Capacity and Coverage Improvements of Adaptive Antennas in CDMA Networks

V1.2

Erik Lindskog and Mitchell Trott

ArrayComm, Inc.
2480 N. First Street, Suite 200
San Jose, CA 95131-1014
USA
Tel: +1 (408) 428-9080
Fax: +1 (408) 428-9083

May 16, 2001

1. Introduction

In this document we present analysis of the effect of adaptive antennas on network capacity and coverage. This analysis covers general first order effects.

The analysis in this document does not take diversity effects into consideration. The fading on the channels to each of the antennas is assumed to be completely correlated. In a real system, depending on how the antennas are configured and the propagation environment, there is usually some decorrelation between the channels of the different antennas. In the uplink, such decorrelation between receive channels gives additional *uplink* capacity and coverage beyond what is presented here. In the downlink, decorrelation between the transmit channels can be exploited by combining a transmit diversity scheme with adaptive antennas to give additional *downlink* capacity and coverage beyond what is presented here. The antennas at the base station can be configured to maximize the benefits from both adaptive antennas and receive and transmit diversity.

The analysis in this document also does not take into consideration the effect of active interferer suppression in the uplink and active interferer mitigation in the downlink. This will also increase capacity and coverage, especially when the network includes high data rate users.

2. Uplink Capacity and Coverage

As a basis for the analysis of the effect of uplink capacity of coverage we can use the following formula for the received bit energy per power spectral density of the thermal noise plus interference, $E_b \ / I_0$ [Kim et al.]:

$$\frac{E_b}{I_o} = MG \frac{S}{FN_{th}W + \alpha(1+\beta)(N-1)S}, \qquad (1)$$

where

E_b = Bit energy
I_0 = Power spectral density of thermal noise plus interference
F = Base station noise figure
N_{th} = Power spectral density of the thermal noise
S = Received signal strength per antenna
G = Processing gain
α = Voice activity factor
β = Intercell interference factor

N = Number of users in the cell
W = System bandwidth
M = Number of antennas

We can use (1) to express the capacity of the cell as

$$N = N_{pole} - \frac{FN_{th}W}{\alpha(1+\beta)S}, \qquad (2)$$

where N_{pole} is the *pole capacity* defined by

$$N_{pole} = \frac{MG}{\alpha d(1+\beta)} + 1 \qquad (3)$$

and where d is the required $E_b\ / I_0$. Note that the pole capacity is proportional to the number of antennas. The pole capacity is the theoretical maximum capacity if the mobiles have infinite transmit power available, i.e., the capacity in the limit where coverage is no longer a concern and interference alone limits capacity. In practice the mobiles don't have infinite power. The practical capacity is therefore typically a fraction of the pole capacity. Typical values are 50-60% of the pole capacity [Kim et al.]. Depending on how close we are operating to the pole capacity, the required received signal power per antenna, S, will differ. From (2), the required received signal energy per antenna may be expressed as

$$S = \frac{FN_{th}W}{N_{pole}\alpha(1+\beta)(1-N/N_{pole})}. \qquad (4)$$

Assuming that the user terminals have a limited power, P_t, and assuming path loss with a path loss exponent of γ, we can express the cell 'radius', *R, as*

$$R = r_0\left(\frac{P_t}{S}\right)^{1/\gamma}, \qquad (5)$$

where r_0 is a constant. Given that the area, *A*, of the cell is proportional to the cell 'radius' squared, and using (4) and (5) we can derive the relation

$$A^{-\gamma/2} = k\frac{1}{N_{pole} - N}, \qquad (6)$$

where k is a constant. If we approximate N_{pole} as being proportional to M (i.e., neglecting the '1' in (3)), assuming a nominal pole capacity of 1 when M=1 and absorbing the constant k into a normalized coverage area, we can rewrite (6) as

$$A^{-\gamma/2} = \frac{1}{M-N}\,. \qquad (7)$$

We can now express the uplink normalized capacity, N, as a function of the normalized coverage area, the number of antennas at the base station, and the path loss exponent:

$$N = M - A^{\gamma/2}\,. \qquad (8)$$

For a given number of antennas and a given path loss exponent there is thus a trade-off between coverage and capacity. Figure 1 plots these trade-offs for 1 and 4 antennas with a path loss exponent of 3.5.

As mentioned above, a CDMA system is normally operated at a certain fraction of its maximum capacity (the pole capacity). Figure 1 illustrates how capacity and coverage increase when the fractional loading is held constant when going from a single- to multiple-antenna base station. With constant fractional loading and with the assumption that the pole capacity is proportional to the number of antennas, the increase in capacity is of course

$$\text{Constant load capacity gain} = M. \qquad (9)$$

To see how the coverage area increases we can divide (8) by M, introduce the per-antenna loading factor, $\mu = N/M$, and rewrite it as

$$A = (1-\mu)^{2/\gamma} M^{2/\gamma}\,.$$

Now, as μ remains constant, the coverage area gain for constant loading is given by

$$\text{Constant loading coverage area gain} = M^{2/\gamma}\,. \qquad (10)$$

Both of the gains in uplink capacity and uplink coverage area in (9) and (10) can thus be achieved simultaneously.

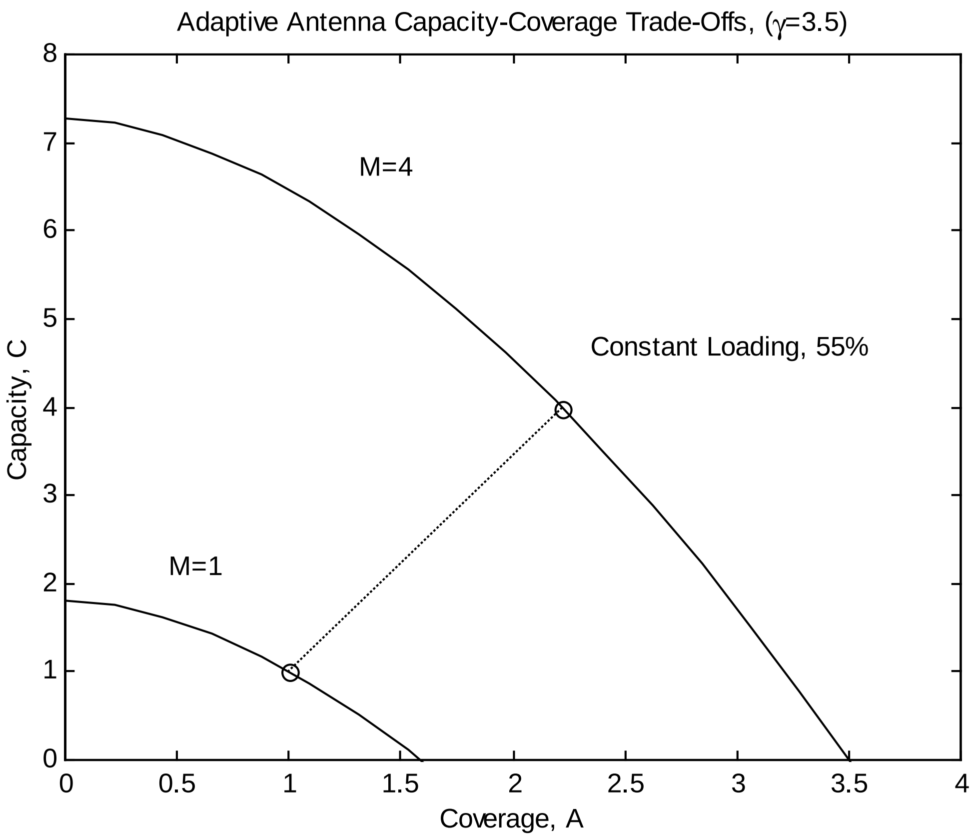

Figure 1: Capacity-Coverage trade-offs for 1 and 4 antennas. Path loss exponent $\gamma = 3.5$. *The* $M = 1$ *curve represents the capacity-coverage trade-off when a single antenna is used and the* $M = 4$ *curve represents the capacity-coverage trade-off when an adaptive antenna with four antennas is performing beamforming without nulling. Also illustrated are the points where the loading equals 55% of maximum capacity (pole capacity). With the adaptive antenna, keeping the same relative loading, we simultaneously increase capacity by a factor of 4 and coverage by a factor of 2.2.*

3. Downlink Capacity and Coverage

A slightly different analysis is required to estimate the effect of adaptive antennas on downlink capacity.

Let us assume that we can express an average signal to interference and noise ratio for the user terminal as

$$SINR_{avg} = \frac{P_{delivered,avr}}{N_{thermal} + P_{base}(1-\eta_{avg})(1+\beta_{avg})\rho_{avg}}, \qquad (11)$$

where

$P_{delivered,avg}$ = Average power delivered to the user terminal

$N_{thermal}$ = Thermal noise power

P_{base} = Total power transmitted by the base station

η_{avg} = Average orthogonality factor

β_{avg} = Average inter- to intra-cell interference ratio

ρ_{avg} = Average path loss for interference

We can further model the average delivered power to the user terminal as

$$P_{delivered,avr} = k\frac{P_{base}}{MN}M^{2}R^{-\gamma} = k\frac{P_{base}}{N}M \;\; R^{-\gamma}. \qquad (12)$$

We have here divided the total available base station power among the *N* users and the *M* antennas, multiplied it with the coherent power combining gain M^2 and multiplied it with the path loss factor $R^{-\gamma}$, *R* being the cell radius and γ being the path loss exponent. The constant *k* is for normalization.

Among the variables in the denominator of (11), the only variable that depends on the radius of the cell is the average path loss for the interference, ρ_{avg}, which we can model as

$$\rho_{avg} = \rho_0\left(\frac{R}{R_0}\right)^{-\gamma}, \qquad (13)$$

where ρ_0 and R_0 are constants. Using (12) and (13) we can rewrite (11) as

$$SINR_{avg} = \frac{kR_0^{-\gamma}P_{base}MR^{-\gamma}/N}{N_{thermal}+P_{base}(1-\eta_{avg})(1+\beta_{avg})\rho_0 R^{-\gamma}}. \qquad (14)$$

Using (14) we can make the following observations.

If we increase the number of base station antennas by a factor of *M*, keep the total base station power constant, and keep the cell radius constant, then we can increase the number of users by a factor of *M*. (This assumes perfect downlink beamforming. In reality the factor of *M* is somewhat reduced due to imperfect downlink beamforming.) When we have increased the number of user per base station we cannot increase the radius of the cells. That would lower the signal to interference ratio at the user terminals.

However, if we increase the number of base station antennas by a factor of M, keep the total base station power constant, and keep the number of users constant, then we can increase the cell radius by at least a factor of $M^{1/\gamma}$. It can actually be increased more as the interference in the denominator is reduced.

If we increase the number of antennas by a factor of M and increase the total power of the base station by a factor of M (i.e., we keep the same power amplifiers), then we can *simultaneously* increase the number of users by a factor of M and increase the radius of the cells by a factor of $M^{1/\gamma}$.

The downlink coverage area gains are of course given by the square of the gains in cell radius.

4. Summary and conclusions

We summarize the impacts of adaptive antennas on the capacity and coverage of a CDMA system as follows.

- If we increase the number of *uplink* antennas with a factor of M, then the uplink capacity and coverage area increase by a factor of M and $M^{2/\gamma}$, respectively. These gains are achieved simultaneously.
- If we increase the number of *downlink* antennas by a factor of M but keep the total base station power constant, then we can either increase the downlink capacity by a factor proportional to M (M de-rated due to imperfect downlink beamforming) or we can increase the downlink coverage area by a factor slightly higher than $M^{2/\gamma}$ (M de-rated due to imperfect downlink beamforming).
- If we increase the number *downlink* antennas by a factor of M and increase the total power of the base station by a factor of M (i.e., keep the same power in the power amplifiers), then we can *simultaneously* increase the downlink capacity by a factor proportional to M (M de-rated due to imperfect downlink beamforming) and increase the downlink coverage area by a factor proportional to $M^{2/\gamma}$ (M de-rated due to imperfect downlink beamforming).

The above capacity and coverage effects do not include additional benefits that can be achieved from diversity. In the uplink, decorrelation among receive channels results in additional uplink capacity and coverage. In the downlink, decorrelation among transmit channels can, if adaptive antennas are combined with a transmit diversity scheme, improve downlink capacity and coverage. The antennas at the base station can be configured in order to maximize the benefits from both adaptive antennas and receive and transmit diversity.

The above capacity and coverage effects also do not consider the effect of active interferer suppression in the uplink and active interferer mitigation in the downlink. This will also increase capacity and coverage, especially when the network includes high data rate users.

References

[Kim et al.] Kyoung Il Kim et al., “Handbook of CDMA System Design, Engineering and Optimization, Prentice Hall, 2000.