Optimal CDMA network design with uplink and downlink rate guarantees

Dinesh Rajan and Eli V. Olinick
Southern Methodist University, Dallas, Texas. Email: rajand@lyle.smu.edu

Abstract— **In this paper, we propose an optimization framework for the design of CDMA-based cellular networks. The framework incorporates both the uplink (UL) and downlink (DL) quality of service (QoS) constraints to determine the base station (BS) selection and base-station-to-mobile-user association. The framework also allows the network planner the flexibility to trade-off the net profit with the total transmission power. The framework also allows the network operator to examine the effect of varying number of service classes and frequency reuse factor. Representative numerical results of the optimization are given.**

I. INTRODUCTION

Cellular network planning tools that optimize system performance are critical both from a commercial viability and practical utility perspective. Current and future 3G networks, such as UMTS [1], [2], are based on code division multiple access (CDMA). In a CDMA network, the entire bandwidth allocated to a cell is available to all the users. The signals of the users are transmitted using different spreading codes and the received signal is usually a linear combination of the transmit signal of all the users. For all successful calls in a CDMA network, the system operator ensures that the signal-to-interference ratio (SIR) of each user lies above a desired threshold.

Optimal designs for CDMA networks have been the topic for several studies [3]–[13]. Due to the large investments involved in setting up a new network, many of these studies focus on: i) minimizing the cost (including minimizing the number of BSs) of setting up the network [3]–[8] or ii) maximizing the net profit [9]. The objective function and constraints in these optimization problems include different subsets of system capacity, network coverage, blocking probability, SIR, transmit and receive power. A CDMA cellular network is, typically, interference limited. While some studies suggest that a CDMA network is limited by the uplink (UL) capacity [14], others suggested that it is limited by downlink (DL) capacity [15]. Prior work on CDMA network design has primarily focused on the UL performance. In contrast, this paper addresses the CDMA network design problem jointly from the UL and DL perspectives.

The main contributions of this paper: i) We present a unified optimization framework for base station (BS) selection and the BS-MS (mobile station) assignment problem that satisfies the desired UL and DL quality of service (QoS) requirements. This framework supports the use of arbitrary frequency reuse factors, different time varying UL and DL data rates, and multiple service classes. The optimal design problem is formulated as an integer linear program (ILP). ii) The proposed framework allows the designer to select an objective function based on the total profit, sum transmit power in UL and in DL. Although BSs typically have access to a large supply of power, lowering their transit power reduces the interference. Lower power consumption in the mobiles, leads to increased talk times and stand-by times and result in higher customer satisfaction, and iii) To optimize network performance, the MS might transmit data to one BS in the UL and receive data from a different BS in the DL.

The proposed framework can be also used for periodic (*e.g.* annual) redesign of existing networks to reflect changing user demand distribution. Power control (PC) is typically undertaken in real-time by a radio resource manager. In contrast, this paper demonstrates the advantages of optimizing the average transmit power during the design. This approach does not preclude the need for short term PC based on channel fading.

We make a few simplifying assumptions to derive the results in this paper. We use simple single user detectors and a simple inversion PC. The proposed formulation assumes an FDD mode of operation.[1] To save space, we only provide one representative numerical example to illustrate each of the main ideas. Extensive numerical examples are provided in [16].

The rest of the paper is organized as follows. In Section II, we discuss the optimization framework. Representative numerical results are discussed in Section III, followed by our conclusions in Section IV.

II. SYSTEM MODEL

A. Inputs for the optimization framework

Notation: Superscripts u and d as in x^u and x^d represent the corresponding UL and DL quantities; while x used generically without a superscript refers to both UL and DL.

Let L denote the set of candidate locations where a base station (BS) could be commissioned/operated.[2]

---

[1] Results apply directly to TDD mode if the BSs are synchronized.

[2] We use the term building a BS to mean either commissioning/activating an existing BS or truly building and installing a new BS. As explained later, the framework allows different costs to be imposed for building a new BS and using an existing BS.

Network planners typically address the uncertainty in the demand by solving the model with a variety of demand forecasts before deciding on the BS locations. The set T represents the time epochs over which the variation in demand is modeled, *e.g.* $T=\{1$ (AM commute), 2 (day time), 3 (PM commute), 4 (night time) $\}$. Let $M(t)$ denote the set of subscriber locations at time $t \in T$. The demand for UL service in customer area $m \in M(t)$ is denoted by $d^u_{m,t}$ (in calls/unit time) and is assumed to be a point forecast for either the average or peak demand ($d^d_{m,t}$ is similarly defined for DL). Thus, our model is a deterministic model. Let sets F^u and F^d contain indices of the available frequency bands in the UL and DL, respectively. Allowing different BSs to use different frequencies allows us to model different frequency reuse factors. For instance, if the entire bandwidth is divided equally among a *cluster* of $|F|$ cells, the frequency reuse factor is $1/|F|$.

A subscriber handset in location m that transmits to a BS at location l must transmit with sufficient power to ensure that the receiver can reliably decode the signal. We use signal-to-interference-ratio (SIR) as the metric for reliable performance and impose a constraint that the received SIR must be greater than a minimum threshold. The capacity of a CDMA system depends logarithmically on the received SIR; thus, guaranteeing a minimum SIR ensures that a minimum desired data rate is obtained.

Multiclass service: The proposed framework supports multiple time-varying service classes in the design represented by parameters $SIR^u_{min}(m,t)$ and $SIR^d_{min}(m,t)$ for the UL and DL, respectively. Having different SIR thresholds for the UL and DL enables the network operator to provide diverse asymmetric services. With multiple service classes, the admission control policy affects overall system performance. While admission control is primarily a run-time issue, we address it implicitly in the network design as discussed in Sec. II-E.

Signal propagation model: The average signal power reduction due to path loss, shadowing and fast fading, between subscriber m and BS l at time epoch t is denoted by g_{mlt}. Any one of the numerous models that exist for each of these effects can be used in the proposed framework. For illustration, we use the popular Hata-Okumara path loss model [17], the log-normal shadowing model and Rayleigh fast fading model.

Let $P^u_{max}(m)$ and $P^d_{max}(l)$ denote, respectively, the maximum transmission power at mobile m and BS l. The set $C^u_{m,t} \subseteq L$ denotes the set of candidate BSs that can provide UL service for customers in location $m \in M(t)$. Similarly, $P^u_{l,t} \subseteq M(t)$ denotes the set of customer locations that can be serviced in the UL by BS at location $l \in L$. The values of P^u_{max} and P^d_{max} along with the minimum required SIR thresholds are used to determine $C^u_{m,t}$ (the set $C^d_{m,t}$ is similarly defined) as $C^u_{m,t} = \{l : l \in L, \frac{P^u_{max}(m) g_{mlt}}{N^u_l} \geq SIR^u_{min}(m,t)\}$, where N^u_l and N^d_m denote respectively the effective noise at the receiver in BS l and in MS m. The main use of the sets $C_{m,t}$ is to reduce the computational complexity of the optimization. We can further restrict $C_{m,t}$ by considering only the $K-$closest BSs to mobile m at time t.

Power Control (PC): In this paper, we consider a simple inversion PC [14], [18], [19] to determine the transmit power. Our goal is to ensure a received power of P^u_{target} (P^d_{target}) for all users (for equal SIR requirements) in the UL (DL). This simple PC in addition to being intuitively fair is optimal for despreading CDMA signals with the near-far problem [20]. In order to ensure sufficient received power at BS location l, a user in location m transmits a signal of power P^u_{target}/g_{mlt}, which after attenuation of g_{mlt} is received at BS l with power P^u_{target}.

For users with different UL SIR requirements, each user scales its transmit power by a factor $p^u_{m,t}$ in proportion to their SIR, *i.e.*, $SIR^u_{min}(m,t)/p^u_{m,t} = SIR^u_{min}(m',t)/p^u_{m',t} \forall m, m' \in M(t),\ t \in T$. Similarly, we scale the transmission power at BS l for user m by factor $p^d_{m,t}$ where $SIR^d_{min}(m,t)/p^d_{m,t} = SIR^d_{min}(m',t)/p^d_{m',t} \forall m, m' \in M(t),\ t \in T$. Clearly, we require the following natural constraints to be satisfied in selecting the parameters: $P^u_{target} p^u_{m,t}/N^u_l > SIR^u_{min}(m,t)$ and $P^d_{target} p^d_{m,t}/N^d_m > SIR^d_{min}(m,t)$.

B. Decision variables in the optimization framework

The decision to build/activate a BS at candidate location $l \in L$ is represented by variable y_l which takes a value of one if the BS is built and zero otherwise. Binary variable y^u_{lf} indicates whether BS l uses frequency $f \in F^u$ in the UL (similarly y^d_{lf} in DL). Binary variables z^u_{mltf} and z^d_{mltf} indicate, respectively, whether any user at location m is serviced by the BS at location l at time t on frequency f in the UL and DL. These binary variables take a value of one if any user in that location is serviced and zero otherwise. As noted before, the proposed optimization framework does not restrict each user to obtain service from the same BS in the UL and DL, *i.e.* we do not impose a constraint that $z^u_{mltf} = z^d_{mltf}$. Further, the framework allows two users at the same location to receive service from different BSs, *i.e.*, more than one z_{mltf} can be nonzero for a given m, t, and f. Integers x^u_{mltf} and x^d_{mltf} represent, respectively, the number of customers at $m \in M(t)$ that are serviced by a BS at $l \in L$ in the UL and DL.

The following natural constraints on the domains of these decision variables arise:

$$x^u_{mltf}, x^d_{mltf} \in \mathbb{Z}^+, \forall f \in F^u \text{ or } F^d \quad (1)$$

$$z^u_{mltf}, z^d_{mltf}, y_l, y^u_{lf}, y^d_{lf} \in \{0,1\} \quad (2)$$

Clearly, $z^u_{mltf} = 0$, if $l \notin C^u_{m,t}$ and $z^d_{mltf} = 0$, if $l \notin C^d_{m,t}$. The next set of constraints limits the maximum number of customers served to the service demand:

$$x^u_{mltf} \leq d^u_{m,t} z^u_{mltf} \text{ and } x^d_{mltf} \leq d^d_{m,t} z^d_{mltf} \quad (3)$$

We consider mobile m to have an active connection at time t only if it receives service on both the UL and DL and the appropriate constraint is given by,

$$\sum_{l \in C^u_{m,t}, f \in F^u} x^u_{mltf} = \sum_{l \in C^d_{m,t}, f \in F^d} x^d_{mltf} \qquad \forall t \in T, m \in M(t) \tag{4}$$

Constraint (4) can be relaxed if a user only requests service in one direction, *e.g.* while downloading a large file. In this paper, we do not consider soft handoff and thus each mobile might connect to at most one BS at time t,

$$\sum_{f \in F^u, l \in C^u_{m,t}} z^u_{mltf} \leq d^u_{m,t} \tag{5}$$

Further, mobile m can connect to BS l on frequency f only if that BS uses that particular frequency and hence, $z^u_{mltf} \leq y^u_{lf}$ and $z^d_{mltf} \leq y^d_{lf}$. Each BS may use at most one frequency when it is operational, *i.e.* $\sum_{f \in F^u} y^u_{lf} = \sum_{f \in F^d} y^d_{lf} = y_l$. The next condition provides the network operator the flexibility to design the network to satisfy desired percentage, δ_t, of the maximum demand, *i.e.*,

$$\sum_{m \in M(t), l \in C^u_{m,t}, f \in F^u} x^u_{mltf} \geq \delta^u_t / 100 \sum_{m \in M(t)} d_{m,t}, \tag{6}$$

For example, the network operator might build the network to satisfy 95% of the demand during peak times and 99% of the demand during remaining times. Note that imposing constraint (6) might make the optimal network design problem, which is formally posed in (10), infeasible. For instance, the entire set of potential BSs might not be sufficient to meet 100% of the demand if the system is overloaded. In such cases, the network operator could decrease δ_t or increase the available infrastructure and then solve the new problem.

C. *Revenue and cost*

Let $r_{m,t}$ (measured in dollars) denote the amortized revenue generated from each subscriber at location m that receives service at time epoch t.[3] The total subscriber revenue, R, is given by $R = \sum_{t \in T, m \in M(t), l \in C^u_{mt}, f \in F^u} (r_{mt} x^u_{mltf})$. The amortized cost of building and operating BS $l \in L$ and connecting it to the backbone network is represented by a_l which has units of dollars. The value of a_l depends on the location of the BS and could be different for each BS. The total cost, C, of building/operating all the active BSs is given by $C = \sum_{l \in L} (a_l y_l)$ Thus, the profit, D, of the network operator is given by, $D = \sum_{t \in T, m \in M(t), l \in C^u_{m,t}, f \in F^u} (r_{mt} x^u_{mltf}) - \sum_{l \in L} (a_l y_l)$

D. *Quality of Service (QoS) Constraint*

1) UL QoS Constraint: Recall that x^u_{mltf} customers in location m are assigned to BS l for service at time t using frequency f in the UL. Each mobile user at subscriber location m transmits with power $\frac{P_{target} p^u_{m,t}}{g_{mlt}}$, which is received at BS l with power $P_{target} p^u_{m,t}$. Similarly, x^u_{njtf} users in location n that are serviced by BS j will transmit with power $P_{target} p^u_{n,t} / g_{njt}$. The received power at BS l from each of these customers equals $\frac{P_{target} p^u_{n,t} g_{nlt}}{g_{njt}}$. Thus, the total received power, $P^{TOT}_l(t,f)$, at BS location l at time t on frequency f is given by,

$$P^{TOT}_l(t,f) = P_{target} \sum_{m \in M(t), j \in C^u_{m,t}} g_{mlt} \frac{x^u_{mjtf} p^u_{m,t}}{g_{mjt}}. \tag{7}$$

Out of this total power, $P_{target} p^u_{m,t}$ represents the signal of a user at location m and $(P^{TOT}_l(t,f) - P_{target} p^u_{m,t})$ represents the interference from the other users UL powers. The total UL transmit power of all the mobiles is given by, $P^u_{TOT}(t) = \sum_{m \in M(t), l \in C^u_{m,t}, f \in F^u} \left(\frac{x^u_{mltf} p^u_{m,t}}{g_{mlt}} \right) P_{target}$. For a user at location m to receive service on frequency f in the UL from BS l, the SIR must be greater than the threshold $SIR^u_{min}(m,t)$ and the appropriate constraint can be written as,

$$\sum_{\substack{m' \in M(t) \\ j \in C^u_{m',t}}} \frac{g_{m'lt} p^u_{m',t} x^u_{m'jtf}}{g_{m'jt}} \leq p^u_{m,t} + \frac{p^u_{m,t}}{SIR^u_{min}(m,t)} - \frac{N^u_l}{P_{target}} + (1 - y^u_{lf})\alpha \tag{8}$$

where N^u_l is the noise at the receiver of BS l and α is any constant with a value "large" enough to ensure that constraint (8) is automatically satisfied if BS l does not use frequency f. We set $\alpha = \max_{t \in T, l \in L} (\sum_{m \in M(t)} p^u_{m,t} d_{m,t} \max_{j \in C_{m,t} \setminus \{l\}} \frac{g_{mlt}}{g_{mjt}})$.

2) DL QoS Constraint: The BS at location l transmits the signal for a user in location m with power $P_{target} p^d_{m,t} / g_{mlt}$, which is received with power $P_{target} p^d_{m,t}$ at subscriber location m. Similarly, BS j transmits with power $P_{target} p^d_{i,t} / g_{ijt}$ to each of the customers at location i. The received power at customer location m due to the signals transmitted by BS j equals $g_{mjt} P_{target} p^d_{i,t} / g_{ijt}$. Thus, the total received power, $P^{TOT}_m(t,f)$ at subscriber location m from all the BSs using frequency f at time t is given by, $P^{TOT}_m(t,f) = P_{target} \sum_{i \in M(t), j \in C^d_{i,t}} x^d_{ijtf} p^d_{i,t} g_{mjt} / g_{ijt} = P_{target} \sum_{j \in L, i \in P_{j,t}} x^d_{ijtf} p^d_{i,t} g_{mjt} / g_{ijt}$. The total DL power, P^d_{TOT}, transmitted by all the BSs equals $P^d_{TOT}(t) = \sum_{m \in M(t), l \in C^d_{m,t}, f \in F^d} x^d_{mltf} p^d_{m,t} P_{target} / g_{mlt}$. In a CDMA DL, each BS uses orthogonal spreading codes (*e.g.* Walsh codes) before transmission. In theory, the interference at any mobile is only from the signals transmitted by BSs that do not service that mobile: usually referred to as intercell interference. In practice, multipath fading leads to a loss of orthogonality in the received signal and causes a part of the signal transmitted by the serving BS to be perceived as intracell interference at the mobile receiver. The effective intracell interference is modeled using an orthogonality factor k (typically in the range 0.06-0.5 [21]) as k times the received power of the interfering intracell signals.

---

[3] While a time varying $r_{m,t}$ models a pay-per-use approach, other revenue models can be easily incorporated into the design framework.

For a user at location m to receive service in the DL from BS l, the SIR must be greater than the minimum desired $SIR^d_{min}(m,t)$ and the appropriate constraint can be obtained as,

$$\sum_{j \in L\backslash\{l\}, i \in P^d_{j,t}} \frac{p^d_{i,t} g_{mjt}}{g_{ijt}} x^d_{ijt} \quad + \quad k \sum_{i \in P^d_{l,t}} \frac{p^d_{i,t} g_{mlt}}{g_{ilt}} x^d_{ilt} \leq \frac{p^d_{m,t}}{SIR^d_{min}(m,t)} - \frac{N^d_m}{P_{target}} \quad + \quad k p^d_{m,t} + \left(1 - z^d_{mltf}\right) \beta \tag{9}$$

where, $\beta = \max_{m \in M(t)} \sum_{i \in M\backslash\{m\}} \max_{j \in C_{i,t}} \frac{d_{i,t} p^d_{i,t} g_{mjt}}{g_{ijt}}$. Similar to the α factor in the UL, β is a constant selected to ensure that SIR constraint is automatically satisfied when z^d_{mltf}=0.

E. The Optimization Framework

The proposed optimization framework provides the freedom to select any linear objective function based on the operator revenue, MS power and DL transmit power. We show that there exists a design trade-off between the total revenue and the total transmit power. By leveraging this trade-off, network operators can sacrifice a portion of their net profit to ensure a substantial reduction in the total transmit power for their subscribers. Such lowered transmit powers in the UL would lead to increased usage times of mobile batteries (by 50% in some cases).

The optimization problem for network design is formally posed as follows:

$$\max \quad \lambda_r D - \lambda_u \sum_{t \in T} P^u_{TOT}(t) - \lambda_d \sum_{t \in T} P^d_{TOT}(t) \tag{10}$$

subject to the UL and the DL QoS constraints given by (8) and (9) and the constraints on the variables given by (1)-(6). Note that the terms being summed together in (10) have different units; the weighting terms λ_u, λ_d, and λ_r have the appropriate units to ensure conformability and can be selected based on the relative importance of the UL power, DL power and profit. If $\lambda_u = \lambda_d = 0$, then (10) is equivalent to maximizing the profit. If in addition, $a_l = 0$ and $r_{m,t} = 1$, then the objective function (10) is equivalent to maximizing the total number of users.

As noted before, admission control can affect system performance critically. In the design phase, the admission control is handled implicitly by the choice of the objective function in the optimization problem. For instance, if $\lambda_u = \lambda_d = 0$, the choice between supporting x video streams (higher SIR requirement) and y voice streams (lower SIR requirement) depends on the revenue from the video and voice streams.

Recognize that objective function (10) is linear in all the variables, the constraints are also linear, and the decision variables are integer valued. Thus, the optimization problem is an integer linear program and can be solved using any *ILP-solver*. We use the AMPL modeling language and the CPLEX ILP solver.

The proposed optimization framework can also be used by a network provider to periodically add, remove or reallocate resources in an existing network, to better service the changing demand. The installation cost for existing BSs is zero; there is only a small operating cost for these BSs. Thus, a_l would be set to significantly smaller values for active BSs than for unused BSs. The reduced cost for using an existing BS would ensure a solution that minimizes the number of new BSs that are built, thereby optimizing the available resources. Representative solutions of network redesign are given in [16] and not presented here due to space limitations.

III. NUMERICAL RESULTS

We now present representative numerical results of the optimization and discuss their implications. Unless otherwise noted, all subscribers have equal importance, *i.e.*, the amortized revenue, r_m, from each subscriber is set to $\$428.20$. The amortized cost, a_l, of installing a BS is taken to be $\$1459.45$. The minimum SIR thresholds are fixed to 0.03125 for both the UL and DL.[4] The exact numerical values of these parameters have been obtained from [22] and have no special significance. Orthogonality factor $k = 0.06$ [21] and the noise variances at the BS and mobile handset are taken to be 4. By default, the relative importance of profit, $\lambda_r = 1$.

A. BS selection differences in UL and DL network design

Consider a topology with 22 potential BS locations ($l \in L = \{1, \ldots, 22\}$) and 95 subscriber locations ($m \in M = \{1, \ldots, 95\}$) that are uniformly distributed over an entire $1\ Km \times 1\ Km$ area. The demand at each of these subscriber locations equals one, *i.e.*, $d_{m,t} = 1 \forall m$. The system is designed to meet at least 90% of the demand.

When the network is designed to satisfy the UL SIR constraints only, the following BSs (X and Y coordinates are given in brackets) are selected: 7 (0.45,0.01) ,11 (0.61,0.78), 12 (0.79,0.44), 14 (0.74, 0.21), 15 (0.18,0.64), 21 (0.06,0.26) and 22 (0.35,0.44). On the other hand, when the network is designed to meet the DL SIR constraints only, the following BSs are selected: 3 (0.61,0.05), 5 (0.89,0.3), 8 (0.02,0.77), 11 (0.61,0.78), 20 (0.89,0.74), 21 (0.06,0.26) and 22 (0.35,0.44). As seen from these results, only BSs 11, 21 and 22 are selected in both UL and DL designs; all the other selected BSs are different for UL and DL designs. Consequently, the BS-MS association is also different for a large fraction of users when the UL and the DL are considered separately. In this example, 62% of the users connect to different BSs in the UL and DL. This example suggest the following principle.

Principle 1: The BS locations selected when a CDMA network is designed from the UL perspective *could be* different from the BS locations selected when the network is considered from a DL perspective.

---

[4] This implies that each BS can support at most 1/0.03125 = 32 users.

B. Base Station-Mobile Association joint design: UL vs. DL

The optimization framework in (10) is used to solve the same topology as before. When the network is designed to meet both UL and DL SIR constraints, the following BSs (represented by filled circles in Fig. 1) are selected: 2 (0.23,0.6), 3 (0.61,0.05), 5 (0.89,0.3), 10 (0.44,0.99), 11 (0.61,0.78), 16 (0.41,0.32), 20 (0.89,0.74) and 21 (0.06,0.26). Comparing the result with earlier designs, we find that 2 of these BSs are the same as in UL design, 5 of these BSs are the same as in DL design, 2 BSs are common to all three designs and 3 of these BSs are not selected in either independent UL or DL designs. Thus, independently designing the network in UL and DL and then picking a unified set of BSs would lead to a suboptimal design. The user BS association in the UL is represented by continuous lines while that in the DL is represented by dotted lines for two users labeled, X and Y in Figure 1. The user at location X receives DL and UL data, respectively, from BSs 21 (0.06,0.26) and 2 (0.23,0.6). Similarly, user Y receives DL and UL data, respectively, from BSs 16 (0.41,0.32) and 5 (0.89,0.3). In this example, 15% of the users receive service from different BSs in the UL and DL. Based on the above observations we postulate the following principle.

Principle 2: The BS that serves the mobile in the UL need not be the same as the BS that serves the mobile in the DL. Hence, a MS might not connect to the closest BS and purely SIR based BS-MS association may be suboptimal.

C. Power-Revenue trade-off

1) UL Design: In the earlier example, the operator can support about 85% of the users with just 3 BSs. Clearly, the network operator can also provide service to the mobiles by constructing more BSs. Constructing more BSs, decreases the average distance between the mobiles and the active BSs; thus directly reducing the transmit power required. Naturally, constructing more BSs leads to a reduction in profit. Thus, there is a inherent trade-off between total power of the mobiles and the profit, which is quantified by varying the values of λ_u, and λ_r. The trade-off is illustrated in Figure 2. It should be reiterated that all points on the curve satisfy at least 90% of total demand, *i.e.* the same demand can be satisfied using different amounts of power and at different costs. A reduction in the net profit, for example, from \$30987.40 to \$28068.50 (about 10% reduction) results in 3.2 dB reduction in the total power in the network.

2) DL Design: A similar trade-off between profit and BS transmit power is shown in Figure 2 and is obtained by solving the optimization problem for different values of λ_d. Similar to the UL, a nearly 10.9% reduction in the net profit results in approximately 5 dB decrease in the total power in the network. In Figure 2, for the DL case, the profit does not extend to as high a value as the UL because the desired 90% demand cannot be satisfied in the DL with fewer than 7 BSs.

Clearly, the power-profit trade-off can also be characterized when the network is designed considering both the DL and the UL SIR constraints. In this case, we set $\lambda_u = 10\lambda_d$ to indicate that reducing mobile power is 10 times more important than reducing BS power. Consider the same example as before. A reduction in the net profit, for example, from \$26609.05 to \$23690.15 (10% reduction) results in a 2.6 dB reduction in the UL power and 4.9 dB reduction in DL power. These trade-offs suggest the following principle.

Principle 3: A trade-off exists between the net revenue and the total transmit power in the network. Thus, a network operator may sacrifice a small portion of the net revenue to ensure significant reduction in the transmit power for the mobiles. This reduction in transmit power would lead to increased battery life time and result in higher customer satisfaction.

D. Changing frequency reuse factor

The total bandwidth available to a network operator is usually limited and purchasing additional bandwidth (*e.g.* through FCC spectrum auctions) is expensive. The proposed framework can be used to study the additional benefits that such increased spectrum would provide. Consider a simple example where 9 BSs are located on a regular 3×3 grid in the coverage area. Two different demand scenarios are considered: i) 400 users and ii) 600 users. The maximum number of users that can be supported by the system are computed and tabulated in Table I for different cluster sizes. These results indicate that increasing cluster size only provides diminishing returns. As $|F|$ increases from 1 to 4, the total number of users supported increases by 20% when $|M| = 400$ and by only 9% when $|M| = 600$. Further increasing $|F|$ to 9 does not increase the total number of users significantly. However, the total power required decreases by around 2 dB with $|F| = 9$ as compared to $|F| = 4$, even though more users are supported in the former case.

E. Effect of diverse QoS requirements

Consider the same 1 Km × 1 Km coverage area with 9 BSs located on a regular 3×3 grid inside the coverage area. Let cluster size $|F| = 3$ (*i.e.* frequency reuse is 1/3). We also consider 3 different demand periods ($|T| = 3$). There are 200, 100, and 50 active users, respectively, during peak, regular and night times. The UL SIR threshold for all users equals 0.03125. However, the DL has 95 low rate users with a DL SIR threshold of 0.03125 and 105 high rate users with a DL SIR threshold of 0.0625. The revenue from a high rate users is set to 1.5 times the revenue from a low rate user. The minimum demand satisfaction percentage, δ_t, is set to $100\%, 95\%$ and 90%, respectively, for the night, regular and peak times. In the resulting solution, the actual demand satisfaction was $100\%, 98\%$ and 92%. In this case, 85 out of 95 low rate users and 99 out of 105 high rate user data are serviced.

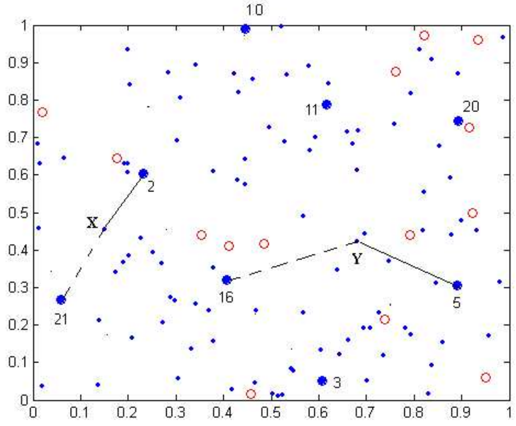

Fig. 1. BS selected and BS-MS association in optimal network designed based jointly on UL and DL constraints. Open circles represent potential BS locations, filled circles represent selected BSs and dots represent MS locations. Dashed and solid lines represent BS-MS association in DL and UL, respectively.

Now, if the revenue from high rate users is set to two times the revenue from the low rate users then the actual demand satisfaction was 100%, 99% and 91.5%, respectively, during night, regular and peak times. In this case, 81 out of 95 low rate users and 102 out of 105 high rate user data are serviced during peak time. This change in the number of high and low rate users supported illustrates how admission control is implicitly handled by changing the revenue.

IV. Conclusions

In this paper, we provide a framework for the design of cellular CDMA networks with UL and DL rate guarantees. We also characterize the optimal trade off between network power and revenue. The results in this paper can be extended in several different ways, *e.g.*, by considering multiple antennas and macro-diversity techniques.

Acknowledgment This work has been supported in part by ONR contract N00014-10-1-0330.

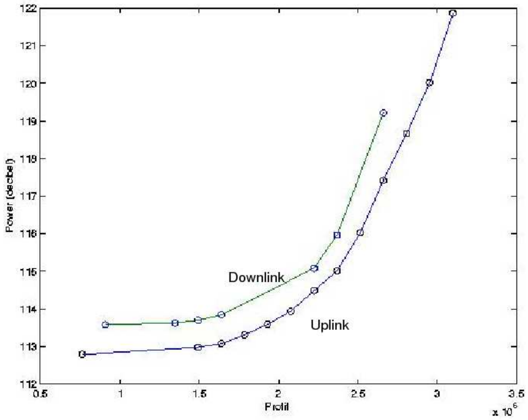

Fig. 2. Trade-off between total power and profit in UL and DL

TABLE I

Effect of varying frequency reuse factor with $|L|$ = 9.

$\|F\|$	Num. of mobiles $\|M\|$=400			$\|M\|$ = 600		
	Num. MS	UL pwr (dB)	DL pwr (dB)	Num. MS	UL pwr	DL pwr
1	232	92.9	93.8	265	90.8	90.8
2	254	94.7	95.0	280	92.3	92.6
4	279	98.4	97.6	289	93.7	94.2
9	297	97.1	97.1	292	93.1	92.6

References

[1] E. Amaldi et. al., "Planning UMTS base station location: Optimization models with power control and algorithms," in *IEEE Trans. Wirel. Comm*, vol. 2(5), 2003, pp. 939–952.

[2] M. Galota et. al., "A polynomial time approximation scheme for base staion positioning in UMTS networks," in *Proc.* 5^{th} *Int. Work. on Disc. Alg. and Methods for Mobile Comp. and Comm.*, 2001.

[3] R. A. Stanley, "A methodology for evaluating and optimizing wireless system infrastructure costs," in *Proc. PIMRC*, Taipei, Taiwan, 1996.

[4] D. Kristic and L. M. Correia, "Optimization of microcellular areas by minimizing the number of base stations," in *Proc of* 9^{th} *PIMRC*, Boston, MA, 1998.

[5] D. Tcha et al, "Base station location in a cellular CDMA system," in *Telecommunications Systems*, vol. 14, 2000, pp. 163–173.

[6] L. Nuaymi and P. Godwelski, "Association of uplink power control and base station assignment in cellular CDMA," in *Proc. of* 5^{th} *IEEE Symp. on Comp. and Comm.*, 2000, p. 705.

[7] R. Bose, "A smart technique for determining base-station locations in an urban environment," in *IEEE Trans. Veh. Tech.*, Jan 2001.

[8] C. Y. Lee and H. Kang, "Cell planning with capacity expansion in mobile communications: a tabu search approach," in *IEEE Trans. Veh. Tech.*, vol. 49(5), September 2000, pp. 1678–1691.

[9] R. Mathar and M. Schmeink., "Optimal base station positioning and channel assignment for 3G mobile networks by integer programming," in *Annals of OR*, vol. 107, 2001, pp. 225–236.

[10] R. G. Akl et al, "Multicell CDMA network design," in *IEEE Trans. Veh. Tech.*, vol. 50(3), August 2001, pp. 711–722.

[11] K. Takeo and S. Sato, "Evaluation of a CDMA cell design algorithm considering nonuniformity of traffic and base station locations," in *IEICE Trans. Fundamentals*, vol. E81-AZ(7), July 1998.

[12] S. Papavassiliou and L. Tassiulus, "Improving the capacity in wireless networks through integrated channel base station and power assignment," in *IEEE Trans. Veh. Tech.*, vol. 47(2), May 1998.

[13] I. Siomina and D. Yuan, "Optimization of pilot power for load balancing in WCDMA networks," in *Proceedings of GLOBECOM*, 2004.

[14] K. S. Gilhousen et al, "On the capacity of a cellular CDMA network," *IEEE Trans. Veh. Tech.*, vol. 40, pp. 303–312, May 1991.

[15] M. Soleimanipour and G. H. Freeman, "A realistic approach to the capacity of cellular CDMA systems," in *Proc. of VTC*, 1996.

[16] D. Rajan et. al., "A unified framework for design of CDMA cellular networks with uplink and downlink rate guarantees," Southern Methodist University, Tech. Rep. 10-EMIS-04, 2010.

[17] M. Hata, "Empirical formula for propagation loss in land mobile radio service," in *IEEE Trans. Veh. Tech.*, vol. 29, 1980, pp. 317–325.

[18] J. S. Evans and D. Everitt, "Effective bandwidth based admission control for multiservice CDMA cellular networks," *IEEE Trans. Veh. Tech.*, vol. 48, pp. 36–46, January 1999.

[19] S. Hanly and R. Mathar, "On the optimal base station density for CDMA cellular networks," *IEEE Trans. Comm.*, vol. 50, no. 8, pp. 1274–1281, August 2002.

[20] A. J. Viterbi, *CDMA : Principles of Spread Spectrum Communication*. Addison-Wesley Publishing Company, 1995.

[21] El-Sallabi et. al., "Investigations on impact of bandwidth on orthogonality factor for WCDMA systems," in *Proc. WCNC*, vol. 2, 2004, pp. 1138– 1142.

[22] J. Kalvenes et. al., "Hierarchical cellular network design with channel allocation," *Eur. Jn. of OR*, vol. 160, no. 1, Jan. 2005.