Analysis of Interference and Signal Quality in Cellular Wireless Networks

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Abstract. An analytical model to compute the effect of co-channel interference from the base stations at the Multi-cell CDMA systems is proposed. The objective is to study the effect of multiple-access interference generated by the neighbor cells on multi-cell CDMA and W-CDMA systems capacity. The potential of adaptive antennas in interference reduction and signal quality improvement in CDMA mobile communications systems is analyzed. The study shows that improvement in base-station sensitivity can boost system performance.

Keywords: Interference Analysis, CDMA Capacity, Path loss Modeling, Mobile Spatial Location, Cellular Network Capacity.

1. Introduction

The limited radio spectrum allocated for a cellular system results in crowded communication channels making the cellular network capacity increasing to be an important issue for cellular service providers to face the extraordinary demand for cellular communication services\textsuperscript{[1]}. Multiple access and channel assignment are mostly used techniques to maximize the efficient use of the available radio frequency spectrum\textsuperscript{[2]}. Frequency reuse technique is usually used in wireless networks to improve capacity. It implies that the radio frequency used to serve a cell can be reused in a different cell for completely different transmission. This introduces interference in cells that use the same channel thereby decreasing the system capacity and its service quality\textsuperscript{[3]}.

In multi-cell Code Division Multiple Access (CDMA) networks, and Wideband Code Division Multiple Access (WCDMA) that use a spread spectrum technique for capacity extension, base stations transmit power to all users within their coverage area introducing (intra-cell interference) in addition to interference from neighboring cells causing other cell interference(inter-cell interference). Since the interference produced by users in other cells cannot be fully power controlled by their serving base stations, the CDMA, and WCDMA networks are interference limited\textsuperscript{[4-6]}.

In \textsuperscript{[7]}, a model to estimate the number of interferers in adjacent cells of CDMA networks is proposed. The effect of user density and the cell radius in CDMA systems was presented through two different propagation models in \textsuperscript{[8]}. In \textsuperscript{[9]}, a mathematical analysis is presented to investigate the propagation model parameter effects on cellular network performance considering the effect of multiple tiers of co-channel cells at different frequencies. The effect of user location on other cell interference and CDMA network capacity is investigated in \textsuperscript{[10]}. The WCDMA network capacity and coverage area are evaluated in terms of the number of co-channel interferers, and the antenna gain. The interference probability model has been established based on a random distribution of mobiles in time and space with the utilization of Monte Carlo Simulation (MCS) in \textsuperscript{[11]}. 
This paper aimed to characterize the average inter-cell interference and the average number of users that can be managed by the cellular CDMA–WCDMA systems. In the following, a model to evaluate the number of the users moving at surrounding interfering cells will be presented in section II. The propagation channel and the other cell interference will be characterized and analyzed in Sections III. The simulation results are presented and discussed in section IV.

2. Derivation of the Cell Size and Number of Users

Assume that the typical cellular network illustrated in Figure 1, having cells of hexagonal shape that approximated by circular cells each with a radius of \( R_c \). All cells are assumed to be fully covered by their serving base stations. The average number of mobile stations \( \bar{m} \) located within any cell in the system including cell edges have the potential to contribute to other cell interference and traffic can be evaluated from the cell coverage area and the average mobile station density \( \rho_m \) that denotes the number of mobiles per unit area. Therefore, the average number of mobiles can be obtained by integrating the elementary surface \( (r dr d\phi) \) of radius \( r \):

\[
\bar{m} = \int_{\phi=0}^{2\pi} \int_{r=0}^{R_c} r \rho_m dr d\phi = \pi R_c^2 \rho_m
\]

The actual carried traffic per interfering cell is given by the product of the traffic produced by each mobile station for the active user \( A_u \) and the total number of mobile stations located within the interfering cell.

\[
\text{Traffic/Cell} = \pi R_c^2 \rho_m A_u
\]

The offered traffic intensity by each user is equal to the call request rate \( \lambda \) by the user multiplied by the call time \( H \) [1-2].

\[
A_u = \lambda H
\]

The actual carried traffic intensity carried by a channel related to the volume of the offered traffic intensity by the relation:

\[
\text{Carried traffic/ cell} = (1-P_B) \times (1-P_o) \times \text{Offered Traffic per cell}
\]

where \( P_B \) is the system blockage probability, and \( P_o \) is the outage probability of the system. Equation (4) implies that the actual load (traffic carried by a cell) depends upon system blockage probability, outage probability and the offered traffic that is a function of the users' number within the cell. The outage probability depends upon the location probability that the received signal does not satisfy the required level in the cell with a certain radius \( R_c \). Equations (2), and (4), allow us to write

\[
R_c = \sqrt{\frac{(1-P_B) \times (1-P_o) \times \text{Offered Traffic per cell}}{\pi \rho_m A_u}}
\]

It can be noticed that the cell size (radius) is a function of the actual traffic managed. The acceptable blockage and outage probability for the network must be known to decide the cell size(radius). Higher mobile unit density requires lower the cell radius to become [2,12].

In the downlink, base stations radiate power shared between traffic and control channels, introducing interference at mobile stations from other cells, as well as from the users at the home cell. The multi-cell CDMA network capacity depends on the SNR required for each user, which can be expressed as a function of bit energy \( (E_b) \) and total interference \( N_t \). The total interference \( (N_t) \) can be given as \( P f (M-1)(1+f) \) where \( f \) is the other-cell interference factor. If the imperfect power control factor(\( \eta \)) is added, the actual number of users (M) that can be supported by the system is given as[13-14]:

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2
\[ M = 1 + \frac{\eta G_p}{(E_b / N_i) (1 + f) \nu_f} - \frac{W N_o}{(1 + f) \nu_f P} \]  

(6)

Where \( P \) is the signal power, \( N_o \) is the thermal noise, \( E_b/N_i \) represent the required SNR required for the reliable link, \( W \) is the bandwidth, \( \nu_i \) is the voice activity factor, \( G_p \) is the processing gain\( (G_p = W/R) \) where \( R \) is the data rate of the user, and \( f \) is the interference factor, that denotes the other cells interference to same cell interference ratio. The reliable link between the mobile and base station requires sufficient \( E_b/N_t \) to cover all the active users at any cell. Any mobile should exceed the base station sensitivity value \( P \) to tolerate interference from other mobiles[15].

3. Propagation and Interference Modeling

Assuming uniform mobile station density in target and interferer cells over the whole system, the actual coverage area will be located at the region between \( (A_1) \) and \( (A_2) \) that represents the far-field zone of the serving base station antennas located at the cell center. This area can be given as:

\[
A_2 = \pi R_c^2 \\
A_1 = \pi R_o^2 \\
A_{actual\ coverage} = \pi (R_c^2 - R_o^2)
\]

Any active user can be at a location of distance \( r \) from its home base station, then the probability of the distance \( r \) is \( (R_o - R_o) \), which means it can be at the shadowed area whose circumference is \( 2\pi (R_c - R_o) \) as shown in Figure 1. The probability distribution function (PDF) of any mobile location relative to its serving base station or its distance and direction relative to its home base station can be given in polar coordinates as

\[
Pr(b(r)) = \frac{2\pi (R_c - R_o)}{\pi (R_c - R_o)^2} = \frac{2(R_o - R_o)}{(R_c - R_o)^2}; \quad \forall r > R_c
\]

(7)

\[
Pr(b(\phi)) = \frac{1}{2\pi}
\]

(8)

![Figure 1. Mobile Stations Distribution](image)

The power received from the reference cell base station \( (P_{ri}) \) at mobile station \( i \) is directly proportional to the average transmitted power from the reference base station \( P_t \), and inversely proportional to the separation distance between the mobile and its serving station \( r_i \) raised to the propagation path loss exponent(\( \gamma \)). Therefore, the power received by a mobile station at distance \( r_i \) can thus be expressed as:

\[
P_{ri} = K r_i^{-\gamma} P_t
\]

(9)

Where \( K \) is the proportionality constant that will be the same for all base stations as all base stations are assumed to produce the same transmitted power. The power received by the mobile \( P_{ri} \) will be also received by other mobiles in the same cell causing the same cell interference (intra-cell interference). In order to determine the inter-cell interference generated by all of the operating base stations in the
system, we will assume omnidirectional base stations that are uniformly distributed over the whole network coverage area. Let us assume the elementary surface \((r \, dr \, d\theta)\) at a distance \(r\) from the user \(i\).

With a circular shape coverage area whose radius is \(R_{ca}\), the number of network base stations is equal to the number of base stations located within a ring of width \(dr\) and the base station density evaluated in base station per unit area. Then, the elementary surface contains \((\rho_{BS} \, r \, dr \, d\theta)\) base stations as shown in Figure 2.

**Figure 2.** Cellular Network Configuration

The closet base station is located at a distance \((2R_c - r_i)\) from the user \(i\), and the farthest base station will be at \((R_{ca} - r_i)\), where \(R_{ca}\) is the radius of the whole area covered by the cellular system. Therefore, the interference may be caused by the total number of the base station can be given as:

\[
P_i = \int_{0}^{2\pi} \int_{2R_c-r_i}^{R_c} \frac{K}{r^\gamma} P_t \, r \, dr \, d\theta
\]

\[
P_i = 2\pi \, \rho_{BS} K P_t \int_{2R_c-r_i}^{R_c} r^{-\gamma} \, r \, dr
\]

\[
= 2\pi \, \rho_{BS} K P_t \int_{2R_c-r_i}^{R_c} r^{2-\gamma} \, dr
\]

\[
= \frac{2\pi K \rho_{BS}}{\gamma - 2} P_t \left[ (2R_c - r_i)^{2-\gamma} - (R_{ca} - r_i)^{2-\gamma} \right]
\]
The ratio of the other-cell interference power received from other base stations to the same cell interference power received from the serving base station that is the interference factor $f$ can be used to determine the reuse efficiency, then the network capacity (the number of users can be supported).

$$f = \frac{P_i}{P_{ri}} = \frac{2\pi K \rho_{BS} r_i^{\gamma}}{\gamma - 2} \frac{1}{P_i} \left[ (2R_c - r_i)^{2-\gamma} - (R_{cu} - r_i)^{2-\gamma} \right]$$

$$f = \frac{2\pi \rho_{BS} r_i^{\gamma}}{\gamma - 2} \left[ (2R_c - r_i)^{2-\gamma} - (R_{cu} - r_i)^{2-\gamma} \right] \quad (11)$$

From equation (11), it can be noticed that the interference factor depends on user location within its own cell.

4. Simulation and Results

Interference signals coming from the surrounding cells depends on the interference factor. As the W-CDMA system capacity is interference limited, any interference will result in a linear increase in the system capacity. The link performance for each user increases as the number of users decreases.

Figure 3 shows the base station sensitivity and the capacity (number of users) dependence for different values of the interfering factor. It can be noticed that the reduction in interference factor results in more users supported by the system. Furthermore, increasing the required $E_b/N_t$ will decrease the number of mobiles as illustrated in Figure 4.

Figure 3. BS Sensitivity With Capacity

Figure 4. BS Sensitivity With Users
Due to the potential of the adaptive antenna in increasing the directivity by focusing the pattern in the desired direction other than jamming sources, it will provide a good reduction in base station number required in the system. Figure 5, shows that increasing the gain by 6.0 dB, will result in decreasing the base station density by 50%. The base stations number reduction can be translated into cell size extension, and interference reduction. In a 50% loaded system, increasing the gain by 4.0 dB gain in the receiver's sensitivity could lead to a power reduction of about 6 dB as shown in Figure 6. The reduction in base station transmitted power is translated into the mobile battery life extension.

Figure 5. BS Density Reduction with Adaptive Antenna

Figure 6. Power Reduction with Adaptive Antenna

In our proposed model, it can be noticed that as the mobile unit approaches the cell edge, it will experience more interference as shown in Figure 7. It is clear that the interference factor is increased as the mobile station approaches the cell boundary.
Figure 7. Mobile Location with Interference Factor

5. Conclusion
The results presented have focused on the multi-cell CDMA systems. It has been shown that any improvement in base station sensitivity can increase the network capacity or the number of mobiles held by the system. The adaptive antenna technique can provide more diversity gain in rich multipath urban areas. It should be noticed that the utilization of adaptive antenna has a good potential in power consumption enhancement and can decrease the base station density contributing to interference reduction.

References
[1] Rappaport T S 2002 Wireless Communications Principles and Practice, Prentice Hall, Upper Saddle River NJ, Second Edition.
[2] Garg Vijay K 2007 Wireless Communications and Networking, Morgan Kaufmann Publishers, USA, First Edition.
[3] M Taranetz and M Rupp 2014 A circular interference model for wireless cellular networks, in Wireless Communications and Mobile Computing Conference (IWCMC), 2014 International, pp. 827–832.
[4] Krzysztof Wesolowski, 2002 Mobile Communication Systems, Jhon Wiley and Sons Ltd, First Edition.
[5] B P Laiithi 1998, Modern Digital and Analog Communication Systems, Third Edition, Oxford University Press.
[6] Theophilus Alumona 2014, Effects of variation in Transmitter Power, Antenna Height and Antenna Tilt in a Wideband Code Division Multiple Access network, International Journal of Advanced Research in Electronics and Communication Engineering 3(9), pp.1236-41.
[7] X Tang and H Yang 2012, Effect of User Distribution on the Capacity of Cellular Networks, National Conference on Information Technology and Computer Science.
[8] Dalal Kanaan Taher and Adheed Hassan Sallomí 2018, Proposed Model for Interference Estimation in Code Division Multiple Access, TELKOMNIKA 16(6), pp. 125–132.
[9] K A. Anang, P B Rapajic, L Bello and R Wu 2012, Sensitivity of Cellular Wireless Network Performance to System & Propagation Parameters at Carrier Frequencies Greater Than 2GHZ, Progress in Electromagnetics Research 40, PP. 31-54.
[10] A Lebl, D Mitić, M Popović, Ž Markov, M Mileusnić and V Matić 2016 Influence of Mobile Users’ Density Distribution on the CDMA Base Station Power, J. Electr. Eng. 67(6), pp. 390–398.
[11] Solomon T Girma , Dominic B O Konditi and Ciira Maina 2019, Frequency re-use distance calculation in cellular systems based on Monte-Carlo simulation, Heliyon, Article No. 01302, Published by Elsevier Ltd.
[12] El Zooghby Ahmed 2001 Potentials of Smart Antennas in CDMA Systems and Uplink Improvements, IEEE Antennas and Propagation Magazine 43(5).
[13] C A D Pahalson, N S Tarkaa and G A. Igwue 2019 Method for Analysis of System Coverage and Capacity for a GSM Based Cellular Network, International Journal for Modern Trends in Science and Technology 05(8), pp. 74–87.
[14] Sofia Sousa, Fernando J Velez and Jon M Peha 2017 Impact of Propagation Model on Capacity in Small-cell Networks, International Symposium on Performance Evaluation of Computer and Telecommunication Systems.
[15] Ifeagwu E N, Ekeh j and Ohaneme C, Okezie C. 2012 Evaluation of Spectral Efficiency, System Capacity and Interference Effects on CDMA Communication System, *International Journal of Advanced Computer Science and Applications* 3(6), pp.20-25.