Capacity Simulation of cdma2000 1xEV-DO Forward Link With Opportunistic Beam Forming

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***Abstract*— This paper addresses possible capacity gains in a cdma2000 1xEV-DO system that utilizes the Opportunistic Beam Forming (OBF) scheme. Contrary to the voice-oriented cdma2000 systems, where it is desirable to maintain a fixed signal-to-interference-and-noise ratio (SINR) level at the access terminal (AT), the 1xEV-DO system is designed to take advantage of the natural SINR fluctuations in a wireless channel. The resulting gain in capacity is called the "multi-user diversity gain." In certain channel conditions, the rate of the natural SINR fluctuations may not be high enough, resulting in low multi-user diversity gain. In such a case, SINR fluctuations may be induced artificially by the OBF scheme in order to increase capacity.**

***Index terms*— Wireless Internet Access, HDR, 1xEV-DO, IS-856, Opportunistic Beam Forming.**

I. Introduction

The cdma2000 1xEV-DO standard (also known as IS-856) is based on the high data rate (HDR) system proposed by Qualcomm [1]. The 1xEV-DO system can best be described as wireless cable modem (fat pipe) with peak rates up to 2.4 Mbps. In order to achieve high spectral efficiency, the system utilizes techniques such as fast channel state feedback, adaptive modulation and coding, low rate turbo codes, higher-order modulation, incremental redundancy, multi-user diversity, forward link receive diversity, and "virtual" soft handoff.

Traditionally, voice-oriented code division multiple access (CDMA) systems, such as IS-95 and cdma2000, have been based on power control to flatten the natural time-varying fading in the received signal-to-interference-and-noise ratio (SINR) level. This is accomplished by slow power control on the IS-95 forward link and more advanced power control schemes in the cdma2000 forward link. The cdma2000 system further provides transmit diversity schemes, such as orthogonal-transmit diversity (OTD) and space-time spreading (STS), which utilize multiple transmit antennas for each sector. These transmit diversity schemes serve the same purpose as power control, namely flattening the received SINR level seen by the access terminal (AT) as much as possible. The data-oriented 1xEV-DO system is able to take just the opposite approach to improve capacity. In the 1xEV-DO system, due to its rate-control mechanism as opposed to power control, fluctuations in the SINR process received independently at each AT in a sector can be exploited to provide a capacity gain. Multiple transmit antenna systems may also be utilized in a 1xEV-DO system for the purpose of increasing the rate and dynamic range of the SINR fluctuations seen by each AT. One such scheme is called "Opportunistic Beam Forming" (OBF) proposed in [6].

In this paper, we will present network level simulation results that address possible capacity gains by utilizing the OBF scheme in a 1xEV-DO system.

The outline of the paper is as follows. In Section 2, we overview the 1xEV-DO physical layer design. In Section 3, we will summarize the OBF scheme. In Section 4, the simulation model is described. Simulation results will be presented in Section 5. Finally, conclusions are given in Section 6.

II. 1xEV-DO Overview

The 1xEV-DO forward link consists of time-division multiplexed (TDM) Pilot, Medium Access Control (MAC), and Traffic/Control Channels. The Pilot channel is used in system acquisition, tracking, and demodulation, active set management, channel estimation and prediction, and handoff. The Traffic channel carries user data and the Control channel carries control, signaling, and may carry user data. The resulting forward link waveform is direct-sequence (DS) spread at the chip-rate of 1.2288Mcps in a 1.25MHz bandwidth. Further details of the forward link structure and operation can be found in [1,3-5].

Each AT determines the highest data rate that it can support based on the prediction of the received SINR process and informs the base station via the reverse link Data Rate Control (DRC) channel. The rate requests can be updated as often as 600 times per second. The base station decides on which user to serve by means of a scheduling algorithm.

In this paper, it is assumed that the proportional fair scheduler (PFS) is used for scheduling data to various ATs on the forward link [6,7]. Note that the effect of PFS is to serve the AT that requests the highest data rate relative to its own average throughput whenever the forward link is available for a new packet transmission. Consequently, the scheduling of packets is fair among users, and at the same time the forward link throughput of the base station is improved in the presence of multiple ATs in the sector. This improvement in throughput generally increases with the increasing number of ATs. This gain is often referred to as the "multi-user diversity gain."

The PFS uses a filter to estimate the average throughput of an AT. The bandwidth of the filter is an important parameter: the rate of received SINR fluctuations at each AT must be higher than the bandwidth of the filter in order to achieve multi-user diversity gain. Note that reducing the bandwidth of the filter is not a solution since it would increase the delay variability of the served packets, hence degrade the transport layer (TCP) throughput.

III. OBF Overview

The following is a brief description of OBF based on the idealized conditions described in [6]. The problem definition involves a base station antenna array consisting of *N* elements. The same signal is applied to all array elements with possibly different amplitude and phase shifts which may be written in vector form as $\mathbf{m} = [\ m_i\ ],\ i = 1,\ldots,N$ where $m_i = \sqrt{\alpha_i}\, e^{j\theta_i}$, with the constraint $\|\mathbf{m}\|^2 = P$. The effect of the channel that connects the array to the *k*'th mobile station can be represented by a complex random vector $\mathbf{h}_k = [\ h_{i,k}\ ],\ i = 1,\ldots,N$. These definitions are illustrated in Fig. 1. The SNR at the mobile station may be written as $\mathrm{SNR}_k = \left\|\mathbf{m}^T\mathbf{h}_k\right\|^2 / N_0$. The peak value of SNR is obtained when $\mathbf{m}$ is a complex multiple of $\mathbf{h}_k^*$, where the superscipt "*" indicates complex conjugation. In this case $\mathrm{SNR\_PEAK}_k = (P / N_o)\|\mathbf{h}_k\|^2$.

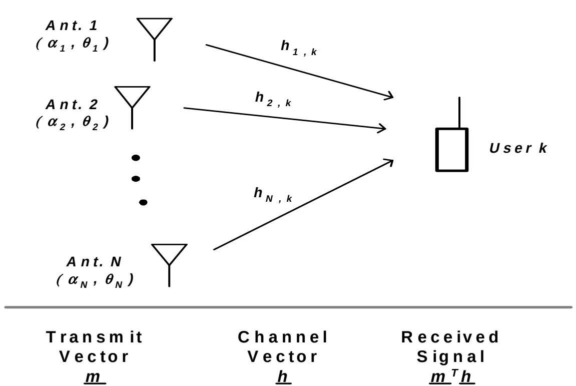

Fig. 1. The forward link model for OBF.

With these definitions, the Theorem of OBF proceeds as follows [6]:

OBF Theorem (summary): Let *K* be the number of users (ATs) in idealized conditions (that is, instant SNR feedback to the base station, no rate quantization, all data packets are of the same fixed duration, infinite time-constant for the PFS throughput measurement filter, the served data rate based on the Shannon capacity for the instantaneous SNR, and $\boldsymbol{h}_k$'s are independent identically distributed). The average throughput per user T_k is independent of time (due to infinite time constant assumption for the PFS). Under these conditions, if $\mathbf{m}$ is time-varying and its stationary distribution is similar to the distribution of $\mathbf{h}_k^* \sqrt{\mathbf{P}} / \|\mathbf{h}_k\|$, then as *K* goes to infinity, we have:

- KT_k converges to $\log(1 + \mathrm{SNR\_PEAK}_k)$,
- Users are scheduled at their respective beam forming configurations,
- Each user is allocated an equal fraction of time.

Note that in this subsection, we use the term SNR instead of SINR, since a single base station system is assumed. In the presence of multiple base stations, as suggested in [6], an additional benefit of OBF is "opportunistic nulling" which refers to the fact that the SINR level seen by an AT may also become high when the interference level from other sectors happen to be low due to induced fluctuations.

Note that the OBF Theorem allows for statistical correlations between the elements of the random channel vector $\mathbf{h}_k$. Extreme cases of interest are the fully uncorrelated and fully correlated channel vectors. Summarizing the conclusions of [6] in these two extreme cases, we have:

- Independent Rayleigh fading: Set individual element complex gains to independent complex Gaussian values, and then apply a common scale factor to normalize the power.
- Fully correlated fading with equally spaced linear array: Set individual element gains to a constant value and linearly increment the phase gradient as a function of time.

IV. Simulation Model

A. Network Level Simulation Setup

The simulation is based on a network model of 37 tri-sectored cells arranged in three tiers. Most of the details of the network level simulations are as in [5]. One important difference in this paper is that we avoided the "reciprocity principle" (that is, placing the ATs only in one embedded sector with the assumption that if an AT hands off to another sector, there is an AT in another sector in similar conditions that hands-off to the embedded sector), and we assumed that most of the network is populated. Consequently, the "number of users" per sector no longer represents the precise number of users communicating with that sector's base station. The sector throughput values are based on three of the center sectors to avoid edge effects. The channel models based on [2] are summarized in Table I.

TABLE I
Simulation Models

Model #	Speed (km/hr)	Multipath & Pathloss	Rice K (dB)
1	3.0	Ped.A	-100.0
4	120.0	Ped.A	-100.0
5	0.826	Ped.A	10.0
8	120.0	Veh.A	-100.0

B. Beam Forming Methods

In this paper, we will assume a two-element base-station antenna model, each element having the same 65-degree half-power beam width, and with parallel boresight vectors. The exact same signal is assumed to be transmitted from both antennas except for a time-varying complex scaling for each antenna. The antennas are assumed to be separated by a distance δ (measured in wavelengths). The signals transmitted from the two antennas are assumed to go through a fading channel with complex fade correlation denoted by γ. In particular, $\gamma = 0$ implies uncorrelated fading, and $|\gamma| = 1$ implies fully correlated fading.

Although, the OBF Theorem suggests that the time-variation of the complex antenna gains must "match" the channel fade statistics, we will separate the two and consider matched and mismatched cases. In particular, we will define two methods regardless of γ:

Method 1: The gain and the phase reference of the first antenna is fixed. The gain of the second antenna is set to a lower value than that of the first and its phase is incremented linearly in time relative to the phase of the first antenna. The rate of phase change of the second antenna is denoted by f_{obf}, and the relative gain is denoted by G_{dB}. The two antenna complex gains are further scaled at all times to ensure that the total transmitted power remains the same. This scheme is an approximation to the "fully correlated" solution of the OBF Theorem, with the exception that the antenna gains are different to avoid deep nulls.

Method 2: The complex gains of the antennas are generated by two independent complex Gaussian processes, each with flat spectrum and bandwidth denoted by f_{obf}. The complex coefficients are further scaled at all times to maintain a fixed level of total transmitted power. Note that this corresponds to the "uncorrelated" solution of the OBF Theorem.

We will also consider the following idealized method:

Method 3: Based on a wedge shaped antenna gain pattern. A quarter of the total transmit power is uniformly distributed in a 120 degree arc spanning a sector. The remaining power is uniformly distributed over a 30 degree wedge shaped beam. The beam sweeps the sector at a uniform rate of f_{obf} cycles per second. The overall gain is scaled to maintain constant transmitted power.

V. RESULTS

A. Correlated versus Uncorrelated Fading

It has been noted in the literature, and is easy to argue by simple geometry, that if the scatterers that cause fading in a channel are much closer to the mobile station than to the base station, then the complex fade process: (1) decorrelates as the mobile moves on the order of a wavelength, (2) takes a much longer distance to decorrelate at the base station site. In all simulations that assume γ=1.0, we will assume an antenna separation of δ = 1 wavelength.

Note that if the transmitted signals from the individual array elements go through fully correlated fading (that is γ=1.0 in the two antenna model of the previous section), then the array behaves as a single antenna system with well-defined antenna gain pattern. In the uncorrelated case, no such interpretation holds. As an example, consider the two-element array described in the previous section. Assume that an AT is located at an azimuthal angle of θ radians relative to the boresight. Let $m_0(t)$ and $m_1(t)$ be the complex gains applied to the two elements, respectively. Also, let $f_0(t)$ and $f_1(t)$ denote the jointly complex Gaussian stationary and ergodic fade processes with unit variance that apply to the signals transmitted from the antenna elements. As in the previous section, the fade correlation between the two base station antennas is denoted by γ, that is $\gamma = E\{f_0(t)\, f_1^*(t)\}$, where the ensemble average can be replaced by time average. The received signal by the AT is proportional to

$$\sqrt{d(\theta)}\left[f_0(t)m_0(t) + f_1(t)m_1(t)e^{j2\pi\delta\sin\theta}\right]$$

where $d(\theta)$ represents the antenna gain as a function of the azimuthal angle θ. Note that if $\gamma = 0.0$, then by the fixed power assumption, we have $m_0(t)^2 + m_1(t)^2 = P$. Therefore, for any fixed setting of $m_0(t)$ and $m_1(t)$, the term in square brackets in the above expression has precisely the same statistical properties as $\sqrt{P}\, f_i(t)$, $i = 0,1$. The time variations in $m_0(t)$ and $m_1(t)$ will affect the fading speed of the received signal energy, but not its long-term average power. If the fading speed of $f_0(t)$ and $f_1(t)$ is sufficiently fast compared to the scheduler's time constant (which is often the case in most simulation models with the possible exception of Model 5), then one wouldn't expect gains via OBF schemes.

If $\gamma = 1.0$, then $f_0(t) = f_1(t)$ with probability one. Hence, the above expression can be rewritten as

$$\sqrt{d(\theta)\left\|m_0(t) + m_1(t)e^{j2\pi\delta\sin\theta}\right\|^2}\; e^{j\varphi(t)}\; f_0(t)$$

Notice that the term inside the square root can now be interpreted as an overall time-varying antenna gain pattern from which the transmitted signal goes through a fade process $f_0(t)$. Consequently, with $\gamma = 1.0$, it is possible to control the average power received by the AT as a function of time and the azimuthal angle.

B. Parameter Selection

The parameters of interest for the various schemes discussed in Section 4 are f_{obf}, and G_{dB}. Our simulation results indicated that a good choice for f_{obf} is 2 Hz. This provides a balance between predictability of the SINR fluctuations and the effects of the scheduler's time constant. Since, in the simulations, the scheduler's filter time constant is taken to be 1024 slots (1.71 seconds), it is desirable to have at least a few induced fluctuation cycles per second.

Note that if G_{dB} is set close to 0dB, and assuming the fade correlation $\gamma = 1.0$, then the overall gain pattern will contain deep nulls which are undesirable from the point of view of the predictability of SINR. We tried candidate values of G_{dB} = 0, 1, 3, 10. The results are as shown in Fig. 2. It appears that a good choice of G_{dB} is 3dB.

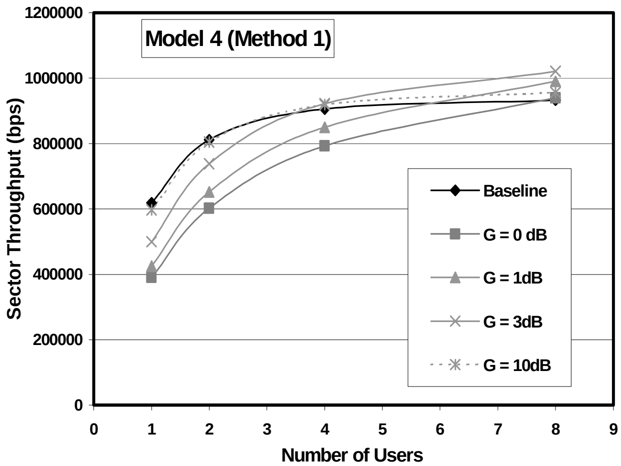

Fig. 2. Effects of the *G* parameter on sector throughput for Method 1 with γ = 1.0 (120 km/hr, 1 path).

Even though the results presented in Fig. 2 correspond to very fast fading (120 km/hr), induced fluctuations are still able to effect the multi-user diversity gains. This is because, in such a fast fading channel, the short term Rayleigh fading is unpredictable, therefore the rate control algorithm tends to pick a constant or slowly varying (due to shadow) data rate to request via the DRC channel. By beam forming, a predictable slow time-varying average power is induced, which is then reflected into the requested rates. Note that, although we are trying to induce fluctuations in SINR, the really important thing is the fluctuations in the DRC process that can be exploited by the scheduler.

Note from Fig. 2 that when G_{dB} = 10dB, the performance is almost similar to the baseline performance since the second antenna is practically turned off. As the value of G_{dB} increases, the performance for small number of users gets worse. This has two main reasons as listed below:

- The predictability of the received SINR by the AT is degraded by the deep nulls,
- Due to the concavity of capacity (data rate versus SINR), for the single-user case, the best capacity for a given mean SINR value would be achieved if the variance of SINR were zero. When there are large number of ATs, the PFS, by serving users at their peak SINR, alleviates this concavity issue and provides capacity gains via multi-user diversity.

C. Sector Throughput

In this subsection, it is assumed that all ATs have infinite amount of data waiting at the access network to be transmitted. The sector throughput versus number of users (per sector) results for Model 1 are shown Fig. 3. The figure shows the results for Method 1 and Method 2, both with γ = 0.0. It is seen that there is no change in performance. This is because, as discussed earlier, when the fade correlation is zero, the antenna system is not able to beamform. Consequently, the marginal distribution of the received complex Gaussian process, and hence the received average power, does not change. The autocorrelation of the fade process will be affected, but since the natural fluctuations due to the speed of the AT are already “predictably fast” and faster than the induced fluctuations, there is no benefit in using the OBF techniques.

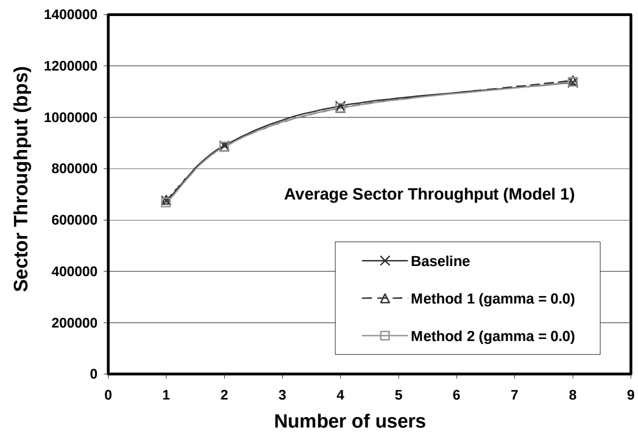

Fig. 3. Sector throughput versus number of users (Model 1).

The above result in fact applies to almost all models. In other words, without fade correlation, it is hard to provide any gains, except for the very slow fading cases such as Model 5.

In Fig. 4, results are shown for Model 4. For the above stated reason, we will only consider the γ = 1.0 case where a time-varying antenna gain pattern is well defined. In particular, Fig. 4 shows the results for Methods 1 and 3. Note that there is a loss for small number of users cases, but there is a gain if the number of users is larger than 4. This loss is due to the reasons stated earlier.

In Fig. 5, the results for Model 5 are shown for Method 1 (for both γ = 0.0 and γ = 1.0) and Method 3. For Method 1, note that multi-user diversity gains can be obtained even with γ = 0.0. However, gains are better with γ = 1.0. Method 3 performs the best among the three cases.

In Fig. 6, the results for Model 8 are shown for Method 1 with γ = 0.0, as well as γ = 1.0. As explained earlier, the γ = 0.0 case provides no gains or losses in such a fast fading channel. Notice that with γ = 1.0, however, it appears that with sufficiently many users gains can be obtained. Note also that the performance relative to the baseline case is worse than that of Model 4, even though both models are fast fading (120 km/hr). The difference is that, Model 8 has a second path. Although much weaker than the first path, this second path may often be the limiting factor in the received SINR. Since the strength of the second path also goes through the precise same antenna gain in the simulations, increasing the antenna gain may not result in an increase in the SINR in the presence of multi-path.

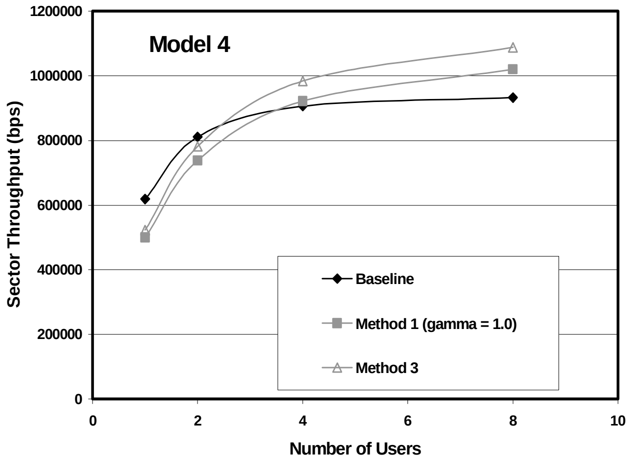

Fig. 4. Sector throughput versus number of users (Model 4).

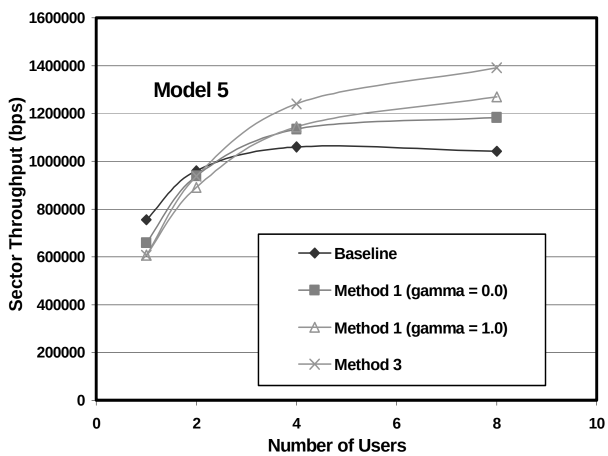

Fig. 5. Sector throughput versus number of users (Model 5).

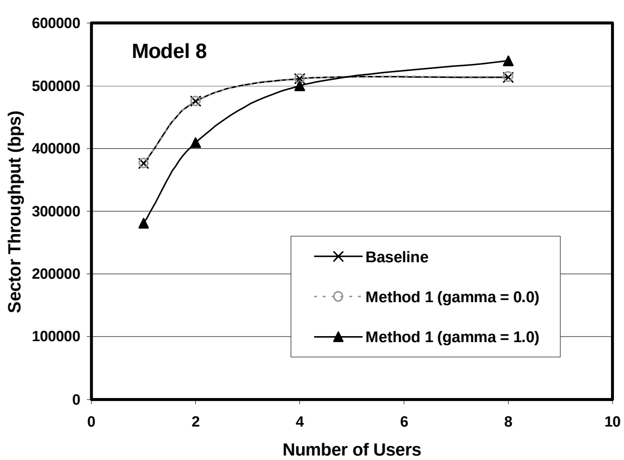

Fig. 6. Sector throughput versus number of users (Model 8).

D. *Individual User Performance*

Fig. 7 shows the CDFs of the average individual AT throughput values based on Model 5. The results are based on 4 users per sector. Simulations have been performed for Methods 1 (with γ = 1.0) and 3. Results indicate a significant degradation for worst case ATs.

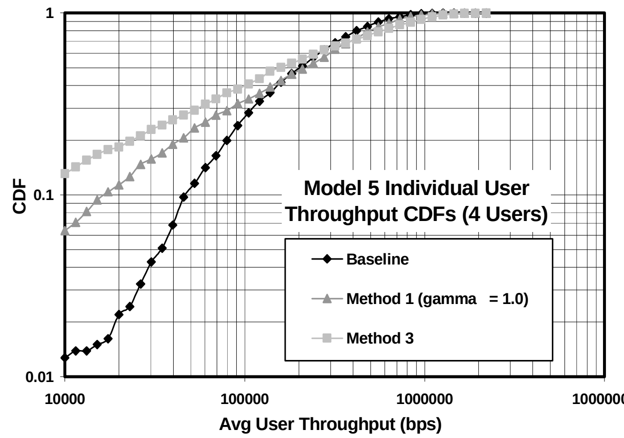

Fig. 7. CDFs of individual AT throughput based on 4 users per sector (Model 5).

VI. CONCLUSION

In this paper, we addressed the performance of a 1xEV-DO system with OBF implementation. The results indicate that only stationary or very fast Rayleigh, or otherwise highly Rician channel models may benefit from OBF schemes. It is also observed that the individual user throughput distribution is severely worsened by the OBF schemes. In fact, part of the gains are due to the worsened individual user performance possibly resulting in the weakest users not requesting any data.

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