

# State of Art on CDMA multiple-access interference mitigation technology

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## ABSTRACT

Code-division multiple access (CDMA) is an algorithm for multiple users to share the same channel simultaneously. As such it comes with several drawbacks, mainly multiple-access interference (MAI). MAI mainly manifests as four different problems: The near-far problem, where data from users further from the base station cannot be received and decoded correctly. The out-of-phase chips problem, where different data is being sent out of phase, making the data impossible to decode. Multipath channel distortion, on which echoes of the signal interfere with the channel negatively. And finally the doppler effect, which worsens data retrieval by users moving in space. The most effective way of mitigating MAI currently, is with Rake CDMA and PN codes, to mitigate out-of-phase chips, multipath channel distortion and a bit of the doppler effect. Space-time coded (STC) CDMA systems, in order to mitigate the near-far problem and line of sight (LOS) issues. Multiuser detectors (MUDS) for further mitigating the near-far problem as well as some problems that come with PN codes. And finally Power Control, in order to completely mitigate the near-far problem, as the near-far problem is the most destructive in CDMA.

## 1 INTRODUCTION

Code-division multiple access (CDMA) is an algorithm for multiple users to use the same channel simultaneously. The way it works is by assigning different orthogonal codes (chips) for each user in such a way that it allows them to represent a 1 or a 0. A 1 is then represented by the original assigned orthogonal code for that user, and 0 represented by its symmetric. CDMA was often used for 2G and 3G mobile networks, and is still used for GPS and military communication.

Because the codes are orthogonal, when they merge it's possible to recover each and every user's message from the joint waves. This is only possible, however, if the waves merge at the exact same phase on the receiver end. Furthermore if one wave from one transmitter/user has higher amplitude (is "louder") than the others, it drowns the others and makes them unrecoverable. This state-of-art report focuses on how modern CDMA and variants deal with these and some other multiple-access interference (MAI) problems.

## 2 MAI (MULTIPLE-ACCESS INTERFERENCE)

### 2.1 Near-Far problem

The near-far problem is the single most fundamental flaw of CDMA. Starting with an example, let's say we have 4 bit chips for each user as such:

- User 1: [+1, -1, +1, +1]
- User 2: [+1, +1, -1, -1]
- User 3: [-1, +1, +1, -1]

ideally, when the waves constructively and destructively interfere, the first bit of the chip will result in  $(1 + 1 - 1) = 1$ . However, due to different distancing, or even different powered RF transmitters, this results in different magnitudes of waves being

sent. What should be  $1 + 1 - 1$  might (anecdotally) actually result in  $2 + 0.1 - 5 = -2.9$  due to the distance and power at which the transmitters are broadcasting.

This destroys the orthogonality of the space, making it impossible to decode the original bits from chips for **every** user. This shows that for vector orthogonality to be achieved, it is mandatory to have uniform amplitudes for the waves. The price for the noncompliance of uniformity being the loss of orthogonality, and thus the loss of information.

## 2.2 Out-of-phase chips

This is the second most substantial problem in CDMA. Also potentially resulting in a complete loss of information. The problem relies in the way the waves constructively and destructively interfere. If the waves are interfering out of phase, this will result in loss of orthogonality. An example follows, analogous to the above.

- **User 1:**  $[+1, -1, +1, +1]$
- **User 2:**  $[+1, +1, -1, -1]$
- **User 3:**  $[-1, +1, +1, -1]$

Imagine that *User 3* either moved in space in relation to the receiving station, has a slight processing delay, or any other problem resulting in a 1-chip delay. Instead of the waves interfering as such:  $(1 + 1 - 1) = 2$ , they will interfere in the following way:  $(1 + 1 + 1) = 3$ . The same applies for all the following chips, resulting in loss of orthogonality, and therefore total loss of data. The same phenomena occurs for half-bit delays and potentially for even smaller delays. The same obviously also applies for greater chip phase shifts (delays).

## 2.3 Multipath channel distortion

Multipath distortion occurs when phase-shifted, lower amplitude replicas of the same wave reach the receiver. This is often the product of waves bouncing on surfaces and reaching the receiver as "echoes", often at later times (phase shifted) and with increasingly lower amplitudes.

As this is not random noise or interference and as such classifies as structured interference, it strongly impacts the decoding process. We are getting "phantom" versions of valid chips, interfering with the rest in such a way that it might cripple the decoding process. The more multipath channel distortion, the worse the decoding error becomes.

## 2.4 Doppler effect

As transmitters move in space, their transmitted waves are subject to the doppler effect, making them higher frequency in the direction of movement and lower frequency in the opposite direction. This creates a continuously changing phase shift, which creates a special case of the out-of-phase chips in which the phase keeps changing, making it seem as if the signal is "spinning" on the receiver end.

# 3 PROBLEM STATEMENTS

## 3.1 Downlink (synchronous CDMA)

The problem downlink, meaning that we want to send data from the central tower to the users is pretty straight forward, we want to broadcast information in the channel so that all users can decode their part of the information. Amplitude of the signal is dictated by the central station and therefore should be "audible" by all users in range. Furthermore there is no MAI to worry about, as long as the user is close enough to a central station in such a way that it's amplitude overpowers other potential stations using CSMA. In other words, this usually means that the distance from the user to one of the stations is lower than others, making MAI not a problem for user decoding.

## 3.2 Uplink (asynchronous CDMA)

The problem uplink, meaning that we want to send data from the users to the central tower is much more complicated than the downlink. It implies that all users, with different locations, different amplitude transmitters, different speeds and different distances from the central tower, need to communicate with the central tower.

This, of course, leads to an amount of MAI that makes the data completely incoherent and impossible to decode by the central station. This is the core limitation of CDMA, and where all the aspects of MAI really come into play in a very destructive way.

## 4 SOLUTIONS

### 4.1 CDMA Rake

The CDMA Rake solution was primarily designed to deal with the multipath channel distortion, but ends up mitigating a lot of the MAI problems. The way it manages this, is by first replacing the orthogonal codes, with quasi-orthogonal codes called PN codes.

#### 4.1.1 PN codes

Assume each user has a unique identification (i.e. A phone's electronic serial number (ESN)). Furthermore, assume the base station has already communicated with the user, and gotten it's unique identification. Upon this, usually based on both the current time and unique identification of the user, using a standard predefined algorithm, an identical seed is generated for the user and base station. Upon the base station and user having the same seed, both then generate a (usually)  $2^{42}$ -long pseudorandom noise (PN) code based on it. Since both have the same seed, and therefore the same PN code, now they're ready to begin CDMA communication.

This PN code is uniformly random, in such a way that the average of all values are 0 (if each bit is encoded between either -1 or 1). This both makes time synchronization easy and makes it that so other parallel PN codes that are being transmitted are equivalent to noise, no longer being structured interference. This way it's as if the chips vectors are orthogonal. The way bits are then encoded in this PN code is as follows: if the chipp sequence length is  $n$ , that means each data bit will be encoded into the chipp sequence

$$C_i = (C_{i \cdot n}, C_{i \cdot n + 1}, \dots, C_{(i+1) \cdot n - 1})$$

and a 0 data bit will be encoded to  $-C_i$ . The next data bit sent, will already be encoded into  $C_{i+1}$ , and so on and so forth.

#### 4.1.2 The Rake System

The rake consists of multiple parallel processing units (called "Fingers"), a controller, and a combiner. Each finger receives the signal and correlates it with phase-shifted versions of the user's PN code (the possible "echoes"). The controller takes all of these signals and searches through all possible delays of the channel, called the "delay spread" of the channel, in order to identify peaks in the correlation profile, finding each echo. The combiner takes these echoes, phase-shifts them such that they all coincide, and they are all summed, acting as gain, amplifying the amplitude of the received signal. Each echo is assigned a different weight proportional to it's amplitude and correlation profile (how probable is it to be an actual echo of the same signal) such that the sum is actually a weighted sum of these signals/echoes.

#### 4.1.3 MAI mitigation

The more fingers, the better the rake system becomes, but it also increases power consumption. In this way, the Rake receiver turns a known weakness into a strength, exploiting the signal replicas and turning them into gain. As such, it severely mitigates multipath channel distortion making it into a non-problem.

Not only that, but the use of PN codes mitigates the out-of-phase chips, as the chips from other senders will cancel out into noise, making each chip orthogonal with the background noise. This gets mitigated to such a degree that out-of-phase chips also stop being a problem. Furthermore, as it tracks out of phase and lower amplitude replicas, it can also diminish the doppler effect in the received signal.

### 4.2 Space-time coded (STC) CDMA systems

The main idea behind space-time coding (STC) is to use multiple antennas to transmit. This introduces structured redundancy in both space and time. In such a way that we get signal gain by listening to all the antennas, or we can still decode messages when other antennas are obstructed.

The way this works is by having each antenna broadcast the same information but at different times with order information. In

	Antenna 1	Antenna 2
$t = 0$	$c_0$	$c_1$
$t = 1$	$c_1$	$-c_0$

**Table 1.** Individual antenna transmission at time  $t$ .

Table 1 is an example of how this can be done for two antennas, for the encoding in chips of the first bit,  $c_1$ , and the encoding of the second bit sent,  $c_2$  (using PN codes).

This way, when the receiver obtains these signals, assuming it knows this configuration beforehand, it can most of the times decode the full message as long as one of the antennas is available at a given time, even if it's a different antenna. The receiver can decode each bit by knowing the sending pattern of each antenna (and knowing which antenna is receiving from). If it were to receive from the second antenna at the second time slot, it would know that it's receiving the first bit. The reason for it's negation is to make this sending space orthogonal. This is how we know which antenna is transmitting.

If each user has a multi-antenna system, STC CDMA is perfect to neutralize the near-far problem, however this comes at a great power cost, which might not be ideal for low power devices. Modern telephones do have multi-antenna systems, being capable of using this system.

### 4.3 Multiuser detectors (MUD)

Multiuser detectors (MUDs) are ways of receiving data through CDMA more reliable, mitigating the near-far problem as long as further mitigating the problem that comes with quasi-orthogonal codes (PN codes).

The way MUDs work is by listening to every single signal instead of taking other signals as interference. This is usually done by using a maximum likelihood detector. This detector tests all possible combinations of data bits from all users and chooses the set that is statistically more likely, given the entire received signal. This provides the **best possible performance** with the minimum error. This algorithm is, however, extremely inefficient ( $O(2^k)$ ), when  $k$  is the number of users transmitting simultaneously.

Upon decoding all the data from every other user, the current user can subtract the all the other data (with included amplitudes) from the main signal, in order to get the highest quality version of the data it's receiving.

### 4.4 Common downlink solution

For downlink, the solution is pretty straight forward. It's also known as synchronous CDMA. We can use common welsh codes (welsh codes provide orthogonal binary strings). Without having to rely on quasi-orthogonal PN codes since all the data is broadcast at once, thus not having out-of-phase chip problems.

Furthermore, since there's only one sender, there is no MAI by definition (multiple access interference). STC CDMA can also be used as long as the station has multiple antennas, in order for the users to receive higher fidelity data.

### 4.5 Common uplink solution

For uplink, a combination of Rake systems on the central station with PN codes, users with STC CDMA systems whenever possible, and both users and (especially) stations employing MUDS is critical.

For further near-far mitigation, a technique called Power Control is employed. The way it works is for the station to tell each user to transmit quieter (lower the amplitude) or louder (increase the amplitude). If the base level is 30db, and a transmitter is transmitting at 37db, the station tells the user to lower the power by 7db, thus employing Power Control. This makes users closer to the tower have to transmit at lower amplitudes, and users far from the tower transmit at higher amplitudes. As the users know the distance between them and the tower, they can calculate what would equate to a  $n$ -db decrease.

## 5 CONCLUSIONS

The worst problems in CDMA are the near-far problem and the out-of-phase chips problem. The out-of-phase chips problem can mostly be mitigated by PN codes, of which their new quasi-orthogonal problem can also be mitigated by MUDS. The near-far problem, can be mitigated most reliably by Power Control, but also by MUDs and a bit by STC CDMA and the Rake system.

Multipath channel distortion, which is a real issue, although a lesser one, can be almost completely mitigated by the Rake system alone, and turned into further gain, mitigating the near-far problem as stated previously.

For downlink transmission, there is essentially no transmission issues, as all that is required is to send all data in orthogonal welsch codes through chip vectors. However, for uplink transmission, a mixture of all the systems and algorithms must be used in order to achieve efficient communication.

## REFERENCES

- S.E. Bensley and B. Aazhang. Maximum-likelihood synchronization of a single user for code-division multiple-access communication systems. *IEEE Transactions on Communications*, 46(3):392–399, March 1998. ISSN 0090-6778. doi: 10.1109/26.662645. URL <http://dx.doi.org/10.1109/26.662645>.
- R. Corvaja and S. Pupolin. Multi-user performance of cdma in the presence of phase noise. In *IEEE GLOBECOM 1998 (Cat. NO. 98CH36250)*, volume 6 of *GLOCOM-98*, page 3314–3319. IEEE. doi: 10.1109/glocom.1998.775819. URL <http://dx.doi.org/10.1109/GLOCOM.1998.775819>.
- L. Ros E. Simon and K. Raoof. Synchronization over rapidly time-varying multipath channel for cdma downlink rake receivers in time-division mode. *IEEE Transactions on Vehicular Technology*, 56(4):2216–2225, 2007. doi: <https://doi.org/10.1109/tvt.2007.897664>.
- Mangala R. Gajbhiye and J. K. Satapathy. Performance comparison of adaptive mmse-mrc mud for ds-cdma system in different multipath channels. In *Proceedings of the 2011 International Conference on Communication, Computing and Security - ICCCS '11*, ICCCS '11, page 56. ACM Press, 2011. doi: 10.1145/1947940.1947953. URL <http://dx.doi.org/10.1145/1947940.1947953>.
- R.A. Iltis. A digital receiver for demodulation of cdma waveforms with a-priori unknown delays and amplitudes. In *MILCOM 91 - Conference record*, page 113–116. IEEE. doi: 10.1109/milcom.1991.258215. URL <http://dx.doi.org/10.1109/MILCOM.1991.258215>.
- Zhongding Lei and Teng Joon Lim. Estimation of directions of arrival of multipath signals in cdma systems. *IEEE Transactions on Communications*, 48(6):1022–1028, 2000. doi: <https://doi.org/10.1109/26.848564>.
- H. Li. Differential and coherent decorrelating multiuser receivers for space-time coded cdma systems. In *Sensor Array and Multichannel Signal Processing Workshop Proceedings, 2002*, page 575–579. IEEE, 2002. doi: 10.1109/sam.2002.1191106. URL <http://dx.doi.org/10.1109/SAM.2002.1191106>.
- E.S. Lohan, R. Hamila, A. Lakhzouri, and M. Renfors. Highly efficient techniques for mitigating the effects of multipath propagation in ds-cdma delay estimation. *IEEE Transactions on Wireless Communications*, 4(1):149–162, January 2005. ISSN 1536-1276. doi: 10.1109/twc.2004.840231. URL <http://dx.doi.org/10.1109/TWC.2004.840231>.
- Richard S. Orr. Code phase and delay settings that minimize cdma interference. In *2009 IEEE Aerospace conference*, page 1–12. IEEE, March 2009. doi: 10.1109/aero.2009.4839397. URL <http://dx.doi.org/10.1109/AERO.2009.4839397>.
- R.D.J. van Nee. Timing aspects of synchronous cdma. In *5th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Wireless Networks - Catching the Mobile Future.*, WNCMF-94, page 439–443. IOS Press. doi: 10.1109/wncmf.1994.529127. URL <http://dx.doi.org/10.1109/WNCMF.1994.529127>.
- Wei Yang and Zhenhui Tan. Joint doa estimation and phase calibration for synchronous cdma with decorrelator. In *IEEE International Symposium on Phased Array Systems and Technology, 2003.*, page 452–457. IEEE. doi: 10.1109/past.2003.1257024. URL <http://dx.doi.org/10.1109/PAST.2003.1257024>.
- Wang Zhaocheng, Yao Yan, Yang Zhixing, and Mao Shaodong. Multiuser synchronization in noncoherent asynchronous cdma. In *Proceedings of Vehicular Technology Conference - VTC*, volume 1 of *VETEC-96*, page 593–595. IEEE. doi: 10.1109/vetec.1996.503517. URL <http://dx.doi.org/10.1109/VETEC.1996.503517>.