A Dynamic Utility-Based Radio Resource Management Scheme for Mobile Multimedia DS-CDMA Systems

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Abstract—Radio resource management is one of the key ways for providing quality-of-service (QoS) to users in wireless networks. In this paper, we propose a utility-based radio resource management scheme for mobile multimedia DS-CDMA systems. The algorithm is aiming at the maximization of the system overall utilities. In order to reduce the computational complexity, the radio resource management is decomposed into two levels of sub-problems. With the proposed algorithm, transmit power and data rate assigned to users are dynamically adjusted according to their QoS requirements, channel conditions and current system load, so that the optimal resource allocation is achieved. Simulation results show that our scheme is flexible and efficient for managing radio resources in mobile multimedia DS-CDMA environments.

Index Terms—Multimedia, DS-CDMA, radio resource management, utility.

I. INTRODUCTION

Providing end-to-end quality-of-service (QoS) guarantees to users is one of the essential issues to be considered in future mobile communication systems, which are expected to support multimedia applications, such as voice, video, and data. Due to bandwidth limitation and the time-varying mobile channels with location-dependent errors, radio resource management is one of the key ways for providing QoS to users. In direct-sequence code division multiple access (DS-CDMA) systems, transmit power and data rate are two important components for radio resource management.

Although most previous studies have interpreted QoS requirements into specific technical parameters such as bandwidth, delay and loss probability, QoS is in fact a perceptual of users. Based on this consideration, some researchers have proposed a utility-based QoS framework [1]-[4]. Utility, which describes the welfare the consumer gets when he or she obtains the resources in mobile multimedia DS-CDMA systems, one of the key ways for providing QoS to users. In direct-sequence code division multiple access (DS-CDMA) systems, transmit power and data rate are two important components for radio resource management.

Utility-based radio resource management has been given more and more attentions recently. Mandayam et al. [1] proposed a distributed power control scheme based on a N-person non-cooperative game model. Ref. [2] improved the scheme by adding cost to the utility functions, which brings Pareto improvement. In [3], a utility-based power control scheme for TDMA systems was proposed. Practically the in the above references QoS are evaluated only by the received signal-to-interference ratio (SIR), therefore no data rate allocation are considered. Lin et al. [4] considered the data rate allocation as well as the time-varying property of wireless channels, and proposed a utility-based wireless resource management scheme for TDMA-based systems. However, the work did not take the power control issue into consideration.

In this paper, we propose a utility-based radio resource management scheme in mobile multimedia DS-CDMA systems, concerning power and data rate joint allocation. The purpose of the scheme is to maximize the system overall utilities (i.e. the sum of utilities of all users in the system). With the proposed radio resource management scheme, users’ transmit power and data rates are dynamically adjusted according to their QoS requirements, channel conditions and current system load. The rest of the paper is organized as follows. Section II investigates the efficiency function and utility functions. In Section III, the system model of the utility-based radio resource management is analyzed in detail. After that, we give a thorough description of the utility-based radio resource management algorithm in Section IV. Section V presents the simulation results. Finally we conclude the paper in Section VI.

II. UTILITY FUNCTIONS AND EFFICIENCY FUNCTIONS

By considering both received SIR and data rate as the measurements of the QoS provided by networks, we define the equivalent bandwidth of user \( i \) as

\[ R_i^o = R_i f_i(\gamma_i) \]  

(1)

where \( R_i \) is the gross bandwidth (data rate) assigned to user \( i \), \( \gamma_i \) is received SIR of user \( i \), \( f_i(\gamma_i) \) is the efficiency function which describes the percentage of successfully transmitted information bits to overall bits transmitted [4]. It is determined by the technologies used at physical layer, such as modulation, coding, interleaving and retransmission (ARQ). Fig. 1 shows the theoretical and simulated curves of two efficiency functions with typical physical layer technologies. We use QPSK modulation on AWGN channel, BCH coding (block length \( n = 31 \)) with coding rate \( R_c = 1/3 \) or no coding, and simple ARQ.

By (1) we know that \( R_i^o \) describes the actual bandwidth that user \( i \) gets when he is assigned a total bandwidth of \( R_i \). Therefore, it is reasonable to use \( R_i^o \) as the measurement of QoS provided by networks, and user \( i \)’s utility is a function of \( R_i^o \), which is expressed as \( U_i = U_i(R_i^o) \).

Since utility function describe the degree of satisfaction according to current QoS, it should be carefully selected so that...
it can reflect the nature of satisfaction. According to some literatures, the utility function $U_i(x)$ is an increasing function, satisfying $U_i(0) = 0$ and $U_i(\infty) = U_{mi} < +\infty$, where $U_{mi}$ represents the maximal welfare that user $i$ can get. $U_{mi}$ may be determined by the money user $i$ paid for the certain type of service, priority, or other facts. For voice, data and multimedia applications, the form of utility functions should be somewhat different. Fig. 2 shows utility functions of typical voice, data, and multimedia applications. For voice application, since the QoS requirement is “hard”, we use step function. For data application, there are no stringent QoS requirements, and more throughput leads to more satisfaction, therefore we use increasing concave function. Multimedia application is between voice and data, and S-shape function (such as Sigmoid function \[3\]) is used. Here for the sake of convenience for mathematical treatment, the very steep S-shape function instead of step function are used for voice traffic. It should be noted that our scheme is not only limited to these kinds of utility functions.

III. SYSTEM MODEL DESCRIPTION

The radio resource management scheme is aiming at maximizing the system overall utilities. Therefore, the system model can be formulated into an optimization problem. We focus on the uplink (from users to base station), since uplink is often the bottleneck of DS-CDMA networks \[7\]. A small modification to the uplink algorithm is proper for the downlink in DS-CDMA networks.

Consider a typical cell in a mobile multimedia DS-CDMA system with $N$ active mobile users. Let $\mathbf{R} = \{R_1, R_2, \cdots, R_N\}$ be the bandwidth assigned to the $N$ users, $\mathbf{P}^t = \{P_1^t, P_2^t, \cdots, P_N^t\}$ be the transmit power, and $\mathbf{h} = \{h_1, h_2, \cdots, h_N\}$ be the propagation gain from each user to the base station (BS). $W$ represents the system bandwidth, and $I_0$, the background interference received at BS. Assume user’s transmit power continuously tunable and bounded by a transmit power constraint $P_{i, \text{max}}^t$, the problem is to find a pair of vectors $\mathbf{P}^t$ and $\mathbf{R}$ which maximizes the sum of utilities of all users in the system, formulated as

\[
\max_{\mathbf{R}, \mathbf{P}^t} \sum_{i=1}^{N} U_i(R_i^o)
\]

s.t. $0 \leq P_i^t \leq P_{i, \text{max}}^t$, $(i = 1, 2, \cdots, N)$ \hspace{1cm} (2)

where $R_i^o$ is expressed as (1) and $\gamma_i$ is given by \[6\]

\[
\gamma_i = \frac{W}{R_i} \sum_{j \neq i} h_j P_j^t + I_0, \quad (i = 1, 2, \cdots, N)
\]

The system model presented by (2) is a nonlinear optimization problem with $2N$ decision variables. Generally solving such a problem by typical algorithms (such as steepest decent method and gradient projection method \[8\]) is of high computational complexity, which is very time-costing and impractical for implementation. In order to reduce the computational complexity, we further decompose the problem into subproblems: equivalent bandwidth maximization for single user and system-wide utility optimization.

A. $R_i^o$ Maximization for Single User

Since $U_i$ is an increasing function of $R_i^o$, maximizing utility of user $i$ is equivalent to maximizing $R_i^o$. Let $I_{-i}$ be the multiple access interference (MAI) received by user $i$, which is given by $I_{-i} = \sum_{j \neq i} h_j P_j^t + I_0$. It is easy to know that when transmit power keeps constant, $I_{-i}$ is also unchanged. By rewrite $R_i^o$ as a function of $\gamma_i$, we have the single user throughput maximization subproblem as

\[
\max_{\gamma_i} R_i^o = \max_{\gamma_i} \frac{W}{\gamma_i} \frac{h_i P_i^t}{I_{-i}} f_i(\gamma_i)
\]

The optimal solution of the above problem, denoted by $\gamma_i^*$, is only determined by the efficiency function. Stabilizing users received SIR to $\gamma_i^*$ is the necessary condition of the utility optimization problem. In other words, $\mathbf{R}$ and $\mathbf{P}^t$ are no longer independent, and are related by $\gamma_i^*$.
If $R_i^\circ(\gamma)$ is unimodal, $\gamma_i^\ast$, the solution of the optimization problem (4) is given by

$$\frac{\partial R_i^\circ}{\partial \gamma_i} = 0$$

which is equivalent to

$$f_i(\gamma_i) = \gamma_i f'_i(\gamma_i)$$

The value of $\gamma_i^\ast$ can also be obtained by simulation or measurements in real systems.

B. System-Wide Utility Optimization

According to discussions above, $\gamma_i$ should be stabilized to $\gamma_i^\ast$, for $i = 1, 2, \cdots, N$. Therefore, from [7] we know that the transmit power constraints in system model (2) is equivalent to

$$\sum_{i=1}^{N} \gamma_i f_i(\gamma_i)$$

Define the Lagrangian function

$$g_i = \frac{1}{W_{\text{max}}} + 1$$

and $g_\Sigma = \sum_{i=1}^{N} g_i$. Now the utility optimization model is equivalent to

$$\max_R \sum_{i=1}^{N} V_i(R_i)$$

s.t. $\sum_{i=1}^{N} g_i \leq \min_i \left\{ 1 - \frac{g_i I_0}{h_i P_{i,\text{max}}} \right\}$

where $V_i(R_i) = U_i(R_i f_i(\gamma_i^\ast))$. This is the system-wide utility optimization problem, with the $R$ be the decision variable vector.

Define the Lagrangian function

$$\mathcal{L}(R, \lambda) = \sum_{i=1}^{N} V_i(R_i) - \lambda \left( \sum_{i=1}^{N} g_i - T \right)$$

where $T = \min_i \left\{ 1 - \frac{g_i I_0}{h_i P_{i,\text{max}}} \right\}$. According to [8], there is no duality gap between the optimization problem (6) and its dual problem

$$\min_\lambda \left[ T - \sum_{i=1}^{N} g_i(\hat{R}_i(\lambda)) \right]$$

s.t. $\hat{R}(\lambda) = \arg \max_R \mathcal{L}(R, \lambda)$

which means the solution of (8) is the solution of (6). Here $g_i(\hat{R}_i(\lambda))$ means taking $\hat{R}_i(\lambda)$ as $R_i$ into eq. (5), the definition of $g_i$.

Eq. (7) illustrates that the Lagrangian maximization problem

$$\max_{R_i} \mathcal{L}(R, \lambda)$$

in (8) can be decomposed into $N$ separate subproblems

$$\max_{R_i} \left\{ V_i(R_i) - \lambda g_i \right\}, \quad (i = 1, 2, \cdots, N)$$

If $V_i(R_i) - \lambda g_i$ is a concave function of $R_i$, each of the subproblems has unique optimal solution, given by the $V_i'(R_i) = \lambda g_i$. By defining function $f_\lambda(R_i)$ as

$$f_\lambda(R_i) = \frac{dV_i(R_i)}{dR_i} / \frac{dg_i}{dR_i}$$

the solution of subproblems (9) could be written as

$$\lambda = f_\lambda(R_i) \iff R_i = f_\lambda^{-1}(R_i)$$

$f_\lambda(R_i)$ is the called user $i$’s characteristic function.

Fig. 3 shows the characteristic functions of the three applications whose utility functions are shown in Fig. 2. Define

$$\lambda_{i,\text{max}} = \max_{R_i} \frac{V_i(R_i)}{g_i}, \quad R_i_{\text{min}} = \arg \max_{R_i} \frac{V_i(R_i)}{g_i}$$

As a result, if $\lambda > \lambda_{i,\text{max}}$, $V_i(R_i) - \lambda g_i < 0$. This indicate that $R_i$ assigned to user $i$ should be set to zero. The values of $\lambda_{i,\text{max}}$ and corresponding $R_i_{\text{min}}$ of applications are also shown in Fig. 3. We see that for all types of applications, when $R_i \geq R_i_{\text{min}}$, $f_\lambda(R_i)$ is a decreasing function of $R_i$, which means $V_i(R_i) - \lambda g_i$ is concave of $R_i$. In other words, subproblems (9) can achieve the unique optimal solution by (10). Thus, by restricting $R_i$ to $R_i \geq R_i_{\text{min}}$, we can always achieve the optimal solution of the Lagrangian maximization problem by decomposing it into the $N$ subproblems (9). As a result, the time-costing system-wide nonlinear optimization problem is avoided and the computational complexity is reduced.

The problem

$$\min_\lambda \left[ T - \sum_{i=1}^{N} g_i(\hat{R}_i(\lambda)) \right]$$
could be solved asymptotically by binary search method [8]. The utility based radio resource management algorithm for mobile multimedia DS-CDMA systems is described in detail in the next section.

IV. ALGORITHM DESCRIPTIONS

According the discussion above, the value of the following parameters should be calculated when a connection is accepted by the system: its $\gamma_i^*$, $\lambda_{i\text{ max}}$, its corresponding $\lambda_{i\text{ max}}$, and $g_{i\text{ min}}$ (by taking $R_{i\text{ min}}$ into eq. (5)). At each resource management point, the power and rate joint allocation algorithm performs the following steps:

1) [Channel Prediction and Shutoff Procedure] Predict the channel gain $h_i$, $i = 1, 2, \ldots, N$. Since there is a minimal data rate constraint $R_{i\text{ min}}$ for each user, a shutoff procedure is called to check if $R_i \geq R_{i\text{ min}}$ for all users could be satisfied. If not, shut off user $k$ that

$$ k = \arg \min_i \left\{ 1 - \frac{g_{i\text{ min}} I_0}{h_i R_{i\text{ max}}} \right\} $$

by setting $R_{k\text{ shutoff}} = 0$.

2) [Initialize Iteration] let $m = 1$, $\bar{\lambda} = \max_i \lambda_{i\text{ max}}$, $\lambda = 0$.

3) [Update $R_i$] The value of $\lambda$ is set to

$$ \lambda^{(m)} = 0.5(\bar{\lambda} + \lambda) $$

For user who keeps active (have not been shut off by the shutoff procedure), update $R_i$ by

$$ R_i^{(m)} = \begin{cases} f^{-1}_\lambda(\lambda^{(m)}), & \lambda^{(m)} \leq \lambda_{i\text{ max}} \\ 0, & \lambda^{(m)} > \lambda_{i\text{ max}} \end{cases} $$

4) [Update $g_i$ and $T$] Update $g_i$ by $g_i^{(m)}(R_i^{(m)})$ and $g_{i\text{ max}}^{(m)} = \sum_{i=1}^N g_i^{(m)}$ calculated $T(m)$ by

$$ T(m) = \min_i \left\{ 1 - \frac{g_i^{(m)} I_0}{h_i R_{i\text{ max}}} \right\} $$

5) [Update $\lambda$] Adjust $\bar{\lambda}$, $\lambda$ and $\lambda$ by binary search method: if $g_{i\text{ c}}^{(m)} < T^{(m)}$, $\bar{\lambda} = \lambda$; otherwise $\bar{\lambda} = \lambda$.

6) [Stop Condition] If $m = M$ or $\bar{\lambda} = \lambda$ or $\varepsilon$, stop; otherwise $m = m + 1$, and goto step 3. Here $\varepsilon$ is the desired precision [8], and $M$ is the maximal iteration times. According to our simulation, $M=6$ is good enough for the algorithm to converge.

7) [Resource Normalize] Calculate $g_i$ for each active user by

$$ g_i = \frac{g_i^{(m)} g_{i\text{ c}}^{(m)} I_0}{g_{i\text{ c}}^{(m)} + g_{i\text{ c}}^{(m)} I_0} $$

where

$$ k = \arg \min_i \left\{ 1 - \frac{g_i^{(m)} I_0}{h_i R_{i\text{ max}}} \right\} $$

By normalization, we have $g_{i\text{ c}} = \min_i \left\{ 1 - \frac{g_i I_0}{h_i R_{i\text{ max}}} \right\}$, and the maximal transmit power is adjusted to $P_{i\text{ max}}^t$.

Therefore, no system resource is wasted as well as the maximal transmit power constraint is guaranteed.

8) [Transmit Power and Data Rate Allocation] Data rate assigned to active user (who have not been shut off) is given by

$$ R_i = \frac{W}{\gamma_i(\frac{1}{\gamma_i} - 1)} $$

and transmit power,

$$ P_t^i = \frac{g_i}{h_i(1 - g_{i\text{ c}})} I_0 $$

which can be easily derived from the eqs. (3) and (5). For users who have been shut off, $R_i = 0$ and $P_t^i = 0$.

V. NUMERICAL RESULTS

Our simulation system is a round 1km DS-CDMA cell. Users moves with an velocity from 1m/s to 30m/s, and their directions alter randomly. QPSK modulation, (511,175,46) BCH coding (with coding rate $r = 1/3$) and simple ARQ scheme is used. As a result, $\gamma_i^* = 1.1764$. The system bandwidth $W$ is 3.84MHz, and the background interference $I_0$ is $2.5 \times 10^{-6}$W. Users’ transmit power constraints are 0.2W. Three types of applications are considered, including voice, data and multimedia applications. Parameters of these applications are shown in Table I.

<table>
<thead>
<tr>
<th>Traffic Type</th>
<th>$U_m$</th>
<th>$R_{i\text{ min}}$ (Kbps)</th>
<th>$\lambda_{i\text{ max}}$</th>
<th>$g_{i\text{ min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>1.22</td>
<td>37.74</td>
<td>88.01</td>
<td>0.0137</td>
</tr>
<tr>
<td>Data</td>
<td>3</td>
<td>7.52</td>
<td>69.96</td>
<td>0.0028</td>
</tr>
<tr>
<td>Multimedia</td>
<td>7.2</td>
<td>257.66</td>
<td>70.72</td>
<td>0.092</td>
</tr>
</tbody>
</table>

TABLE I

Parameters of the three types of applications

Our simulation shows the achieved utilities of three different users representing the three types of applications respectively. When the system load is low, all applications can achieve the utilities close to their $U_{m}$. However, if the system is heavily loaded, differences clearly appear. The utility level of voice application is almost unchanged at high system load, since its utility curve is the steepest, which indicates the most stringent QoS requirements. Furthermore, though not as well as voice, the utility level of multimedia applications also keeps high. On the other
systems. The goal of the scheme is to maximize the system utility, whose average utility is always close to its upper bound. The change of system load has little influence on voice application, whose average utility has little chance to approach its upper bound. On the other hand, data performs much worse than the other three applications, in that its utility has little chance to approach its upper bound. The feasibility of our algorithm is clearly revealed by this figure.

Fig. 6 presents the average achieved utilities for different applications normalized by $U_m$ at different system load. The change of system load has little influence on voice application, whose average utility is always close to its upper bound, while average utility of multimedia application can also keeps a relatively high level when system load is high. On the other hand, for data application, the average achieved utility decreases very fast as the system load increases. This figure illustrates that the proposed utility-based radio resource management algorithm is flexible and efficient in managing radio resources in mobile multimedia DS-CDMA systems.

VI. Conclusion

In this paper, we have proposed a utility-based radio resource management scheme in mobile multimedia DS-CDMA systems. The goal of the scheme is to maximize the system overall utilities. We decompose the utility optimization problem into two subproblems so that the computational complexity is reduced. With the proposed scheme, transmit power and data rates of users are dynamically adjusted according to their QoS requirements, channel conditions and current system load. Simulation results have shown that our scheme is flexible and efficient for managing radio resources in mobile multimedia DS-CDMA systems.

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