Performance Analysis of Downlink Power Control in CDMA Systems*

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Abstract

Three downlink power control algorithms have been studied and evaluated in this work. Additionally, an uplink power control algorithm has been modified and adapted for downlink. An enhancement has been proposed to one of the studied algorithms based on the concept of hysteresis to mitigate oscillations observed at low outage probabilities in the existing algorithms. It has been shown that the behavior of outage with number of iterations in the modified algorithm converges as rapidly as the original algorithm; however the oscillations at low outage percentages have been mitigated using this enhancement.

1 Introduction

Spread spectrum multiple access communication, in the form of Code Division Mulitiple Access (CDMA), is fast emerging as the driving technology behind the rapidly advancing personal communications industry. Its greater bandwidth efficiency and multiple access capabilities make it the leading technology for relieving spectrum congestion caused by the explosion in popularity of cellular mobiles and fixed wireless telephones and wireless data terminals [11]. Power control is one of the most important issues in a CDMA system because it has a significant impact on both performance and capacity— it is the most effective way to avoid the near–far problem and to increase capacity [10]. Power control refers to the strategies or techniques

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required in order to adjust, correct and manage the power from the base station *and* the mobile station in an efficient manner. In the IS-95 system [9], downlink power control was far less sophisticated than uplink power control, resulting in the downlink capacity being more constrained than uplink [8, 3].

Downlink power control serves the following important functions [11, 6, 7]:

- It equalizes the system performance over the service area (good quality signal coverage of worst–case areas).
- It provides load shedding between unequally loaded cells in the service areas by controlling the inter-cell interference to the heavy loaded cells.
- It minimises the necessary transmission power level to achieve good quality of service. This reduces the cochannel interference in other cells, which increases the system capacity.

2 CDMA Power Control

Power control is needed in CDMA systems to compensate for the interference caused by high-powered mobiles against weak ones near the base station. In a time-varying channel, the propagation environment is modeled as d^{-4} and the total range path loss is of the order of $80dB$. With a typical link budget for the IS-95 system, this means that the mobile transmitter must vary its power from about 2.5 nW to 0.25 W. Another reason why power control is needed in IS-95 is to reduce the near–far problem effects, which is caused by near-orthogonal codes that make other users appear as interference noise at the receiver. This implies that high-transmit power levels of mobiles near the base station raise the noise level at the base station. The use of power control reduces the average transmit power of the mobiles, thus preserving battery power at the mobile.

Based on propagation conditions, the mobile may receive a power control command that specifies at what power level the mobile should transmit. However, the losses on uplink and downlink are not symmetric because Rayleigh fading is frequency–selective. To mitigate this, a closed-loop power control is needed to vary the transmitted power by the mobile based on measurements made at the base station, so that it can receive an equal E_b/I_0 from all mobiles. However, because of the existence of a multipath fading environment, it is useful to add another power control mechanism to adjust the desired E_b/I_0 level according to the mobile's error rate measured at the bases station— this is known as the outer loop power control.

Uplink power control serves the following functions:

- It equalizes the received power level from all mobiles at the base station. This function is vital for system operation. The better the power control, the greater the reduction in cochannel interference and thus, increase in capacity. The power control compensates for the near-far problem, shadowing, and partially for slow fading.
- It also minimizes the necessary transmission power level to achieve good quality of service. This reduces the cochannel interference, which increases the system capacity. Moreover, it saves battery power [11] by 20 to 30 dB on the average as compared to the Advanced Mobile Phone Service (AMPS).

Uplink power control achieves the above functions through the following mechanisms:

1. Open–loop power control, and
2. Closed–loop power control, which can be sub-divided into—
   (a) closed outer–loop power control, and
   (b) closed inner–loop power control.

In the downlink, the base station periodically reduces transmit power to each mobile (in steps of ± 0.5 dB every 15 to 20 ms), until the mobile senses an increasing error rate. It might be added that to maintain orthogonality in the downlink channel, IS-95 utilises Walsh codes to transmit and differentiate each mobile.

Following are the downlink algorithms that were studied in the project.

2.1 Distance Based Power Allocation Algorithm [4]

The distance-based power allocation algorithm (DBPA) uses the distance between base station and each mobile station to allocate transmitted power to each each of its served mobile. No correction or feedback is provided, and this is therefore an open–loop power control mechanism.

If power control is not employed (*i.e.*, the transmitted power is same for all users), the most constrained value of the signal-to-interference ratio (SIR) will be for a user at the boundary of the cell. Thus, more transmitted power should be allocated to mobiles which are far from their corresponding base station.

The DBPA algorithm computes the transmitted power of mobile m according to the following equation:

$$p_m = kx_{a_m m}^n \tag{1}$$

$$\text{where, } x_{a_m m} = \begin{cases} \frac{d_{a_m m}}{R}, & \text{if } d_{a_m m} > d_{min} \\ \frac{d_{min}}{R}, & \text{if } d_{a_m m} \leq d_{min} \end{cases} \tag{2}$$

$k =$ positive constant
$n =$ real positive value
$R =$ maximum base-to-mobile distance
$d_{a_m m} =$ distance between mobile m and its assigned base station

In order to avoid having very small transmitted powers for mobiles close to the base, mobiles whose distance $d_{a_m m}$ is less than a certain threshold value d_{min}, the same transmitted power is allowed.

2.2 Distributed Balancing Algorithm [2]

The distributed balancing (DB) algorithm is an adaptive approach that uses the received SIR at the mobiles to adjust the transmitted of the base station in order to achieve better global transmission quality, *i.e.*, for the entire network.

The algorithm calculates the optimal transmit power assignment for each mobile within the cell, taking into consideration all the neighboring cells. The optimal trasmit power assignment for a mobile is proportional to ratio of the total received power of the mobile to the link gain between its base station and itself.

If N_i denotes the number of communicating mobiles in cell i, B_j denotes the base j, M_{ik} denotes the mobile k in cell i, Z_{ikj} denotes the link gain from B_i to M_{ik}, and P_{ik} denotes the downlink power transmitted from B_j

to M_{IK}, then the signal-to-interference ratio (SIR) at the kth mobile in the ith cell may be written as:

$$SIR_{ik} = \frac{P_{ik} Z_{iki}}{\Sigma_j \Sigma_{m=1}^{N_j} P_{jm} Z_{ikj} - P_{ik} Z_{iki}} \tag{3}$$

where it has been assumed that since self–jamming is more dominant on the SIR compared to the background noise, that the latter may be neglected. If the SIR at any mobile station has been balanced by the DB algorithm, the SIR_{ik} is independent of mobile k in cell i, *i.e.*, $SIR_{ik} = SIR_i$.

Rearranging (3) leads to:

$$P_{ik} = \frac{SIR_i}{1 + SIR_i} \frac{\Sigma_j \Sigma_{m=1}^{N_J} P_{jm} Z_{ikj}}{Z_{iki}} \tag{4}$$

Eq. (4) implies that the optimal transmitted power assignment for M_{ik} is proportional to the ratio of the total received power of this mobile to the link–gain between its home base and itself. By expressing $\Sigma_m P_{jm} = Q_j$, this may be written as:

$$(P_{ik})_{opt} \propto \frac{\Sigma_j Q_j Z_{ikj}}{Z_{iki}} \tag{5}$$

A new parameter C_{ik} may be defined as:

$$C_{ik} \cong \frac{\Sigma_j Q_j Z_{ikj}}{Z_{iki}} \tag{6}$$

The optimal power allocation is consequently obtained as:

$$P_{ik} = Q_i \frac{C_{ik}}{\Sigma_m C_{im}} \tag{7}$$

The operation of the DB algorithm may be summarised as follows:

1. The power allocation for each mobile station is calculated at the base station in a centralised manner. The power control of each link is assumed to operate synchronously and periodically (typically every 1.25 ms, or 800 times per second).

2. At the beginning of a control period, each mobile measures the total received power, which includes both the signal and the interference, and the signal link-gain between its home-base and itself, over a certain time interval.

3. Based on these measurements, the mobile station transmits a control signal to its base station, and the power allocation algorithm in the latter allocates a certain downlink power based on this feedback.

4. As the base station updates its transmission power to each mobile based on their feedback, this affects the received power at each mobile, and the corresponding SIR.

The method arguably gives the best achievable performance, but is relatively difficult to implement and has additional overheads. It has been suggested [2] that if the cost of a separate high–bandwidth control channel were acceptable, then the DB algorithm is a suitable downlink power control method to guarantee high capacity and good quality of service.

2.3 Multi-Step SIR-based Power Control Method [2]

Multiple step power control (MSPC) is a closed–loop power control algorithm in which feedback from the mobile is used to adjust the transmitted power of the base station. In this power control scheme, the base station updates its transmitted power for the mobile based on the average SIR received at the mobile, and the updates usually occur in multiple steps, which explains the name.

The steps involved in the operation of the MSPC algorithm are (Fig. 1):

1. The mobile stations measure the observed value of the SIR over time and compare it with a pre-determined threshold value.

2. If the observed SIR is larger than the threshold, then the mobile sends a power–down command to the base station. Otherwise, it sends a power–up comand.

3. The base station interprets the power control command from each of its mobile stations and updates the transmitted power accordingly.

4. The power control updates usually take place in multiple fixed-size steps. This distinction is important in the light of Adaptive Step Power Control (ASPC) [5], discussed in the next subsection.

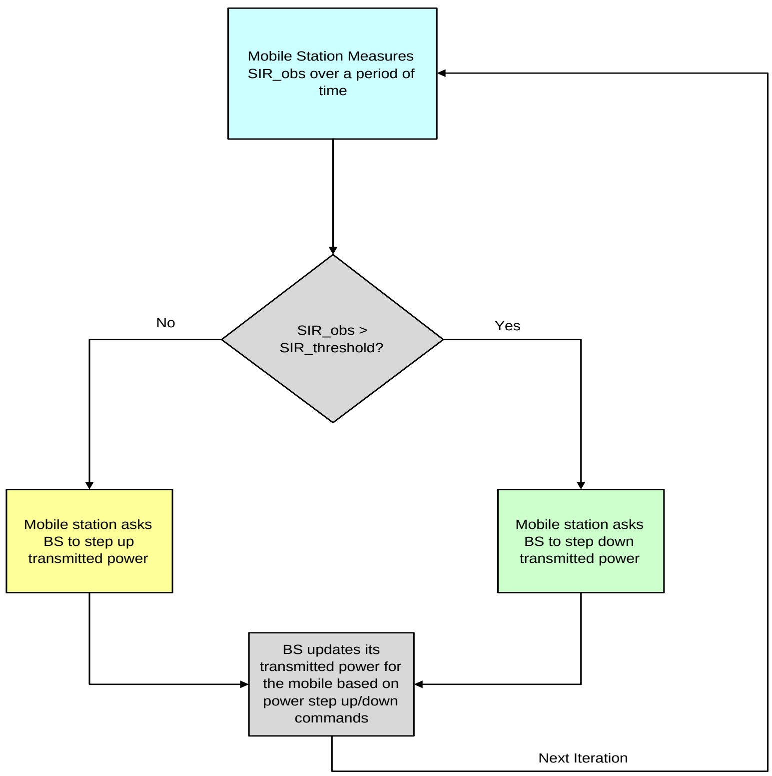

Figure 1: Flowchart illustrating the logical sequence of the Multiple Step Power Control algorithm.

2.4 Adaptive Step Power Control [5]

The Adaptive Step Power Control (ASPC) is a closed–loop power control method that was originally proposed for uplink power control using adaptive step sizes, as opposed to fixed step sizes, to achieve faster convergence towards the target SIR.

The ASPC algorithm was adapted for downlink power control by utilising the idea proposed in [2]. The steps of operation are shown in Fig. 2 and are summarised below:

1. The mobile stations measure the observed value of the SIR at each iteration and compare it with a preset threshold value.
2. If the observed SIR is larger than the threshold, then the mobile sends a power–down command to the base station. Otherwise, it sends a power–up comand.
3. The first power update command is interpreted as a fixed step modification, as suggested in [2]. However, the step size is adapted dynamically if successive feedback commands request additional change in the power level in the same direction (for instance, two or more consecutive power–up commands result in a larger step size).
4. The base station interprets the power control command from each of its mobile stations and updates the transmitted power accordingly.
5. The power control updates take place in multiple steps of different sizes.

2.5 Modified Adaptive Step Power Control (with buffer)

The modified adaptive step power control algorithm (M-ASPC) is an improvement on the adaptive step power control algorithm proposed in [5]. In the ASPC algorithm, it was observed that while the outage plot had a faster convergence rate than MSPC [2], there was significant instability even at low outage percentages. This can be attributed to a single threshold value separating the outage and non-outage regions. As a result of this, the mobiles tend to toggle between the two regions whenever they were near the threshold. In order to mitigate this effect, a buffer region was introduced, resulting in two threshold levels— the lower critical threshold and higher critical threshold.

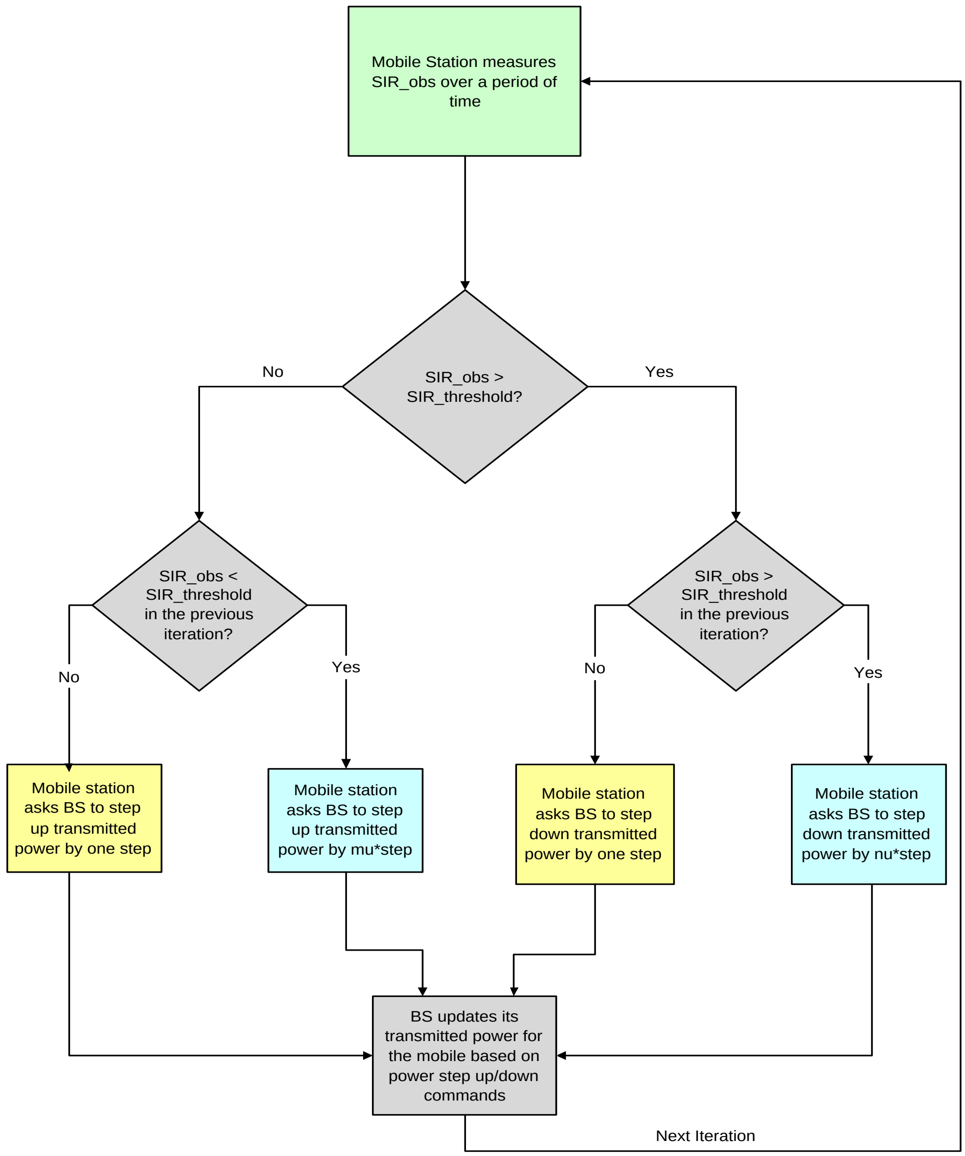

Figure 2: Flowchart illustrating the logical sequence of the Adaptive Step Power Control algorithm.

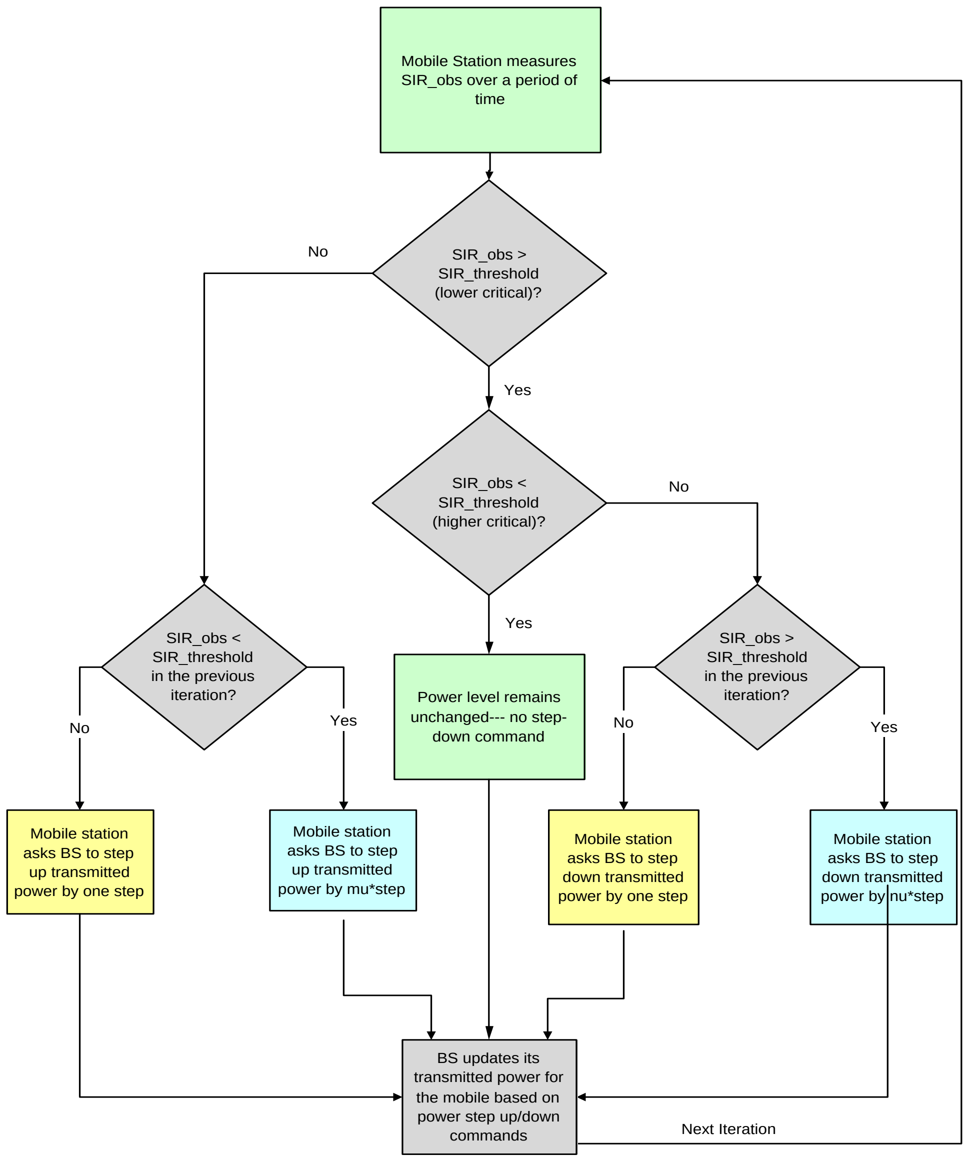

Figure 3: Flowchart illustrating the logical sequence of the Modified Adaptive Step Power Control algorithm.

The steps of operation in the M-ASPC algorithm are listed below and illustrated in Fig. 3:

1. The mobile stations measure the observed value of the SIR at each iteration and compare it with the preset lower and higher critical threshold values.
2. If the observed SIR is smaller than the lower critical threshold, then the mobile sends a power–up command to the base station. The first power update command is interpreted as a fixed step modification; however, the step size is adapted dynamically if successive feedback commands request additional change in the power level in the same direction.
3. If the observed threshold is between the lower and the higher critical threshold values, then the mobile does not send any control signal to the base station.
4. The increment step size is chosen larger than the decrement step size. This ensures that mobiles in outage can quickly come out of outage.
5. Once the mobiles are out of outage and not in the buffer region, the smaller decrement step size brings the mobile into the buffer region. As pointed out in step (3), when the mobile is in the buffer region, it does not send power change commands. This eliminates the oscillations observed at low outage percentages in MSPC.

3 Simulation and Results

The performance analysis and comparison of the power control algorithm was carried out using Matlab version 6.5 release 13. Following is a list of assumptions common to all the algorithms simulated.

1. Characteristics of each forward link are independent and identical.
2. There are a fixed number (M) of mobile stations per cell.
3. The mobiles are located uniformly within the cell.
4. All mobiles are listening at all times.
5. Outage is defined as the condition when the observed value of the SIR is below the threshold value ($SIR_{threshold} = -14dB$ [2]).

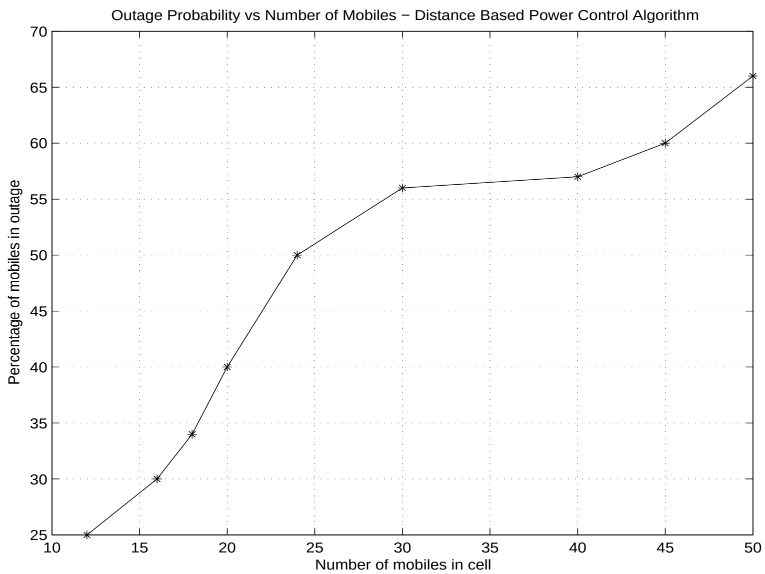

Figure 4: Outage percentage versus number of mobiles for the Distance–Based Power Allocation algorithm.

3.1 Distance–Based Power Allocation Algorithm (DBPA)

This is an open–loop power control algorithm that uses the base station-to-mobile distance to allocate transmit powers for each mobile.

The pseudo-code for the simulation is as follows.The complete MATLAB code is included in the Appendix and Fig. 4 plots the outage percentage against the number of mobiles.

Pseudo-code

1. Initialize number of *iterations*
2. Initialize number of *mobiles*
3. Initialize d_{min}, R, k, n
4. for $i = 1$ to *iterations*
    - Generate uniformly distributed vector of mobile-to-base station *distance*

- Initialize *power*
- for $j = 1$ to *mobiles*
- if *distance* $\leq d_{min}$
- $power(j) = k\left(\frac{d_{min}}{R}\right)^n$
- else
- $power(j) = k\left(\frac{distance(j)}{R}\right)^n$
- end
- calculate $SIR_{observed}(j)$ and compute *outage*
- end

5. Calculate the outage percentage using the *outage* counter and the number of *mobiles*.
6. Plot *outage* percentage versus *mobiles*

3.2 Distributed Balancing Algorithm (DB)

The distributed balancing algorithm calculates the optimal transmission power assignment for each mobile within the cell, taking into account all the neighboring cells. The scenario consists of a central cell surrounded by six other cells. This power is proportional to the ratio of the total received power of the mobile to the link gain between the base station and that mobile.

The pseudo-code for the simulation is as follows. Note that the complete MATLAB code is included in the Appendix.

Pseudo-code

1. Initialize number of *iterations*
2. Initialize number of *mobiles*
3. for $i = 1$ to *iterations*
   - Generate uniformly distributed vector of mobile-to-base station *distance*
   - Generate a vector of link–gains of mobiles from their own base station *gain*

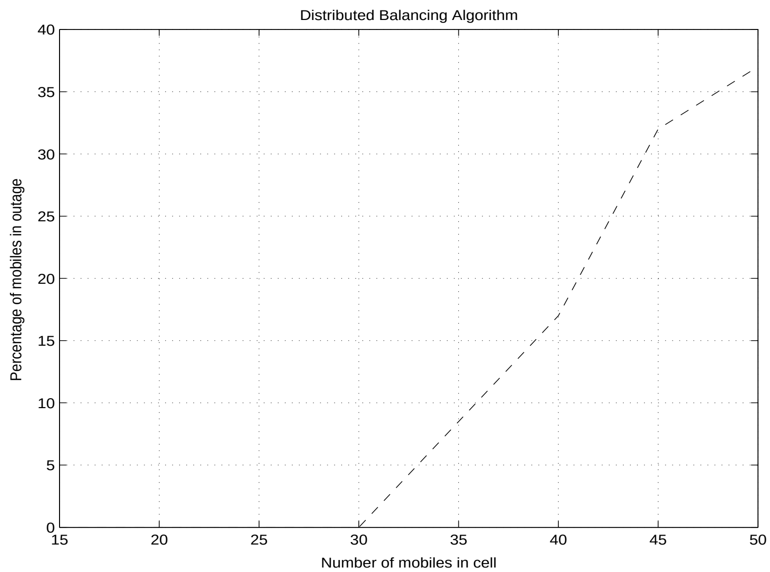

Figure 5: Outage percentage versus number of mobiles for the Distributed Balancing Power Control algorithm.

- Generate a vector of link–gains of mobiles from other base station $gain'$
- Initialize *power*
- Initialize DB correction coefficient Cik
- for $j = 1$ to *mobiles*
- total received power $= \Sigma power * gain + 6 * \Sigma power * gain'$
- C_{ik}=total received power $/gain$
- $power(j) = \Sigma power * \frac{C_{ik}(j)}{\Sigma C_{ik}}$
- end
- calculate $SIR_{observed}(j)$ and compute *outage*
- end

end

4. plot *outage* percentage versus *mobiles*

The plot of outage percentage versus number of mobiles per cell is shown in Fig. 5.

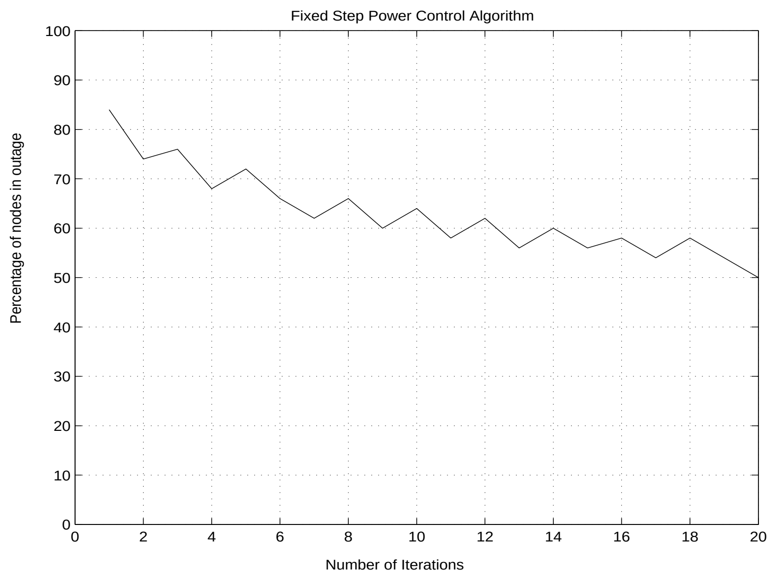

Figure 6: Outage percentage versus number of iterations for the Multiple–Step SIR-based Power Control algorithm.

3.3 Multiple Step SIR–based Power Control (MSPC)

MSPC is a closed–loop power control algorithm that uses feedback fromn the mobiles to adjust the transmitted power of the base station.

The pseudo-code for the simulation is as follows. Note that the complete MATLAB code is included in the Appendix.

Pseudo-code

1. Initialize number of *iterations*
2. Initialize number of *mobiles*
3. Generate uniformly distributed vector of mobile-to-base station *distance*
4. Generate vector of link–gains from each mobile to the base station based on a log–normal distribution with zero–mean and standard deviation = 6 dB

5. Allocate initial power for each mobile at the base station

6. Initialize $SIR_{threshold} = -14\ dB$

7. for $i = 1$ to *iterations*
   for $j = 1$ to *mobiles*

   - Calculate $SIR_{observed}$ at each *mobile*
   - Compare $SIR_{observed}$ with $SIR_{threshold}$
   - if ($SIR_{observed} < SIR_{threshold}$
   - Increment *outage* counter
   - Adjust (increase) power by fixed step
   - else
   - Adjust (decrease) power by fixed step
   - end

   end

8. Calculate the *outage* percentage using *outage* counter and the number of *mobiles*

9. Plot *outage* percentage versus number of *iterations*

Fig. 6 illustrates the behavior of the outage percentage as a function of the number of iterations.

3.4 Adaptive Step SIR–based Power Control (ASPC)

ASPC is a variation of the MSPC algorithm that uses an adaptive step size to achieve faster convergence towards no outage. This algorithm uses the information from the previous iteration in order to adapt the step size accordingly.

The pseudo-code for the simulation is as follows. Note that the complete MATLAB code is included in the Appendix.

Pseudo-code

1. Initialize number of *iterations*

2. Initialize number of *mobiles*

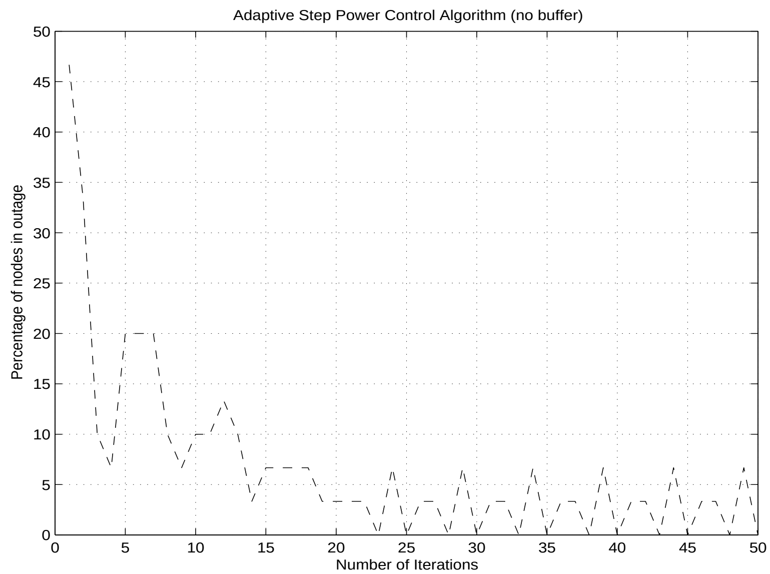

Figure 7: Outage percentage versus number of iterations for the Adaptive Step Power Control algorithm.

3. Generate uniformly distributed vector of mobile-to-base station *distance*

4. Generate a vector of link–gains from each mobile to the base station based on a log-normal distribution with zero–mean and standard deviation = 6 dB

5. Allocate initial power for each mobile at the base station

6. Initialize $SIR_{threshold} = -14\ dB$

7. Initialize μ (increment factor), ν (decrement factor), δ (step size), $flag$ (previous iteration feedback information)

8. for $i = 1$ to *iterations*

    - for $j = 1$ to *mobiles*
    - Calculate $SIR_{observed}$ at each *mobile*
    - Compare $SIR_{observed}$ with $SIR_{threshold}$
    - if ($SIR_{observed} \leq SIR_{threshold}$)

- Increment *outage counter(i)*
- if (previously in *outage*)
-     Adjust (increase) power by $\mu\delta$
- else
-     Adjust (increase) power by δ
- elseif ($SIR_{observed} > SIR_{threshold}$)
- if (previously not in *outage*)
-     Adjust (decrease) power by $\nu\delta$
- else
-     Adjust (decrease) power by δ
- end

end

9. Calculate the *outage* percentage using *outage* counter and the number of *mobiles*

10. Plot *outage* percentage versus number of *iterations*

Fig. 7 shows the behavior of the outage percentage as a function of the number of iterations.

3.5 Modified Adaptive Step SIR–based Power Control (M-ASPC)

M-ASPC is a variation of the ASPC algorithm that uses two thresholds— a higher and a lower end critical threshold for the SIR. This prevents the oscillations observed at lower values of outage in the ASPC algorithm. When the mobiles are in the buffer region, they do not send any feedback and the system converges rapidly without oscillating at lower outage percentages.

The pseudo-code for the simulation is as follows. Note that the complete MATLAB code is included in the Appendix.

Pseudo-code

1. Initialize number of *iterations*

2. Initialize the number of *mobiles*

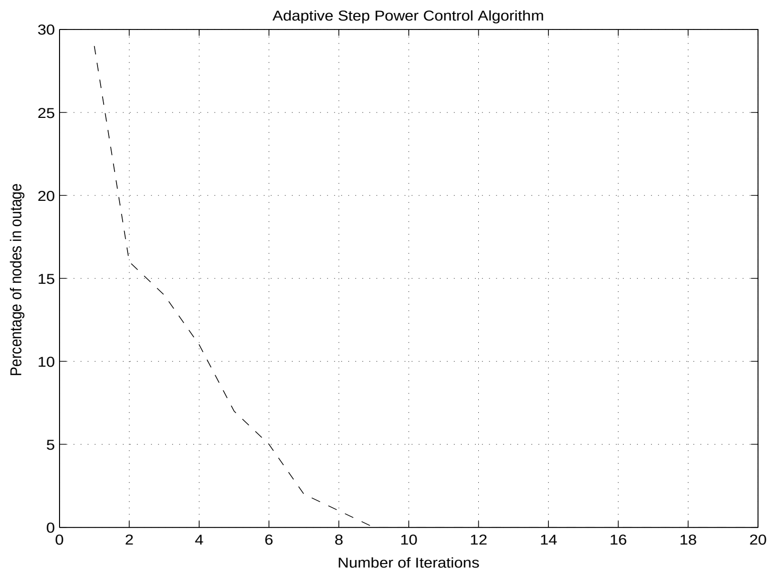

Figure 8: Outage percentage versus number of iterations for the Modified Adaptive Step Power Control algorithm.

3. Generate uniformly distributed vector of mobile-to-base station *distance*
4. Generate a vector of link–gains from each mobile to the base station based on a log-normal distribution with zero–mean and standard deviation = 6 dB
5. Allocate initial power for each mobile at the base station
6. Initialize $SIR_{threshold} = -14\ dB$
7. Initialize μ (increment factor), ν (decrement factor), δ (step size), $flag$ (previous iteration feedback information)
8. Initialize buffer region
9. for $i = 1$ to $iterations$
   - for $j = 1$ to $mobiles$
   - Calculate $SIR_{observed}$ at each $mobile$
   - Compare $SIR_{observed}$ with $SIR_{threshold}$

- if ($SIR_{observed} \leq SIR_{threshold}$)
- Increment *outage counter(i)*
- if (previously in *outage*)
- Adjust (increase) power by $\mu\delta$
- elseif (previously not in *outage* or returning from *outage*)
- Adjust (increase) power by δ
- elseif (initial power allocation caused this outage)
- Adjust (increase) power by $\mu\delta$
- elseif ($SIR_{observed} > SIR_{threshold} + buffer$)
- if (previously not in *outage*)
- Adjust (decrease) power by $\nu\delta$
- elseif (previously in *outage*)
- Adjust (decrease) power by δ
- elseif (initial power allocation caused this "non–outage")
- Adjust (decrease) power by δ
- else
- Do nothing if the $SIR_{observed}$ is in the *buffer* region
- end

end

10. Calculate the *outage* percentage using *outage* counter and the number of *mobiles*

11. Plot *outage* percentage versus number of *iterations*

The behavior of outage percentage versus number of iterations is shown in Fig. 8.

4 Conclusion and Future Work

In this project, three exisiting downlink power control algorithms for CDMA systems were implemented and analyzed based on outage versus number of iterations. Additionally, an uplink power control algorithm was modified and adapted for downlink. The Distributed Balancing (DB) power control algorithm was shown to give better results compared to Distance Based

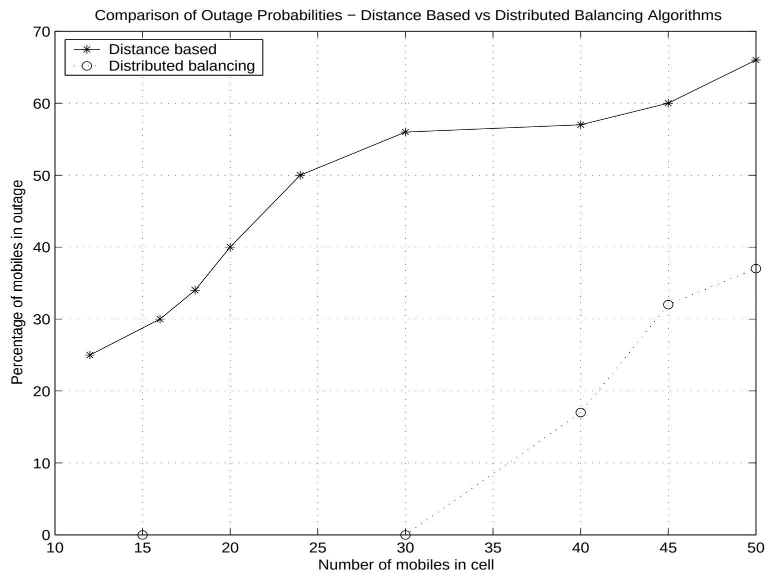

Figure 9: Outage percentage versus number of iterations for the Adaptive Step Power Control algorithm.

Power Allocation (DBPA) algorithm (Fig. 9), since the latter lacked feedback from the mobile to the base station. The Adaptive Step Power Control (ASPC) algorithm performed better than the Multiple Step Power Control (MSPC) in terms of faster convergence to non–outage.

An enhancement to the ASPC algorithm was proposed using the concept of hysteresis, by introducing a buffer region instead of a single SIR threshold. This resulted in a better performance in terms of mitigating the oscillations of the mobiles in outage at lower values of outage percentage (Fig. 10). Future work in this area includes extending the idea of hysteresis for multiple cell scenarios and consideration of power limitations at the base station. Also, the performance with mobility models will be studied for situations where a mobile moves from one base station to another (handover).

5 Acknowledgments

We wish to thank Professor Predrag Spasojevic for his helpful suggestions and comments that helped us narrow down on the project goals and create

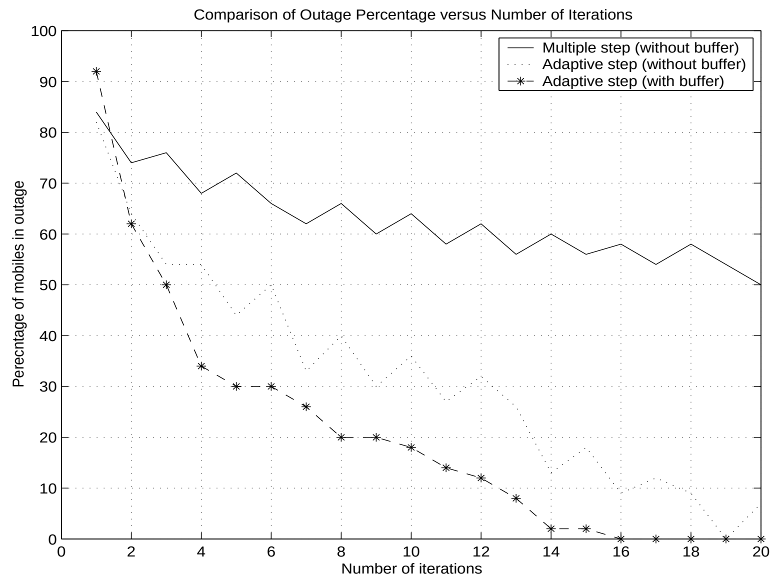

Figure 10: Outage percentage versus number of iterations for the Adaptive Step Power Control algorithm.

a well–defined problem statement. This made it feasible for us to get valuable insight into the area and also propose and evaluate an enhancement to exisiting algorithms.

References

[1] S. C. Bang and Y. Han. Performance of a Fast Forward Power Control Using Power Control Bits for the Reverse Power Control as Power Measurement. In *Proceedings of the Vehicular Technology Conference (VTC'98)*, pages 1414–1418, Ottawa, Canada, 1998.

[2] Chung-Ju Chang and Fang-Ching Ren. Downlink Power Control in DS/CDMA Cellular Mobile Radio Network. In *Proceedings of the 3rd International Conference on Universal Personal Communications (ICUPC'94)*, pages 89–93, San Diego, CA, 1994.

[3] Tatcha Chulajata and Hyuck M. Kwon. Combinations of Power Controls for CDMA 2000 Wireless Communications System. In *Proceed-*

ings of the Vehicular Technology Conference (VTC'00), pages 638–645, Boston, MA, 2000.

[4] Loutfi Nuaymi, Philippe Godlewski, and Xavier Lagrange. Power Allocation and Control for the Downlink in Cellular CDMA Networks. In *Proceedings of the 12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'01)*, volume 1, pages C29–C31, San Diego, CA, 2001.

[5] Loutfi Nuaymi, Philippe Godlewski, and Xavier Lagrange. A Power Control Algorithm for 3G WCDMA Systems. In *Proceedings of European Wireless*, Florence, Italy, 2002.

[6] Kaveh Pahlavan and Allen H. Levesque. *Wireless Information Networks*. John Wiley, New York, NY, 1995.

[7] Man Young Rhee. *Cellular Mobile Communications– CDMA Network and Security*. Prentice-Hall, Upper Saddle River, NJ, 1998.

[8] Lei Song and Jack M. Holtzman. CDMA Dynamic Downlink Power Control. In *Proceedings of the Vehicular Technology Conference (VTC'98)*, volume 2, pages 1101–1105, Ottawa, Canada, 1998.

[9] TIA/EIA Interim Standard-95. Mobile Station—Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System. Technical report, Telecommunications Industry Association, 1993.

[10] W. M. Tam and F. C. M. Lau. Capacity Analysis of a CDMA Cellular System with Power Control Schemes. In *Proceedings of the 6th IEEE International Conference on Universal Personal Communications (ICUPC'97)*, pages 608–612, San Diego, CA, 1997.

[11] Andrew J. Viterbi. *CDMA: Principles of Spread Spectrum Communication*. Addison-Wesley, Reading, MA, 1995.