Minimizing Deviation from Service Curve in Forward Link of DS-CDMA Network

Parameswaran Ramanathan and Lun Tong
Department of Electrical and Computer Engineering
University of Wisconsin-Madison
parmesh@ece.wisc.edu, luntong@students.wisc.edu

Abstract- **In a Direct Sequence Code Division Multiple Access (DS-CDMA) based cellular network, meeting the diverse quality of service (QoS) needs of mobile hosts (MHs) is a challenge because of the fluctuations in the quality of the wireless channel. In this paper, the QoS needs of the MHs application are modelled using service curve. Furthermore, a notion of deviation is introduced as a measure of meeting service curve. The paper describes a forward link scheme whose primary objective is to minimize system deviation from service curve and the secondary objective is to maximize the system throughput. The solution includes constraints on the transmit power of the base station (BS), number of spreading codes and target Signal to Interferences plus Noise Ratio (SINR) for MHs.**

I. Introduction

In this paper, we consider forward link transmission in a single cell of a Direct Sequence Code Division Multiple Access (DS-CDMA) based cellular network. Each mobile host (MH) in the cell is running an application that receives a stream of packets from the base station (BS). The MHs differ in the type of applications they are running, thereby resulting in a wide diversity in the quality of service (QoS) needs of the MHs. For example, some MHs are running data-oriented applications such as secure shell, web browsing, and electronic email while others are running interactive applications such as Voice-over-IP and real audio.

We model the QoS needs of a MH using the notion of a service curve [1]. The service curve specifies the minimum number of bits a MH must receive in given time interval to meet its QoS requirements. The use of service curves to model QoS needs is well studied in wireline networks. If the service curves satisfy certain constraints, then there are well known service scheduling policies for wireline networks to always meet QoS requirements of all users. We believe that such strong guarantees are not possible in wireless networks due to fluctuations in channel quality.

In this paper, we introduce the notion of deviation from service curve to represent a more realistic objective for wireless networks. The deviation $V_i(t)$ is defined to be 0 if MH_i has received more bits than required. Otherwise, the deviation is equal to the lag between what is required and what has been received. We further define system deviation from service curve $V(t)$ at time t to be $V(t) = \sum_i V_i(t)$.

The primary objective of the scheme proposed in this paper is to minimize the system deviation. In situations where the system deviation can be reduced to zero (i.e., all service curves can be met), the secondary objective of the proposed scheme is to maximize the system throughput.

This work differs from those in literature in the following ways. In [2], [3], [4], [5], [6], solutions are proposed to approximate wireline network techniques to Time Division Multiplex Access (TDMA) based wireless network. As mentioned earlier, in this paper, we consider DS-CDMA based wireless networks. Prior work in DS-CDMA networks have often focussed on throughput maximization. For example, in [7], Oh, Wasserman, and Olsen, use a game theoretic approach to dynamically allocate power and processing gain to maximize the total reverse link throughput. In [8], Jafar and Goldsmith characterize the optimal power and rate allocation to maximize the reverse link throughput in a multicode DS-CDMA network. They also describe a search-based algorithm to find the optimal solution. In [9], Elaoud and Ramanathan describe a scheme to adapt the SINR requirements of MHs based on their network QoS needs and channel quality. In [10], Tong, Ramanathan, and Sayeed describe a heuristic rate and power adaptation scheme for dealing with MHs with service curve requirements. The schemes in [7], [8], [9], [10] are for reverse link. In contrast, in this paper we propose an optimal power and rate allocation scheme for forward link with an objective of minimizing the deviation from service curve.

The rest of this paper is organized as follows. In Section II, we formally describe the system model. The proposed solution is described in Section III and simulation results evaluating our approach is presented in Section IV. The paper concludes with Section V.

II. Problem Formulation

We consider a single cell of a DS-CDMA based cellular network. We assume that there are K active mobile hosts (MHs) in the cell. We say that MH_i is backlogged at time t if the BS has packets destined for MH_i waiting for transmission; otherwise, MH_i is idle. Time t is said to be a start of a backlog period for MH_i if MH_i was idle just prior to t and is backlogged at time t. Each MH_i is associated with a service curve

The work reported here was supported in part by U.S. Army Research grant DAAD19-01-1-0504 under a subrecipient agreement S01-24 from The Pennslyvania State University, and by National Science Foundation grant ECS-9979408. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of funding agencies.

S_i to characterize its QoS needs. Let $W_i(s,t)$ be number of bits MH$_i$ has received in time interval (s,t).

Definition 1: Service curve S_i (and thus QoS requirement) of MH$_i$ is said to be assured at time t if there exists a start of a backlog period $s \leq t$ of MH$_i$ such that $S_i(t-s) \leq W_i(s,t)$.

Algorithmically, given a service curve S_i, one can efficiently compute at any time t, a deadline curve D_i, which specifies for any $u > t$, the number of bits MH$_i$ must receive in $[0,u)$ in order to assure its service curve at u[11].

Define the deviation from service curve as

$$V_i(t) = \max\{D_i(t) - W_i(t), 0\} \quad (1)$$

That is, the deviation is zero at time t if MH$_i$ has received more service than $D_i(t)$. Otherwise, the deviation equals the shortfall in the amount of service MH$_i$ has received in $(0,t]$ as compared to $D_i(t)$. Define the system deviation as $V(t) = \sum_{i=1}^{K} V_i(t)$.

The scheme proposed in this paper dynamically allocates transmit power and number of spreading codes assigned to MHs. We make the following modelling assumptions.

- The wireless channel is characterized using flat Rayleigh fading model.
- All MHs use Matched Filter (MF) receiver to decode their data.
- Power and rate adaptation occurs once every Δ time units, where Δ is less than or equal to the coherence time of the channel.

Let $P_i(t,t+\Delta)$ and $n_i(t,t+\Delta)$ respectively denote the transmit power and number of spreading codes used by BS for MH$_i$ in time interval $(t,t+\Delta)$. When the time of the allocation is clear from the context, we use P_i and n_i instead of $P_i(t,t+\Delta)$ and $n_i(t,t+\Delta)$.

The primary objective of our allocation scheme at time t is to minimize the system deviation $V(t+\Delta)$. If $V(t+\Delta)$ can be made zero, the secondary objective is to maximize system throughput $\Omega(t,t+\Delta) = \sum_{i=1}^{K} n_i(t,t+\Delta)$.

Due to typical practical limitations, we impose following constraints.

- **Peak power constraint**: A bound, $P_{\max}$, on the total transmit power of the BS, i.e.,

$$0 \leq \sum_{i=1}^{K} P_i(t,t+\Delta) \leq P_{\max}$$

- **Rate constraint**: Limit on the number of spreading codes MH$_i$ can concurrently decode. i.e.,

$$\forall i : n_i(t,t+\Delta) \leq M_i$$

- **Signal to Interference plus Noise Ratio (SINR) constraint**: Lower bound on the SINR that needs to be achieved for successful decoding at the MH. i.e., if $n_i(t,t+\Delta) > 0$,then

$$\gamma \leq \frac{g_i G P_i / n_i}{\sum_{j=0}^{K} g_j P_j - g_i P_i/n_i + \sigma^2}$$

where g_i is channel gain from BS to MH$_i$.

III. Proposed Solution

A. High Level Solution

Let F be the number of bits the BS can transmit using one spreading code in $(t,t+\Delta)$. Then

$$W_i(t+\Delta) = W_i(t) + n_i(t,t+\Delta)F,$$

and the deviation from service curve at $t+\Delta$ is

$$V_i(t+\Delta) = \max\{D_i(t+\Delta) - W_i(t) - n_i(t,t+\Delta)F, 0\}.$$

Therefore, deviation $V_i(t+\Delta) = 0$ if

$$n_i(t,t+\Delta) \geq \max\left\{\left\lceil \frac{D_i(t+\Delta) - W_i(t)}{F} \right\rceil, 0\right\}.$$

Thus, due to the rate constraint, if $\left\lceil \frac{D_i(t+\Delta) - W_i(t)}{F} \right\rceil > M_i$, the deviation cannot be made 0 at $t+\Delta$. In this case the minimum deviation is achieved if $n_i(t,t+\Delta) = M_i$.

Let

$$\begin{aligned} m_i(t,t+\Delta) &= \max\left\{\left\lceil \frac{D_i(t+\Delta) - W_i(t)}{F} \right\rceil, 0\right\} \\ l_i(t,t+\Delta) &= \min\{M_i, m_i(t,t+\Delta)\}. \end{aligned}$$

From the above discussion, minimum deviation is achieved when $n_i(t,t+\Delta) = l_i(t,t+\Delta)$.

In later discussions, we use the following simpler notations:

$$\begin{aligned} m_i &\equiv m_i(t,t+\Delta) \\ l_i &\equiv l_i(t,t+\Delta) \\ \Omega &\equiv \Omega(t,t+\Delta) \\ \mathbf{n} &\equiv (n_1, n_2, \ldots, n_K) \\ \mathbf{P} &\equiv (P_1, P_2, \ldots, P_K) \end{aligned}$$

Theorem 1: The solution to the following constrained optimization problem also minimizes the average system deviation.

Maximize throughput $\Omega = \sum_i n_i$
Subject to peak power, rate and SINR constraints and
$0 \leq n_i \leq l_i$ for all i.

Proof: Omitted due to length restrictions. ■

Figure 1 shows a high level description of our solution to meet the primary and secondary objectives. The optimality of this solution follows directly from theorem 1. In this solution, we first check whether there exists a feasible allocation of codes and power that meets the service curve of all MHs at time $t+\Delta$. If yes, the average system deviation at $t+\Delta$ is 0 and thus minimum. Therefore, the solution invokes the throughput phase where we maximize the throughput subject to keeping the system deviation 0. On the other hand, average system deviation cannot be made 0, them the solution invokes the deviation phase where it minimizes the system deviation as characterized in theorem 1. In the following subsection, we consider forward link and describe the algorithm in detail.

Check feasible for $\mathbf{n}$=$(l_1, l_2, \ldots, l_K)$
If feasible
*/*throughput phase*/*
Maximize throughput $\Omega = \sum_i n_i$
Subject to: peak power, rate and SINR constraints and
$l_i \leq n_i \leq M_i$
Else
*/*deviation phase*/*
Maximize throughput $\Omega = \sum_i n_i$
Subject to: peak power, rate and SINR constraints and
$0 \leq n_i \leq l_i$
END
Compute $\mathbf{P}$ for $\mathbf{n}$

Fig. 1. High level solution.

Sort MHs according to their channel condition
such that $g_1 \geq g_2 \geq \ldots \geq g_K$
Check feasible for $\mathbf{n}$=$(l_1, l_2, \ldots, l_K)$
If feasible
*/*Invoke throughput phase*/*
Find maximum j and maximum n_j such that
$(M_1, M_2, \ldots, M_{j-1}, n_j, l_{j+1}, \ldots, l_K)$ is feasible.
Else
*/*Invoke deviation phase*/*
Find maximum j and maximum n_j such that
$(l_1, l_2, \ldots, l_{j-1}, n_j, 0, \ldots, 0)$ is feasible.
End If
Compute $\mathbf{P}$ for $\mathbf{n}$

Fig. 2. Pseudo code for optimal rate and power allocation.

B. Solution for Forward Link

Without loss of generality, let $g_1 \geq g_2 \geq \ldots \geq g_K$.

Lemma 1: In a forward link transmission, a code assignment $\mathbf{n}$=$(n_1, n_2, \ldots, n_K)$ is feasible, i.e., there exist a feasible power assignment $\mathbf{P}$=$(P_1, P_2, \ldots, P_K)$ such that peak power, rate and SINR constraints are satisfied, if and only if

$$\frac{\gamma\sigma^2}{G+\gamma}\sum_{i=1}^{K}\frac{n_i}{g_i} \leq P_{\max}\left(1 - \frac{\gamma}{G+\gamma}\sum_{i=1}^{K} n_i\right) \quad (2)$$

$$\frac{\gamma}{G+\gamma}\sum_{i=1}^{K} n_i < 1 \quad (3)$$

where G is the processing gain and σ^2 is power density of background AWGN.

Further more, if $\mathbf{n}$ is feasible, one of the optimal solutions of $\mathbf{P}$ is

$$\forall i : P_i = \frac{\gamma\sigma^2}{G+\gamma-\gamma\Omega}\frac{n_i}{g_i} \quad (4)$$

■

Lemma 2: Suppose $g_1 \geq g_2 \geq \ldots \geq g_K$. Then $(n_1, \ldots, n_j+1, \ldots, n_K)$ is feasible implies that $(n_1, \ldots, n_i+1, \ldots, n_K)$ is also feasible for all $i < j$ and $n_i + 1 \leq M_i$. ■

Lemma 2 implies that, it is better to give as many spreading codes as possible to MHs with better channel.

A pseudo code of an algorithm for identifying an optimal allocation of $\mathbf{n}$ and $\mathbf{P}$ is shown in Figure 2.

In this algorithm, throughput phase is invoked if code assignment $\mathbf{l} = (l_1, l_2, \ldots, l_K)$ is feasible. In this case, since $\forall i : n_i \geq li$, every MH$_i$ must get at least l_i codes. Denote $\mathbf{n}^*$=$(n_1^*, n_2^*, \ldots, n_K^*)$ as optimal solution for code assignment, then $\mathbf{n}^* \geq \mathbf{l}$.

According to lemma 2, to obtain optimal solution, MH$_i$ will always get as much codes as possible before MH$_{i+1}$ can get one extra code other than l_{i+1}. This will result $n_i^* = M_i$ if it is feasible for $i < j$. Thus the solution to the constrained optimization problem in throughput phase can be obtained by finding maximum j and maximum n_j, where $j \leq K$ and $l_j \leq n_j \leq M_j$, such that code assignment $(M_1, M_2, \ldots, M_{j-1}, n_j, l_{j+1}, \ldots l_K)$ is feasible.

Similarly, deviation phase is executed when checking for $\mathbf{l}$=$(l_1, l_2, \ldots, l_K)$ is not feasible. This means that the optimal solution is $\mathbf{n}^* < \mathbf{l}$. The solution to the constrained optimization problem in deviation phase can be obtained by finding maximum j and maximum n_j, where $j \leq K$ and $0 \leq n_j \leq l_j$, such that code assignment $(l_1, l_2, \ldots, l_{j-1}, n_j, 0, \ldots, 0)$ is feasible.

Any search algorithm can be used to find j and n_j in throughput and deviation phase. For example, in deviation phase, first, use binary search algorithm to find j such that $(l_1, \ldots, l_{j-1}, 0, \ldots, 0)$ is feasible and $(l_1, \ldots, l_{j-1}, l_j, 0, \ldots, 0)$ is not feasible. This can be done in $\log K$ steps. Then use binary search algorithm to find n_j such that $(l_1, \ldots, l_{j-1}, n_j, 0, \ldots, 0)$ is feasible and $(l_1, \ldots, l_{j-1}, n_j + 1, 0, \ldots, 0)$ is not feasible. This can be done in $\log M$ steps. Therefore, one can find the solution in $\log K + \log M$ steps. Similarly for throughput phase, the solution can also be found in $\log K + \log M$ steps.

IV. Simulation and Result

A. Simulation Method

In this section, we present results obtained from a Matlab simulation of the proposed schemes. In the simulation, the MHs are initially uniformly distributed in a single cell covering a range of 100 to 1000 meters from the BS. There are 12 active MHs in the cell at all times. At the beginning of every time slot (the time slot is assumed to be 0.02 seconds), each MH has probability $p = 0.02$ of ending its current transmitting session and becoming inactive. For simplicity of simulation, we assume that when a MH becomes inactive another MH becomes active and starts a new session. The location and the speed of the new MH are chosen randomly. The speed of the MH is assumed to be constant during its session. We update the position and channel gain of all active MHs. The channel gain is assigned based on the model described in [12].

$$g = \left[20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10\left(a - bh_b + \frac{c}{h_b}\right)\log_{10}\left(\frac{d}{d_0}\right)\right] + \left[10x\sigma_\gamma\log_{10}\left(\frac{d}{d_0}\right) + y\mu_\sigma + yz\sigma_\sigma\right]$$

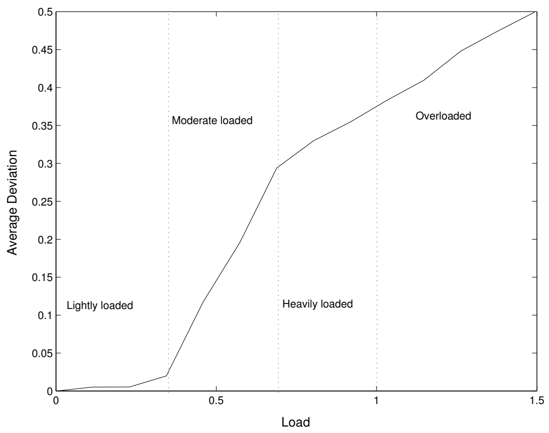

Fig. 3. Deviation vs. service curve rate.

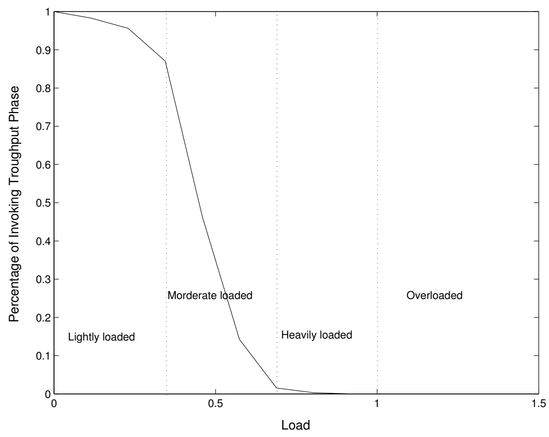

Fig. 4. Percentage of throughput phase vs. service curve rate.

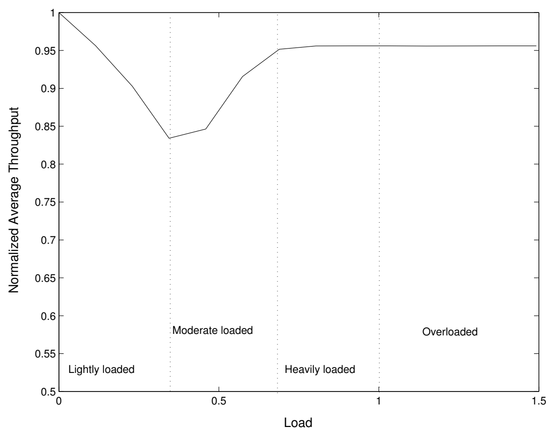

Fig. 5. Throughput vs service curve rate.

where d is distance between BS and MH in meters, h_b is the base station antenna height in meters, $d_0 = 100$ meters and l is the carriers wavelength. The parameter x, y and z are independent standard Gaussian variables. The parameter values used for this model are: the frequency of the carrier is 1.9 GHz, $h_b = 50$ meters, $a = 4.0$, $b = 0.0065$, $c = 17.1$, $\sigma_\gamma = 0.75$, $\mu_\sigma = 9.6$, and $\sigma_\sigma = 3.0$.

For simplicity, we use linear service curves for all MHs. The slope of the service curve is the data rate desired by the MH. We assume $\forall i : M_i = 10$, the processing gain $G = 120$, and the desired SINR $\gamma = 8dB$. The data rate and the maximum transmit powers are varied in the simulation to study their effect on the performance of the proposed scheme.

The simulation is run for a sufficiently long period time T. At the end of a time slot, say at time t, the simulator collects two measures: System Throughput $\Omega(t-\Delta, t)$ and the Normalized System Deviation $\theta(t)$. These two measures are formally defined as follows.

$$\Omega(t-\Delta, t) = \sum_{i=1}^{K} n_i(t-\Delta, t)$$

$$\theta(t) = \frac{\sum_{i=1}^{K} \max\{0, D_i(t) - W_i(t)\}}{\sum_{i=1}^{K} D_i(t)}$$

The graphs in this section plot the average of $\Omega(t - \Delta, t)$ and $\theta(t)$ computed over the entire simulation run. That is,

$$\text{Average Throughput} \qquad \bar{\Omega} = \frac{\Delta}{T} \sum_{l=1}^{T/\Delta} \Omega((l-1)\Delta, l\Delta)$$

$$\text{Average Deviation} \qquad \bar{\theta} = \frac{\Delta}{T} \sum_{l=1}^{T/\Delta} \theta(l\Delta).$$

B. Simulation Result

B.1 Deviation vs. Load

Figure 3 shows the average system deviation as a function of load for forward link. The results here correspond to a maximum transmit power 140 dB as compared to noise power. Figure 4 shows the percentage of time slots in which the proposed scheme invokes the throughput phase for different loads. The average deviation increases with load. The deviation is close to 0 when system is lightly loaded (loads less than 0.4). This is because the service curve can be met most of the time. This can also be seen in figure 4 since the proposed scheme invokes throughput phase only in time instants where the service curve of all the MHs are met. For example, at loads of 0.3, the throughput phase is invoked 90% of the time slots, implying that the service curve of all MHs were met 90% of the time. When the system load is moderate to heavy (0.4 to 1), it is more difficult to meet the service curve of all MHs. As a result, the system deviation starts to increase. Finally, when the system load exceeds 1, it is not possible to meet the service curve requirement almost always (see Figure 4). The deviation therefore continues to increase.

B.2 Throughput vs. Load

Figure 5 shows the normalized average throughput for forward link. The following observations can be made.

- The throughput decreases with the load when the system is lightly loaded (load < 0.4). This is because the service curve requirement forces the scheme to allocate spreading codes to MHs with poor channel. For forward link, a spreading code allocated to a MH with poor channel consumes more transmit power than a spreading code to a MH with good channel. Consequently, there is a decrease in the total number of codes that can be assigned.

- The throughput increases with load when the system is moderate to fully loaded (0.4 to 1). This increase in throughput occurs at the expense of deviation (see Figure 3). To better understand the reason for this, consider the case when system is almost fully loaded. In this case, most MHs are not able to meet their service curves. Therefore, m_i is large for almost all MH$_i$ and $l_i = \min(m_i, M_i) = M_i$ for almost all i. Consequently, the deviation phase maximizes throughput subject to $0 \leq n_i \leq M_i$. Note, its similarity to the case when there is no service curve requirement (load = 0). In this case, $m_i = 0$ and thus $l_i = 0$ and the proposed scheme always uses the throughput phase subject to $0 \leq n_i \leq M_i$. As a result, the throughput achieved when load is close to 1 is almost as high as when there is no service curve requirement. (But the deviation is large). Therefore, the deviation phase of the proposed scheme is almost the same as the throughput phase without any service curve requirement.
- The throughput saturates when load exceeds 1. This is because the maximum throughput achieved in this case cannot exceed the max achievable throughput (i.e., when there are no service curve requirements). The deviation, however, continues to increase. Since the throughput is saturated, the increase in deviation is linear with increase in load (see Figures 3).

V. Conclusion

This paper describes a forward link scheme in wireless DS-CDMA network. Our solution re-allocates rate and transmit power once every Δ time units. The primary objective of the re-allocation at time t is to minimize the average deviation from service curve at time $t + \Delta$. As a result, if the service curves can be guaranteed the proposed scheme will satisfy them. The secondary objective is to maximize the total throughput when then primary objective can be met. Therefore, in situations where the system is underloaded, the proposed scheme not only meets the QoS requirements, but also fully utilizes the available capacity.

References

[1] R. Cruz, "Quality of service guaranteed in virtual circuits switched network," *IEEE Journal on Selected Areas in Communications*, vol. 13, pp. 1048–1056, August 1995.

[2] C. S. Chang and K. C. Chen, "Service curve proportional sharing algorithm for service-guaranteed multi-access in integrated-service wireless networks," in *IEEE Vehicular Technology Conference*, 1999, vol. 2, pp. 1288–1293.

[3] A. Demers, S. Keshav, and S. Shenker, "Analysis and scheduling of a fair queueing algorithm," in *Proceedings of SIGCOMM*, September 1989.

[4] S. Lu, V. Bhargavan, and R. Srikant, "Fair scheduling in wireless packet networks," in *Proceedings of SIGCOMM*, September 1997.

[5] T. S. E. Ng, I. Stoica, and H. Zhang, "Packet fair queueing algorithms for wireless networks with location dependent errors," in *Proceedings of INFOCOMM*, March 1998, pp. 1103–1111.

[6] P. Ramanathan and P. Agrawal, "Adapting packet fair queueing algorithms to wireless networks," in *ACM/IEEE Proceedings of MOBICOM*, August 1998, pp. 1–9.

[7] S. J. Oh, T. L. Olsen, and K. M. Wasserman, "Distributed power control and spreading gain allocation in CDMA data networks," in *Proceedings of INFOCOMM*, 2000.

[8] S. A. Jafar and A. J. Goldsmith, "Adaptive multicode cdma for uplink throughput maximization," in *Vehicular Technology Conference (VTC)*, Rhodes Island, Greece, 2001.

[9] M. Elaoud and P. Ramanathan, "Adaptive allocation of CDMA resources for network-level QoS assurances," in *Proceedings of MOBICOM*, August 2000.

[10] L. Tong, P. Ramanathan, and A. Sayeed, "Service curve assurances versus uplink throughput in cdma networks," in *ACM Wireless Mobile Multimedia Workshop (WoWMoM)*, Rome, Italy, July 2001.

[11] I. Stoica, H. Zhang, and T. S. E. Ng, "A hierarchical fair service curve algorithm for link-sharing, real-time and priority services," *IEEE/ACM Transactions on Networking*, vol. 8, no. 2, pp. 185–199, April 2000.

[12] V. Erceg, L. J. Greenstein, S. Y. Tjandra, S. R. Parkoff, A. Gupta, B. Kulic, A. A. Julius, and R. Bianchi, "An emperically based path loss model for wireless channels in suburban environments," *IEEE Journal on Selected Areas in Communications*, vol. 17, pp. 1205–1211, July 1999.