MUTUAL INTERFERENCE MODELS FOR CDMA MOBILE COMMUNICATION NETWORKS

Vladimír WIESER, Karol HRUDKAY
Dept. of Telecommunications
University of Žilina
Veľký diel, 010 26 Žilina
Slovak Republic

wieser@fel.utc.sk, hrudkay@fel.utc.sk

Abstract

Nowadays we are witnesses of a huge development one of the most progressive communication technology - mobile networks. The main problem in these networks is an elimination of the mutual interference, which, mainly in non-orthogonal CDMA networks, is the principal obstacle for reaching high transmission rates

The aim of this contribution is to give simplified view to mutual interference models for orthogonal and non-orthogonal CDMA networks. The contribution is intended mainly for PhD. students to help them to obtain an orientation in such a complicated areas, as the interference models for CDMA networks are.

Keywords

Mutual interference, interference model, mobile communication network, uplink, downlink, orthogonal CDMA, non-orthogonal CDMA

1. Introduction

The channel capacity of a cellular communication system is influenced by mutual interference, which may be minimized by several methods:

- Effective power adaptation:
  - Downlink – base station power minimization to restrict the transmission to the intended cell area.
  - Uplink – Near-Far effect elimination.
- Mutual interference elimination in receiver – multi-user receivers or adaptive single user receiver.
- Orthogonal spreading codes – this method is effective in synchronous networks.

In this contribution we have tried to give some simplified view to mutual interference problem in orthogonal and non-orthogonal CDMA systems. From the reason of understanding, we have used only simple interference models (only path loss is included). The aim is to help young researchers (Ph.D students) to obtain the basic knowledge about this topic.

2. Uplink Interference Model

In the uplink (mobile transmits and base station receives) there are these signals in the base station receiver input [7]:

- Desired signal (signal from served mobile in its own cell).
- Interfering signals from other mobiles in own cell (Intracell interference).
- Interfering signals from other mobiles in neighbor cells (Intercell interference).
- Gaussian white noise.

In the case of *ideal orthogonal channel separation,* the intracell interference is eliminated. This situation is characteristic in systems with frequency or time channel division, where the exact orthogonal frequency net is created (FDMA), or it is used synchronization, which ensure the orthogonal time slots separation (TDMA).

Of course, the situation is different in code division multiple access systems (CDMA). In *non-orthogonal CDMA system* the value of mutual interference, called multiple access interference - MAI (intercell and intracell) is represented by spreading codes cross-correlation function

$$R_c(\tau) = \int_{-N_cT_c/2}^{N_cT_c/2} PN_i(t) PN_j(t+\tau)\, dt \qquad (1)$$

where N_c is the number of spreading code chips, T_c is their repetition period and τ represents the time difference between two codes.

The cross-correlation function is the measure tool of the identity between two different codes PN_i and PN_j. If $R_c(\tau) = 0$ for all τ, codes are orthogonal. Because of using orthogonal spreading codes in practical CDMA systems, it might be thought that in uplink the intracell interference doesn't exist. The problem with using orthogonal codes (Walsh-Hadamard codes in IS-95 system or orthogonal variable spreading codes - OVSF codes in IMT-2000 family systems) is, that these codes have very good cross-correlation function values only with zero time differences among them (τ = 0), i. e. in synchronous system. Convenient properties of codes are lost if there doesn't exist synchronization or multipath signals are presented.

In FDMA/TDMA systems the elimination of the intercell interference is realized by spatial channel separation, so the interference power received from mobiles will not exceed some defined level.

CDMA systems are characterized by very simple frequency planning, because several broadband channels are used in every cell (reuse factor $K = 1$).

Theoretically, we can talk about two CDMA variants [2]:

1. Orthogonal CDMA system (OCDMA) – the intracell interference is eliminated (completely or partially) by orthogonal spreading codes (W-H codes) using, which are used in every cell in the system. The length of W-H code is the same as spreading factor SF (the number of chips per information bit). In the case of ideal synchronization, the mutual orthogonality is assured and the intracell interference doesn't occur. The dominant source of interference is the intercell one. The number of users is the same as the number of codes. In such system the interfering source is only one active channel in each cell.

2. Non-orthogonal system (PN-CDMA, pseudo-noise CDMA) – every user has its own spreading code. If the received signal power is normalized ($P_r = 1$), than, after despreading, the interference power from other users is 1/SF. The whole interference power is proportional to the number of users and the cell capacity depends on the signal degradation level, which is still tolerable.

2.1 OCDMA system

The simple interference model is in Fig.1. The interference model is similar to models for orthogonal systems FDMA/TDMA with the difference that due to the small value of reuse factor $K = 1$ (i. e. the same group of channels is used in every cell in the system), interfering sources are closer to the base station. This is the reason for taking into account an influence of minimum two interfering tiers of cells.

The signal to interference ratio (SIR) for the most inconvenient mobile position is (in second interfering tier we have taken into account two groups of mobiles)

$$SIR = \frac{P_{MS}\, r_c^{-\alpha}}{\sum_{i=1}^{6} P_{MSi}\, r_{\text{int}1}^{-\alpha} + \sum_{i=1}^{6} P_{MSi}\, r_{\text{int}2A}^{-\alpha} + \sum_{i=1}^{6} P_{MSi}\, r_{\text{int}2B}^{-\alpha}} = \tag{2}$$

$$= \frac{1}{6\cdot 0.87^{-4} + 6\cdot 2^{-4} + 6\cdot 2.6^{-4}} = 0.091 \quad (-10.4\ \text{dB})$$

where P_{MS} is the mobile station power, r_c is the cell radius, α is the path loss exponent (in urban environment $\alpha = 4$), r_{int1} (r_{int2}) is the radius of the 1st (the 2nd) interference tiers.

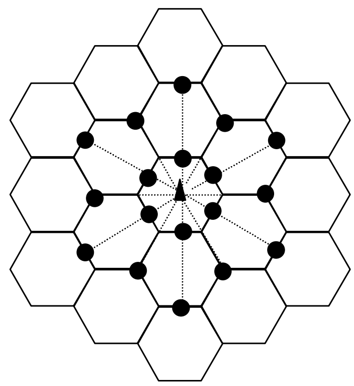

Fig.1 Uplink interference model in OCDMA system

Note: computing the SIR ratio for the center of interfering tiers, the value would be SIR = 1.33 (1.2 dB).

It is clear, that SIR ratio may be smaller than one. For the receiver to be able to demodulate the signal, SIR ratio must exceed one. The tool for doing this is a signal transformation to baseband, when receiver utilizes ***processing gain*** $\boldsymbol{G_s}$. Processing gain originates by spread spectrum signal processing

$$SIR_{out} = G_s \cdot SIR_{in} = \frac{B_{ss}}{R_b} SIR_{in} \tag{3}$$

where R_b is the data rate, B_{ss} is the spread spectrum bandwidth.

It is convenient to express SIR_{in} by E_b/I_0 , where E_b is the bit energy and I_0 is the interference power in 1 Hz. Because of the decorrelating process in receiver, the interference power is changed to noise, so it is often used to express the ratio E_b/N_0, where N_0 is the spectral noise density. So we can write the ratio SNR instead of SIR [4]

$$SNR_{in} = \frac{E_b\, R_b}{N_0\, B_{ss}} = \frac{E_b}{N_0} \cdot \frac{1}{G_s} \cdot \tag{4}$$

From this

$$\frac{E_b}{N_0} = SNR_{in} \cdot G_s = SNR_{out} \cdot \tag{5}$$

Note: In the next text we are going to use the notation E_b/N_0 and SIR (this is generally used in literature).

These equations are valid in FDMA/TDMA systems as well, but for $R_b \geq B$, the processing gain is $G_s \cong 1$.

Let's return to our orthogonal system, where the interference situation is simpler because of the intracell interference elimination. The ratio E_b/N_0 (model in the Fig. 1) with $G_s = 128$ (IS-95 standard: B_{ss} = 1.25 MHz, $R_b = 9.6$ kb/s) is

$$\frac{E_b}{N_0} = SIR \cdot G_s = 0.091 \cdot 128 = 11.65 \ (10.7\ \text{dB}) \cdot \tag{6}$$

This value is sufficient for ensuring the needed value BER < 10^{-3} (with convolutional coding, one–branch spatial diversity) because the needed value is $(E_b/N_0)_n$ = 7 dB [3].

2.2 PN-CDMA system

The main difference in comparison with the orthogonal CDMA system is the existence of the intracell interference, which origins as the consequence of cross-correlation among spreading codes of users who are placed in the same cell. Also, the character of the intercell interference is changed – all mobiles in surrounding cells represent interfering sources.

Non-orthogonal CDMA system uses the same set of spreading codes in every cell of the system, i.e., centers of closest interference areas are in distance of 1.73 r_c.

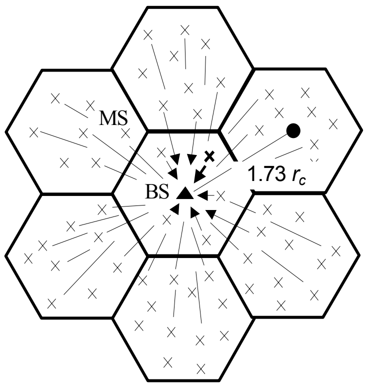

Fig.2 Uplink interference model in PN-CDMA system

It is obvious, that the interference model will be more complicated as it was in the orthogonal system. Let's suppose, that the transmission power of every mobile in central cell will be adapted, so that all signals received in base station have the same power.

If the received power from every user will be P_r, the whole interference power at the input of every user's receiver is [1]

$$I = (k_u - 1)\,P_r \tag{7}$$

where k_u is the number of active users in one cell. The level of received signal power can be expressed as $P_r = P_{MS} \,.\, r^{-\alpha}$. From this we can simply define SIR ratio at the receiver input in *isolated cell*

$$SIR = \frac{P_{MS}\, r^{-\alpha}}{(k_u - 1)\,P_{MS}\, r^{-\alpha}} = \frac{1}{k_u - 1}\,. \tag{8}$$

Let's suppose that demodulator for each user needs, to operate well, particular value of E_b/I_0 (typically 3 – 9 dB in dependence of modem, correcting code, fading, BER).

The interference power density at the input of each demodulator is

$$I_0 = \frac{I}{B_{ss}}\,. \tag{9}$$

Similarly, the received energy per bit is the received signal power divided by data rate R_b

$$E_b = \frac{P_r}{R_b}\,. \tag{10}$$

So

$$\frac{E_b}{I_0} = \frac{P_r/R_b}{I/B_{ss}} = \frac{P_r\, B_{ss}}{R_b\, I} = \frac{P_r\, B_{ss}}{R_b\,(k_u - 1)\,P_r}\,. \tag{11}$$

The number of simultaneous users to be able to exist in the isolated cell is related to the processing gain and the demodulator's E_b/I_0 requirement

$$k_u - 1 = \frac{B_{ss}/R_b}{E_b/I_0} \tag{12}$$

This equation for defining the cell capacity is valid only for the isolated cell and with the perfect power adaptation.

CDMA system can use some methods for diminish the interference (increasing capacity) [1]:

1. *Voice activity gain* (G_V) – voice is active only for about 3/8 of the time, so that G_V = 8/3 = 2.67 [3].
2. *Antenna gain factor* (G_A) – sectored antenna (e.g. 3 x 120^0) diminish interference power three times. If we take the loss from ideal gain to be 1 dB, $G_A \approx 2.4$.

So far, we have dealt only with the isolated cell. In a cellular system CDMA all users employ the whole allocated spectrum B_{ss}, so we must determine the level of intercell interference. In [1] it was found, that in the system with users uniformly distributed in all cells, with perfect power adaptation, the *total intercell interference I_{inter} equals approximately 3/5 of the intracell interference I_{intra} (I_{inter} = 0.6 I_{intra}).*

Using relative values and getting I_{intra} = 1, the individual cell capacity has to be reduced by coefficient $I_{inter} + I_{intra}$, i.e. I_{inter} + 1 = 1.6.

Introducing the voice, antenna gain factors, the relative intercell interference factor, we get the expression for the cellular CDMA system uplink capacity

$$K_u \approx \frac{B_{ss}/R_b}{E_b/I_0}\, G_V\, G_A\, \frac{1}{1 + I_{inter}} \tag{13}$$

Up to now we have supposed, that the perfect power adaptation is applied in cells, i.e., the received signals powers from all mobiles are the same at the base station receiver. Afterwards, the equation represents *the upper bound of cell capacity.*

Let's now suppose, that there is ***no power adaptation in uplink***. We can express the value of SIR by equation (2), which must be supplemented with the intracell interference and also we have to change the number and the distance of interfering tiers, because the interference source is represented by not one but all active mobiles

$$SIR = \frac{P_{MS}\, r_c^{-\alpha}}{\sum_{i=1}^{k_u-1} P_{MSi}\, r_i^{-\alpha} + \sum_{j=1}^{6}\sum_{i=1}^{k_{uj}^1} P_{MSi}\, r_{ji}^{-\alpha} + \sum_{j=1}^{12}\sum_{i=1}^{k_{uj}^2} P_{MSi}\, r_{ji}^{-\alpha}} \qquad (14)$$

where the 1st term in denominator represents the intracell interference with the number of active users k_u, in the distance r_i from the own base station, 2nd and 3rd term is the intercell interference from 1st and 2nd interfering tier with k_{uj}^{1}, k_{uj}^{2} active users. The distance r_{ji} is the distance to the mobile i placed in the interfering cell j.

The calculation of SIR ratio is more complicated in compare with the orthogonal system, because of the need to define the number of active users in each cell and to simulate their stochastic placement in the cell (parameters r_i, r_{ji}). It is obvious, that if the power of mobiles will not be adapted (all mobiles work with maximum relative power $P_{MS} = 1$), the intracell interference will be the main reason for decreasing SIR ratio. The equation is *the lower bound of cell capacity (without power adaptation).*

To make clearer the influence of power adaptation to the cell capacity let's compute the simple example. We have PN-CDMA system with parameters: $G_s = 128$, $I_{inter} = 0.6$, $\alpha = 4$, $(E_b/I_0)_n = 7$ dB. The relative value of maximum mobile power is $P_{MS} = 1$ and the relative cell radius is $r_c = 1$.

Perfect power adaptation – by modification of (8) for multicell system we have

$$SIR = \frac{1}{(k_u - 1) + 0{,}6(k_u - 1)} \qquad (15)$$

and from this

$$k_u = \frac{1}{1{,}6\, SIR_n} + 1 \cdot \qquad (16)$$

From $(E_b/I_0)_n$ we can define the needed value of $SIR_n = (E_b/I_0)_n \,.\, (1/G_s) = 0.039$. Substituting to (16) we can compute the maximum number of users who can communicate in the cell, i.e. $k_u = 17$.

Without power adaptation – we can simplified the equation (13) by supposing $I_{inter} = 0.6 I_{intra}$

$$SIR = \frac{P_{MS}\, r_c^{-\alpha}}{(k_u - 1) P_{MSi}\, r_i^{-\alpha} + 0{,}6(k_u - 1) P_{MSi}\, r_i^{-\alpha}} \qquad (17)$$

where the 1st and 2nd term are the intracell and intercell interference. Let's suppose that in the cell there are only two active users. To be as precise as it is possible for determining the SIR ratio it is necessary to use Monte Carlo simulation and compute the mean value of SIR. For simplicity we use the static model and suppose that the user is in the most inconvenient position (the cell border, $r_c = 1$) and the interfering source, on the contrary, is in the vicinity of base station (e.g. $r_i = 0.1$). So

$$SIR = \frac{1}{1 \cdot 0.1^{-4} + 0.6 \cdot 1 \cdot 0.1^{-4}} = 0.0000625 \quad (-42\,\text{dB}) \qquad (18)$$

It is obvious, that without power adaptation in uplink neither two active users can communicate in the cell, because of the very low SIR value.

3. Downlink Interference Model

In the downlink (the base station transmits and the mobile receives) there are these signals in the mobile's receiver input [6,7]:

- Desired signal (signal from serving base station of own cell).
- Interfering signals from own base station – transmission for other users (Intracell interference).
- Interfering signals from base stations in neighbor cells (Intercell interference).
- White (Gaussian) noise.

The main difference against the uplink interference model is, that because of the fix interfering sources location (base stations), the most inconvenient mobile location will be the border of its own cell. To be more exact, it is the connection point of three neighbor cells, where the mobile is in the same distance from its own base station as from two nearest interfering base stations (Fig.3).

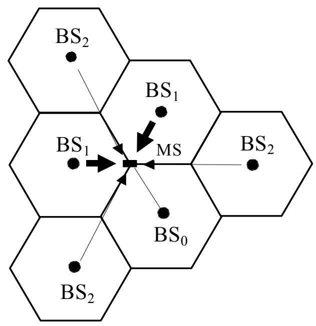

Fig.3 Downlink interference model in CDMA system

The Fig.3 represents non-orthogonal CDMA model, because the interfering sources are all base stations in the system.

In the downlink, the orthogonal system eliminates the intracell interference by orthogonal spreading codes, while the intercell interference either by known spreading code offset (IS-95) or by the cell scrambling code, which is superimposed on the orthogonal spreading code (UTRA).

For the sake of simplicity let's suppose, that the system is orthogonal from the point of view of intracell interference, but the same orthogonal codes set is used in neighbor cells. In this scenario, the intercell interference from the particular cell is represented by the single interfering source (the same spreading code, that the mobile uses).

The SIR ratio for this ***orthogonal system*** is

$$SIR = \frac{P_{BS}\, r_c^{-\alpha}}{\sum_{i=1}^{2} P_{BSi}\, r_{\mathrm{int}1}^{-\alpha} + \sum_{i=1}^{3} P_{BSi}\, r_{\mathrm{int}2}^{-\alpha}} = \frac{1}{2\cdot 1^{-4} + 3\cdot 2^{-4}} = 0.46 \quad (-3.4\ \mathrm{dB}) \tag{19}$$

We have supposed the influence of only two interfering tiers (BS_1 and BS_2). It is obvious, that because of a smaller number of interfering sources, the situation in downlink is more favorable as it was in uplink.

The ratio E_b/N_0 for G_s = 128 (IS-95: B_{ss} = 1.25 MHz, R_b = 9.6 kb/s [5]) is

$$\frac{E_b}{N_0} = SIR \cdot G_s = 0.46 \cdot 128 = 58.9 \ (17.7\ \mathrm{dB}) \cdot \tag{20}$$

This value is large enough to ensure the value of BER < 10^{-3} (convolutional coding, spatial diversity: $(E_b/N_0)_n$ = 5 dB [3]). The smaller value $(E_b/N_0)_n$ in comparison with uplink is due to the application of the pilot signal.

In the case of the ***non-orthogonal system*** we have to take into account intracell interference (signals from own base station intended for other mobiles in the cell) and intracell interference (signals from other base stations for served mobiles). The intercell interference is now, as it was in uplink, represented by the sum of interfering signals powers of all active connections in surrounding cells.

Let's again suppose, that system is working ***without power adaptation***. The SIR ratio is now

$$\mathrm{SIR} = \frac{P_{BS}\, r_c^{-\alpha}}{(k_d - 1) P_{BS}\, r_c^{-\alpha} + \sum_{j=1}^{6} k_j^1 P_{BS}\, r_j^{-\alpha} + \sum_{j=1}^{12} k_j^2 P_{BS}\, r_j^{-\alpha}} \tag{21}$$

where the 1st term represents the intracell interference (k_d is the number of active users in downlink), the 2nd and the 3rd terms are the intercell interference receiving from the 1st and the 2nd interfering tier. k_j^1, k_j^2 is the active users number of cell j, r_j is the interfering base stations distance.

Let's compute the similar example as we performed in the uplink direction (G_s = 128, α = 4, $(E_b/I_0)_n$ = 5 dB). In this model, when the base station power is not adapted (P_{BS} = 1), the position of mobiles is not determining (from the intracell interference point of view), because in the receiver input of the needed user is always SIR = $1/k_d$ (from the intracell interference). The intercell interference will be the highest at the point of three neighbor cells connection (Fig.3).

We use again only static interference model and the SIR ratio in the mobile station is

$$SIR = \frac{1\cdot 1^{-4}}{(k_d - 1)\cdot 1\cdot 1^{-4} + 2k_d \cdot 1\cdot 1^{-4} + 3k_d \cdot 1\cdot 2^{-4}} \tag{22}$$

and the cell capacity is expressed by

$$k_d = \frac{1}{3{,}2\, SIR_n} = 12 \cdot \tag{23}$$

From equation (22) we can see the considerably greater intercell interference influence (without power adaptation) as it was in the uplink (the 2nd term in the denominator represents the two closest cells interference influence) along with the greater cell capacity.

4. Conclusion

In this contribution we have tried to give the simplified view on interference models in CDMA systems uplink and downlink. We have divided CDMA systems into two groups (orthogonal and non-orthogonal) and developed simplified models for both of them. In orthogonal systems the situation is very similar to that in FDMA/TDMA systems except the smaller reuse factor (K = 1).

The interference situation becomes more complicated in non-orthogonal CDMA systems (PN-CDMA). By simple example we have shown that without mobile power adaptation (uplink) neither two active mobiles can operate in the cell.

From the two examples it is seen, that without power adaptation, the capacity in the downlink is greater than it is in the uplink direction. Because of the final capacity is determined by the minimum capacity reached in both directions, it is obvious, that the capacity maximization in the uplink is critical. The exact power adaptation is the main tool for reaching this goal.

References

[1] VITERBI, A. J. CDMA. Principles of Spread Spectrum Communication. New York: Addison-Wesley Publishing Company, 1996.

[2] PRASAD, R.: CDMA for Wireless Personal Communications. London: Artech House, 1996.

[3] GILHOUSEN, K. S., JACOBS, I. M., PADOVANI, R., VITERBI, A. J., WEAVER, L. A., WHEATLEY III, CH. E. On the Capacity of a Cellular CDMA System. IEEE Transactions on Vehicular Technology. 1991, vol. 40, no. 2, p. 303 - 312.

[4] LEE, W. C. Y. Overview of Cellular CDMA. IEEE Transactions on Vehicular Technology. 1991, vol. 40, no. 2, p. 291-302.

[5] WHIPPLE, D. P. North American Cellular CDMA. Hewlett Packard Journal. 1993, p. 90 - 97.

[6] GEJJI, R. R. Forward - Link - Power Control in CDMA Cellular Systems. IEEE Transactions on Vehicular Technology. 1992, vol. 41, no. 4, p. 532 - 536.

[7] WIESER, V. Analysis of System Methods for Minimization of Mutual Interference in Mobile Microcellular Systems DS-CDMA (in Slovak). Habilitation work. 1999, VA Liptovský Mikuláš.