large number of users. For low power and portability reasons, the Infopad terminals do not have any computational power; instead, the computations are carried out at the compute servers. The computational results, together with other types of multi-

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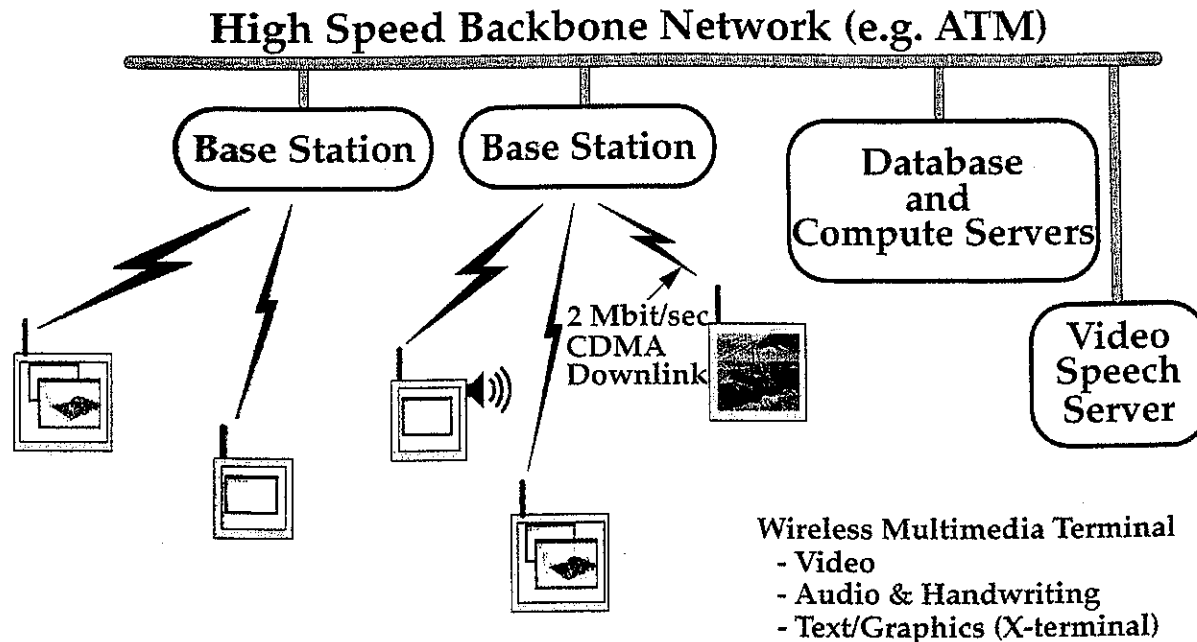


Figure 1. Infopad system overview.

media data, are sent to the terminals via the high speed backbone network, basestation, and wireless channel.

The downlink radio system has a limited capacity due to the limited resources such as transmit power and bandwidth. As will be shown later, the design of this system reduces to a global optimization problem. This optimization trades-off the quality with the quantity of delivered data. In addition, the optimization trades resources among users. The objective of these trade-offs is to maximize the overall user satisfaction by applying power control, variable forward error correction<sup>1</sup> (VFEC), and scheduling.

The CDMA downlink radio is designed to address several user imposed system performance requirements. These requirements can be most easily understood if we consider the differences between our system and conventional wireless systems.

The first difference is that conventional portable communication systems have been designed mostly for low-rate, single-data-type applications such as mobile voice and paging services; our downlink radio, on the other hand, supports multimedia data consisting of real-time video, audio, text/graphics and control data. This difference yields several design requirements:

- (1) The bandwidth requirements are orders of magnitude greater.
- (2) Multimedia data consist of several data types with highly variable qualities of service (QoS) (e.g., typical speech data can tolerate a BER around  $10^{-3}$ , whereas control data require a BER around  $10^{-9}$ ).

<sup>1</sup> Variable forward error correction is a technique of using a family of FEC codes to achieve a wide range of error correction capabilities. For example, we use the family of 63-bit BCH codes with correction capability of  $t = 0, 1, 2, 3, 4, 5, 6, 7, 10, 11, 13, 15, 31$  bit errors.

- (3) A multimedia system requires a scheduler because bandwidth demands vary greatly and will sometimes exceed channel capacity. This scheduler dynamically allocates bandwidth for each application, leading to a priority scheme for multimedia data.

The second difference is the relative burstiness of multimedia data as compared to voice data. For example, the channel that carries X-server display data is only active when there is a screen update. To fully utilize the available bandwidth, statistical sharing between multiple data streams is necessary.

The last difference is that the traditional voice/data communication systems respond to congestion by blocking or dropping calls. However, our strategy is to provide a partial service during congested periods, and thereby gracefully degrading the QoS. This is possible because the use of variable rate compression algorithm for video and text/graphics [6]. Table 1 shows the diversity of four data types supported by the Infopad terminal, and their typical BER and bandwidth requirements.

Table 1  
Multimedia data and QoS requirements.

Data type	Data rate (kbit/sec)	BER range	Relative burstiness
Control information	~ 1	$10^{-8}$ - $10^{-11}$	very
Text/graphics	1-1000	$10^{-4}$ - $10^{-7}$	very
Audio	64	$10^{-3}$ - $10^{-6}$	medium
Video	1000	$10^{-3}$ - $10^{-6}$	low

## 2.2. Practical constraints

Our system is designed to fully utilize the available resources while meeting the various QoS requirements of

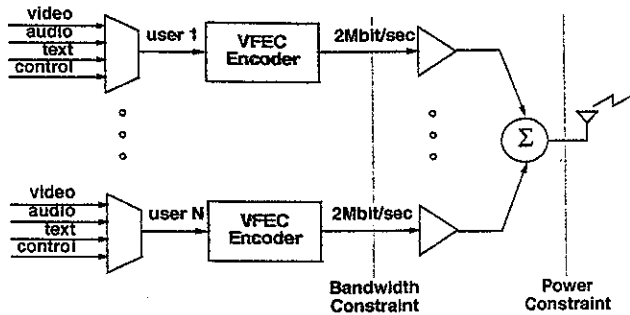


Figure 2. System structure and constraints.

multimedia data. This system has a limited capacity due to certain resource constraints that arise from a DS CDMA radio. These constraints are:

- (1) Each user is allocated a fixed link bandwidth; the total bandwidth allocated to a user's applications after FEC encoding must be less than or equal to this link bandwidth. For example, each Infopad user is given a 2 Mit/sec link bandwidth.
- (2) The total transmit power from a basestation (which serves all users in a cell) must be less than or equal to an allowable power level set by implementation constraint. Figure 2 shows the downlink radio structure together with these practical constraints.

### 2.3. Three "control knobs"

In order to achieve the optimal system performance, three "control knobs" are available for fulfilling various bandwidth or BER requirements. These knobs are: VFEC, power control and scheduling. Among them, VFEC selects a particular FEC code; this FEC then introduces redundancy to combat transmission errors [8,9]. Downlink power control varies the transmit power to adjust the received signal quality. Together VFEC and power control are used to support applications with widely varying QoS and to mitigate excessive interference. Finally, prioritizing (i.e., scheduling) allocates bandwidth among data types; this is especially needed when application demands exceed channel capacity.

The goal of our design is to unify VFEC, power control and scheduling into one system. We claim that the system design is incomplete if the methods of VFEC, power control and scheduling are not considered simultaneously. For example, consider a design that only controls power; if all active applications within a user consume less than the available bandwidth, then the remaining bandwidth is wasted. Compare this to a system that, instead of wasting this bandwidth, uses it for FEC coding; with the coding gain, we are able to reduce the transmit power while maintaining the same QoS. This example illustrates the interaction between power control and FEC. Finally, the result from scheduling affects both the VFEC selection and the transmit power level in order to meet the specific QoS of that data type.

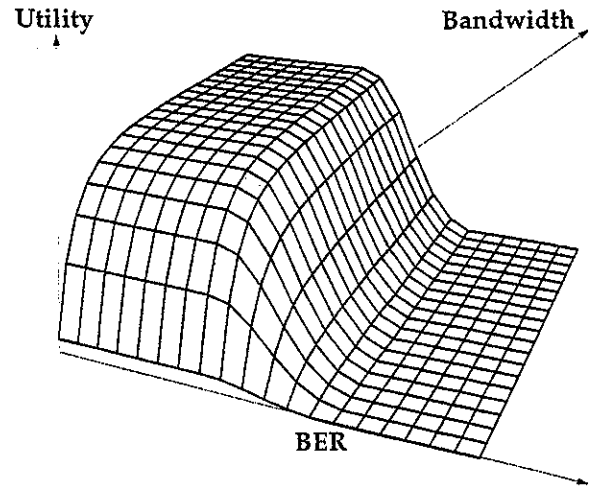


Figure 3. A typical application utility function.

## 3. System objective and control strategies

### 3.1. Concept of utility

A large set of solutions are feasible by various combinations of VFEC, power control and scheduling. For example, a user may choose receiving low resolution video together with text graphics or just high resolution video; or, the system may either support 6 users with high QoS or 10 users with medium QoS, how do we choose between these alternatives? A multi-user, multimedia system is ultimately designed to satisfy users; therefore, any design decisions should be based on user satisfaction. For instance, if users prefer receiving more data at cost of having a higher BER, the system design should reflect that accordingly. Therefore, our objective is to maximize total user satisfaction, which we call "system utility".

In general, the concept of system utility is somewhat vague. However, if we assume that utility is additive, then system utility becomes the sum of user utilities, and a user's utility is the sum of that user's application utilities. For each application, the performance clearly depends on the quality and quantity of data delivered. In this study, we express application utility in terms of delivered BER and bandwidth.<sup>2</sup> An example on application utility function is shown in figure 3.

At this point, let us discuss the qualitative properties of the application utility functions.<sup>3</sup> We proceed by first holding BER constant so that utility only depends on delivered application bandwidth.

For all applications, the application utility is a monotone non-decreasing function with respect to the bandwidth. We can categorize applications into many classes; nevertheless, we will discuss and contrast only two such classes. One class includes applications for which performance gradually improves as their allocated bandwidth increases; how-

<sup>2</sup> End-to-end delay is not considered in this study.

<sup>3</sup> The actual utility function for any particular application can be determined through either simulations or experiments with users.

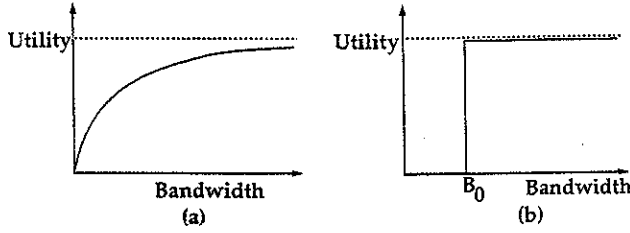


Figure 4. Two classes of utility functions with respect to the bandwidth.

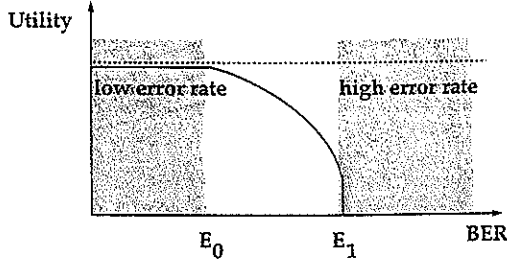


Figure 5. Utility function with respect to the error rate.

ever, with a decreasing marginal utility (e.g., video and text/graphics). The utility functions for this class of applications are therefore concave everywhere, as shown in figure 4(a). Another class includes applications such as control information for which the received data are of no value to users if only partial information is delivered; however, once the necessary amount of data is delivered, there is no extra benefit for receiving more data. Figure 4(b) shows the utility function for this class of applications.

Let us now turn our attention to the other parameter of the utility function, that is, the error rate. When the received BER is high, users are generally unsatisfied with application performance. As the error rate improves, their satisfactions rise as well. However, once the BER improves beyond a certain level, very little additional satisfaction is achieved. For instance, the reception quality of video is nearly identical between BERs of  $10^{-5}$  and  $10^{-8}$ . Figure 5 illustrates the utility function with respect to BER. As a final remark, the application utility as a function of bandwidth and BER shown in figure 3 is obtained by multiplying utilities from figures 4(a) and 5.

### 3.2. Layered approach to utility maximization

Now that we have discussed the qualitative behavior of the application utility functions, let us return to the problem of maximizing the system utility subject to constraints. Suppose a user has several applications, each with utility  $u_i(B_i, E_i)$ , where  $B_i$  is the application bandwidth, and  $E_i$  is the received BER (after FEC decoding). Recall that the utilities are assumed to be additive, therefore, the user, cell, and system utilities can be expressed as

$$\text{user\_util} = \sum_{i=1}^L (\text{appl\_util})_i = \sum_{i=1}^L u_i(B_i, E_i), \quad (1)$$

$$\begin{aligned} \text{cell\_util} &= \sum_{j=1}^M (\text{user\_util})_j \\ &= \sum_{j=1}^M \sum_{i=1}^L (u_i(B_i, E_i))_j, \end{aligned} \quad (2)$$

$$\begin{aligned} \text{system\_util} &= \sum_{k=1}^N (\text{cell\_util})_k \\ &= \sum_{k=1}^N \sum_{j=1}^M \sum_{i=1}^L (u_i(B_i, E_i))_{j,k}. \end{aligned} \quad (3)$$

With this formulation of the utility functions, we are able to overcome the shortcomings from the previous design objectives (from section 1). First, a user may prioritize various applications according to (1). Second, by introducing a weight factor, users in the system can be prioritized as in (2).

Our objective is to maximize (3) subject to constraints, where parameters and are controlled by power control, VFEC, and scheduling. One approach to this global optimization is to apply a centralized algorithm which considers all users' utilities in the system simultaneously. The advantage of this approach is that it does not require any iterative steps for achieving the optimum; however, the computational complexity and communication requirements are impractical for any reasonable sized system.

Instead, we propose a distributed algorithm that divides the system optimization problem into three separate levels: user level, cell level, and system level. Figure 6 shows the optimization hierarchy, in which the optimizations are represented by nodes and communications are represented by edges.

The nodes within each level are independent and can be optimized in parallel. The optimization results, expressed in terms of the resource requirements, are passed up to the higher level. For example, the optimal user utility, expressed in terms of user's channel SNR, is directly proportional to the transmit power level; the transmit power level is then determined by the cell level optimization which performs intra-cell power allocation. In addition, at the system level, a cell communicates with its interfering neighbor cells to negotiate its cell power budget so as to maximize the neighborhood utility. This layering approach yields a distributed algorithm, and the details are explained in the following section using a bottom-up strategy: from user level to cell level, to system level.

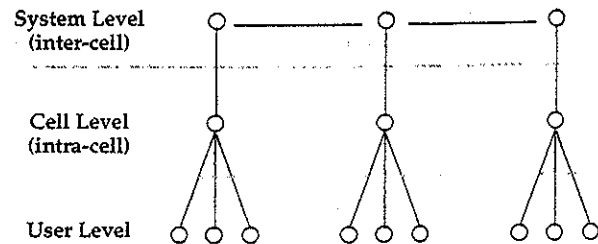


Figure 6. Three levels of optimization hierarchy.

For the rest of the paper, we assume the feedback loop from a portable to a basestation gives the basestation an estimate of the channel SNR. The basestation then calculates the propagation loss and the interference factors for each user, based on the user's channel SNR and the transmit power levels of the neighbor cells.

### 3.3. User level optimization

At the user level, we optimize user utility. Two techniques are applied: first, the system performs scheduling by allocating bandwidth to each application. Second, the system optimizes error rate by applying VFEC; VFEC enables the system to trade-off the quality with quantity of delivered data for each application.

Recall that the user utility is the sum of the application utilities:

$$U_{\text{user}}(\bar{B}, \bar{E}) = \sum_{i=1}^L u_i(B_i, E_i). \quad (4)$$

Our objective is to maximize (4), over  $\bar{B} = (B_1, B_2, \dots, B_L)$  and  $\bar{E} = (E_1, E_2, \dots, E_L)$  subject to the link bandwidth constraint,

$$\sum_{i=1}^L B_i \cdot \eta(\text{SNR}, E_i) \leq \text{link\_bandwidth}, \quad (5)$$

where

$$\eta(\text{SNR}, E_i) = \frac{\text{link\_bandwidth}}{\text{data\_bandwidth}}. \quad (6)$$

The maximal value of user utility is denoted as  $U_{\text{user}}^*$ .

To maximize the user utility, we do not directly choose the received BER  $E_i$ ; instead, we select the level of VFEC which, together with the link SNR, to determine the received BER. The choice of FEC code also determines the "bandwidth expansion factor",  $\eta(\text{SNR}, E_i)$ , which is the ratio of the link bandwidth to the data bandwidth, as shown in (6). Consequently,  $B_i \cdot \eta(\text{SNR}, E_i)$  is the actual channel bandwidth consumed for application  $i$ .

Maximizing (4) under the constraint (5) is an optimization problem over  $2L$  variables ( $\bar{B}$  and  $\bar{E}$ ). The optimal  $\bar{B}$  and  $\bar{E}$  can be obtained by applying the Lagrange multipliers. Observe that the channel SNR is the only undetermined variable during the optimization; as a result, both the optimal  $\bar{B}$  and  $\bar{E}$ , and thus the optimal user utility are functions of the channel SNR, as shown below:

$$U_{\text{user}}^*(\text{SNR}) = \max_{\bar{B}, \bar{E}} U_{\text{user}}(\bar{B}, \bar{E}), \quad (7)$$

such that

$$\sum_{i=1}^L B_i \cdot \eta(\text{SNR}, E_i) \leq \text{link\_bandwidth}.$$

To summarize, two results are achieved through this user level utility optimization. First, for any SNR, we can apply scheduling and FEC selection (i.e., choosing  $\bar{B}$  and  $\bar{E}$ )

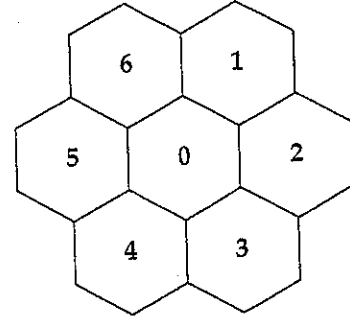


Figure 7. Cell topology.

such that the user utility is maximized. Second, the maximum user utility can be expressed as a function of SNR (presuming an optimal choice of  $\bar{B}$  and  $\bar{E}$ ). As will be shown in the next section, this maximal user utility function becomes the cornerstone of the cell level power allocation.

### 3.4. Cell level optimization

An indoor wireless communication environment is interference limited. In such an environment, users are subject to three sources of interference: intercell interference, intracell interference and background noise. The channel SNR for a user, say user  $j$  located in cell #0, is the ratio of the received signal power to the noise power:

$$\begin{aligned} \text{SNR}_j &= \frac{\text{received\_signal\_power}}{\text{total\_noise\_power}} \\ &= \frac{g_j \cdot \phi_j \cdot P_0}{(\sigma_i^2)_j + (\sigma_I^2)_j + (\sigma_B^2)_j}, \end{aligned} \quad (8)$$

where  $g_j$  is the gain from the basestation to user  $j$ ,  $\phi_j$  is the fraction of the total cell transmit power allocated to user  $j$ ,  $P_0$  is the total transmit power for cell #0, and  $(\sigma_i^2)_j$ ,  $(\sigma_I^2)_j$ ,  $(\sigma_B^2)_j$  are the intracell interference, intercell interference and background noise, respectively.

Assume a cell topology as shown in figure 7, where a center cell has six neighboring cells.<sup>4</sup> Suppose cell # $i$  is in the center, and let  $\bar{P}_i = (P_i, P_1^i, \dots, P_6^i)$  be the total power budget for each of the seven cells, where  $(P_i, P_1^i, \dots, P_6^i)$  are neighboring cell power levels. Using this notation,  $\bar{P}_0$  represents the power budget for a cell neighborhood where #0 is in the center.

Without loss of generality, our focus is on user  $j$  in cell #0 with six adjacent neighbor cells. The intracell and intercell interference are modeled as fractions of cell power levels [7], which are expressed in (9) and (10), respectively.<sup>5</sup> The  $\alpha_j$  and  $\beta_j$  are intracell and intercell interference coefficients which depend on the CDMA spreading factor and

<sup>4</sup> This assumption of having hexagonal cells is not necessary for our algorithm. It is only for illustrative purposes.

<sup>5</sup> Throughout this study, we only consider the first order intercell interference, i.e., interference coming from the adjacent cells.

propagation environment. These coefficients can be determined through measurements.<sup>6</sup>

$$(\sigma_i^2)_j = \alpha_j \cdot P_0, \quad (9)$$

$$(\sigma_I^2)_j = \beta_j^1 \cdot P_0^1 + \beta_j^2 \cdot P_0^2 + \dots + \beta_j^6 \cdot P_0^6. \quad (10)$$

We can combine (9) and (10) using a vector notation to represent the overall interference noise power,

$$(\sigma_i^2)_j + (\sigma_I^2)_j = \bar{\gamma}_j \bullet \bar{P}_0, \quad (11)$$

where  $\bar{\gamma}_j = (\alpha_j, \beta_j^1, \dots, \beta_j^6)$ , and  $\bullet$  is the vector dot product. Consequently, substituting the expression of interference noise power (11) into (8), the channel SNR for user  $j$  is

$$SNR_j = \frac{g_j \cdot \phi_j \cdot P_0}{\bar{\gamma}_j \bullet \bar{P}_0 + (\sigma_B^2)_j}. \quad (12)$$

During the downlink transmission, a CDMA radio transmits to all users within a cell simultaneously and is subject to a power budget which is determined through the higher layer optimization. The goal of performing cell level optimization, for cell #0 in our case, is to distribute the power budget  $P_0$  to each user so that the total cell utility is maximized. This goal is achieved by computing the optimal  $\phi_j$  for all users  $j$ . Suppose cell #0 has  $M$  users, the total cell utility is therefore the sum of maximal user utilities:

$$\begin{aligned} U_{\text{cell},0}(\bar{\phi}, \bar{P}_0) &= \sum_{j=1}^M U_j^*(SNR_j) \\ &= \sum_{j=1}^M U_j^* \left( \frac{g_j \cdot \phi_j \cdot P_0}{\bar{\gamma}_j \bullet \bar{P}_0 + (\sigma_B^2)_j} \right). \end{aligned} \quad (13)$$

Our objective is to maximize (13) subject to the power budget constraint

$$\sum_{j=1}^M \phi_j \cdot P_0 \leq P_0. \quad (14)$$

Maximizing cell utility is an optimization problem of  $M$  variables. The optimal power allocated to each user,  $(\phi_1 P_0, \phi_2 P_0, \dots, \phi_M P_0)$ , can again be obtained by applying the Lagrange multipliers. Notice that the cell power budget for the entire neighborhood,  $\bar{P}_0$ , remains unknown during the optimization; therefore, the optimal user power allocation,  $(\phi_1 P_0, \phi_2 P_0, \dots, \phi_M P_0)$ , thus the maximal cell utility, denoted as  $U_{\text{cell},0}^*$ , is a function of  $\bar{P}_0$ :

$$U_{\text{cell},0}^*(\bar{P}_0) = \max_{\phi_1, \dots, \phi_M} \sum_{j=1}^M U_j^*(SNR_j), \quad (15)$$

<sup>6</sup> The intracell and intercell interference coefficients for a user depend on the location of the user and the indoor environment, both of which are time varying. These interference coefficients can be estimated by correlating total noise power (which can be measured) with this and neighboring cell power levels.

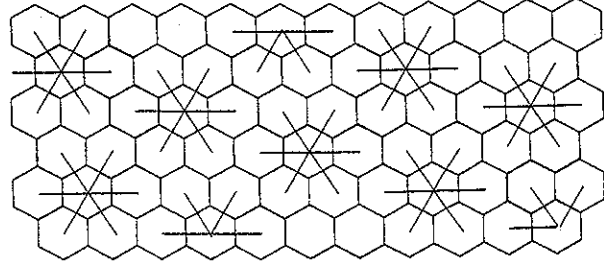


Figure 8. Non-overlapping interference neighborhoods.

such that

$$\sum_{j=1}^M \phi_j = 1.$$

It is rather easy to prove that the above two-step optimization process (i.e., the user level together with the cell level optimization) is equivalent to an one-step optimization at the cell level. This one-step optimization determines the  $B_i$  and  $E_i$  for each application among all users, and  $\phi_j$  for each user in the cell. However, the approach of breaking the problem into two steps allows users to have asynchronous scheduling and FEC encoding.

To summarize, we have achieved the optimal user power allocation for multiple users within a cell. The optimal cell utility depends on the cell power levels for the entire neighborhood. This result provides us with a platform to perform intercell power allocation, which is to determine the total cell power budget for each cell.

### 3.5. System level optimization

Our goal is to maximize the overall system utility which is achieved by setting the cell power budget for each cell. Since a large number of users and cells are in the system, we seek a distributed algorithm that is scalable in both computation and communication.

As intercell interference is localized to a finite region, changing the power level for a cell only affects its nearby cells; we call this region that cell's "neighborhood". This observation suggests that we are able to simultaneously change power levels for several cells, provided that their neighborhoods do not overlap. For this study, we assume only first order interference,<sup>7</sup> and figure 8 shows several non-overlapping neighborhoods (indicated by the "stars" superimposed on the cell topology).

Several key properties result if we restrict ourselves to changing power levels only for the center cells of these non-overlapping neighborhoods. Firstly, the effects from changing a center cell's power level are limited to the neighborhood boundary; therefore, cells only need to communicate within the neighborhood. Secondly, a center cell faces

<sup>7</sup> First order interference means that a basestation only interferes with its six immediate neighbor cells. This assumption is only for illustrative purposes, and is not necessary for our distributed algorithm. If the assumption does not hold, we can increase the neighborhood size, which consequently decrease the rate of convergence.

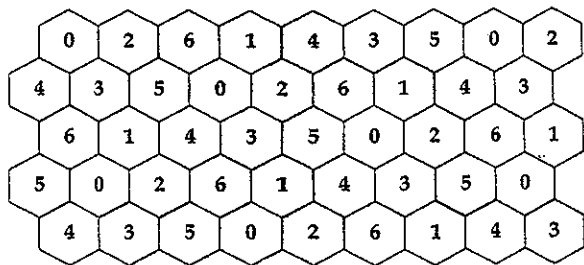


Figure 9. Iteration step assignments.

a fixed interference environment; therefore, calculating the power budget is simplified. Finally, the remaining cells within the neighborhood have exactly one interfering cell which is changing its power; therefore, estimating intracell and intercell interference coefficients ( $\overline{\gamma_j}$  from section 3.4) is simplified.

So far, we have updated cell power budgets for only a fraction of cells. Our ultimate goal is to update power budgets for all cells in the system. This is achieved by iterating according to a periodic schedule,<sup>8</sup> where the system adjusts different subsets of cells at each iteration; after one period, all cells in the system are updated at least once.

We will demonstrate this algorithm using our example of first order interference and hexagonal cell topology. Figure 9 shows the assignment of cells to iteration steps, and the iteration period equals to 7 in this case. Notice at every time step, the subset of cells which change power levels have non-overlapping neighborhoods.

We next describe how we determine the cell power budgets. The procedure is the same for all cells; however, we will focus on cell #0, with neighboring cells 1 through 6.

When updating the power budget for cell #0, its power level is chosen so as to maximize its overall neighborhood utility. We know from section 3.4 that the maximal cell utility for each cell in the neighborhood of cell #0 depends on  $P_0$ . Therefore, the total neighborhood utility, which is the sum of the maximal cell utilities, is also a function of  $P_0$ , as shown below:

$$U_{\text{neighborhood}}(\overline{P}_0, \overline{P}_1, \dots, \overline{P}_6) = U_{\text{cell},0}^*(\overline{P}_0) + \sum_{i=1}^6 U_{\text{cell},i}^*(\overline{P}_i). \quad (16)$$

While  $P_0$  is upper bounded by the implementation limit, the goal of adjusting  $P_0$  is to maximize the total neighborhood utility,  $P_0$  thus has to satisfy:

$$\frac{\partial}{\partial P_0} [U_{\text{neighborhood}}(\overline{P}_0, \overline{P}_1, \dots, \overline{P}_6)] = 0. \quad (17)$$

This is equivalent to

$$\frac{\partial}{\partial P_0} U_{\text{cell},0}^*(\overline{P}_0) = - \frac{\partial}{\partial P_0} \sum_{i=1}^6 U_{\text{cell},i}^*(\overline{P}_i). \quad (18)$$

<sup>8</sup> This schedule is fixed and determined by the system designer.

Notice that on the left side of (18) is cell #0's marginal utility as a function of  $P_0$ , and on the right is the total marginal utility of the neighbor cells. At the optimal point, with respect to  $P_0$ , the marginal utility of cell #0 offsets the marginal utility of the neighbor cells.

The system utility optimization algorithm we described above is indeed an iterative, one-dimensional search algorithm, in which we optimize along each  $P_i$  iteratively until reaching the maximum. There is a known numerical algorithm [10] that meets this purpose; furthermore, this algorithm has been proven to converge.

#### 4. Summary and conclusions

This paper investigated design and control issues faced by multimedia indoor CDMA systems. We have proposed a distributed algorithm that fully utilizes the system resources such as bandwidth and power. Our algorithm integrates three techniques for multimedia downlink transmission; these techniques are: power control, FEC and scheduling. As a multimedia system is designed to satisfy users, our objective is to maximize the overall user satisfaction, which we call "system utility".

We divided this system optimization problem into a hierarchy of three levels: user level, cell level and system level. This partitioning allows us to localize the problem, so that we can perform independent and local optimizations for each user and then each cell. Because users and cells in a CDMA system are subject to bandwidth and power constraints, we achieve the optimization by applying the Lagrange multiplier. The optimization results are then presented to the next level in the hierarchy. At the topmost level, system level, we allocated cell power to one set of cells while keeping their neighboring cell power levels constant. The cell power level is determined based on its effect to the overall utility for its entire neighborhood of seven cells. This layering approach yields a distributed algorithm.

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