CDMA TRANSMITTER FILTERING FOR CELLULAR OVERLAY SYSTEMS

Bradley J. Rainbolt and Scott L. Miller
Wireless Communication Laboratory, NEB 403
P.O. Box 116130
University of Florida, Gainesville, FL 32611
bjrain@eel.ufl.edu miller@dino.ee.ufl.edu

ABSTRACT

The overlay of a CDMA system in a frequency band which is already servicing narrowband users has the potential for significant gains in user capacity [1]. For the single-cell case, it was shown in [2] that interference caused to the narrowband system by CDMA users is significant, even when the CDMA system is very lightly-loaded. The use of notch filtering at the CDMA transmitter to avoid active narrowband users was shown to greatly alleviate the effects of the CDMA interference on the narrowband system. It was also demonstrated that the MMSE receiver can perform well in receiving these filtered CDMA signals. In this paper, overlay will be applied to the cellular case, in which the narrowband users in each cell only utilize a fraction of the system bandwidth even when the system is fully loaded. As in the single-cell case, it will be seen that overlay causes significant degradation to the narrowband system, which can again be alleviated greatly through the use of transmitter notch-filtering. It will be demonstrated that overlay is very promising for cellular systems.

I. INTRODUCTION

The idea of code-division multiple-access (CDMA) overlay, that is the implementation of a CDMA system in a frequency band which already supports a narrowband system, has been investigated as a means of improving user capacity [1]. A single direct-sequence spread spectrum signal which is spread with a large enough processing gain causes a negligible amount of interference over the bandwidth of interest for a narrowband user. However, as more CDMA users are added to the system, the collective interference will eventually degrade the performance of the narrowband user. Because CDMA overlay would most likely involve a pre-existing narrowband system, careful attention must be given to insuring that the narrowband users suffer a minimal amount of performance loss.

The cellular concept seems quite conducive to CDMA overlay, which is feasible only when the existing narrowband system is sparsely-populated. The total system bandwidth of the narrowband system is divided into several frequency groups, each consisting of a number of narrowband channels separated in frequency so as to minimize adjacent-channel interference. The groups are assigned to the cells in an intelligent manner which minimizes the co-channel interference, that is interference caused by users in different cells using the same channel. Thus even when fully-loaded, each cell only utilizes a small fraction of the total system bandwidth, as would be necessary for overlay. A CDMA system could be implemented using the same cellular layout and infrastructure, with the CDMA users in each cell spread in frequency over the whole system bandwidth. A cellular overlay system would be quite beneficial in a situation in which a narrowband cellular system is to be phased out in favor of a CDMA cellular system [3]. With overlay, the transition could be gradual, as a new CDMA product could be introduced, yet the system would still be able to support the existing narrowband products to which it must remain committed contractually.

This paper will look at the realization of overlay in the cellular case. The effects of overlay on the narrowband system will be looked at in Section II. It will be seen that there is a substantial amount of degradation caused to the narrowband system, a problem which can be greatly alleviated by employing notch filtering in the CDMA transmitters to avoid narrowband users. System simulations in Section III will then look at the corresponding effects of that notching on the performance of the CDMA system, and it will be seen that they are manageable. Conclusions will be made in Section IV.

II. NARROWBAND PERFORMANCE

In this section, the effects of overlay on a narrowband system will be investigated. It is important that the overlay not cause too much degradation to the narrowband system, which is likely to be in existence prior to the overlay.

The performance of a single BPSK user operating in an additive white Gaussian noise (AWGN) channel was examined in [2] for the single-cell case, and it was found that even a lightly-loaded CDMA overlay significantly degrades the performance of the BPSK user. These results

1. This work was supported by NSF under grant NCR-9628642.
were extended to the cellular case in [4] and the main points of that work will be summarized in this paper.

In [1], a criterion for determining whether overlay is tolerable to the narrowband system states that if the narrowband user’s probability of bit error is increased from $10^{-6}$ to greater than $10^{-5}$ as a result only of the overlay, i.e. while its signal-to-noise-ratio (SNR) remains constant, then the overlay is excessive. This criterion was employed in conjunction with a convolutional code of rate $r = 2/3$ and a constraint length $m = 9$, and can be summarized in the inequality below, which must hold in order that the overlay not be considered excessive [4]:

$$\frac{1}{N} \sum_{k=1}^{K} \left( \frac{P_k}{P_b} \right) \cos^2(\theta_k) V_k < 0.09$$

where $N$ is the processing gain of the CDMA system, $K$ is the number of CDMA users, $P_k$ and $P_b$ are the $k$th CDMA user’s and the BPSK user’s average power, $\theta_k$ is the $k$th CDMA user’s phase which is uniform on $(0, 2\pi)$, and $V_k$ is a unit-mean exponential random variable.

The CDMA capacity was investigated in the cellular case by first fixing the number of users $K$, and then generating a realization of $(P_k/P_b, \theta_k)$ and $V_k$ for a given trial. Then for a large number of trials, the probability that the condition of equation (1) is satisfied was found. The CDMA capacity was then defined as the maximum number of CDMA users for which equation (1) holds for all but 2% of the trials.

The users, both CDMA and narrowband, were power-controlled such that they would arrive at their assigned base station, which may or may not be the one in the center cell of interest, at a specified power level. It is important to note that it was assumed that a user of either type would arrive at its own base station at the same power level. The users were affected by log-normal shadowing with a standard deviation of $\sigma = 8$ dB, and the path-loss exponent was $n = 3$. The probability density function (pdf) of the $(P_k/P_b)$ ratio that was used is given by [4]

$$f_p(p) = \frac{\delta(p)}{19} + \frac{\exp\left(-\frac{(p+23)^2}{2(128)}\right)}{\sqrt{2\pi(128)}}u(-p)$$

(2)

This distribution characterizes the received power at the center cell of interest in a cellular system for which users are spread uniformly over that cell and two outer layers of cells, amounting to 19 total cells. It should be noted that this is not actually a valid pdf, as it integrates to 1.032, but it is a good approximation to the true pdf and is simple to generate. More details may be found in [4].

It was found that for a processing gain of $N = 32$ chips/bit, it was possible to support only 14 CDMA users spread over the 19 cells, or 0.75 users/cell, which is extremely low. The CDMA capacity here, based solely on the effects of the overlay on the narrowband system, is not related to the more conventional definition of CDMA capacity, which is the number of users for which the multi-access interference (MAI) becomes too severe for the CDMA system itself. A comparison of these two limits will be made in Section III.

A similar conclusion, that only a very light amount of CDMA loading can be tolerated by the narrowband system, was observed in [2] for the single-cell case. One possible way to deal with this problem is to increase the narrowband users' transmitted powers. However, we have approached the overlay problem with the perspective that the narrowband system should require as little change as possible. Such an increase in transmitted power would reduce the battery life of the narrowband mobiles, and that would certainly not be in keeping with the stated goal.

Another possible solution, which would be more accommodating to the existing narrowband system, is that the CDMA users could place notches in their signals in order to avoid interfering with active narrowband users. It was shown in [2] that with CDMA transmitter notching, the loading tolerable to the narrowband system can be increased substantially, likely to a point above which the CDMA system itself is able to operate.

The previous result on the CDMA capacity, found using equation (1), will again be found when the CDMA users employ the DFT-based filtering method described in [2]. It was seen in that work that the interference contribution from a CDMA user to the narrowband system was reduced by about 40 dB when this type of filtering is used.

In the cellular case, the use of notching is more involved than in the single-cell case, where the CDMA signals were notched to avoid all of the narrowband users present. It is quite possible in a cellular system that in addition to those narrowband users located near to it physically, a CDMA mobile may have to avoid a narrowband user that is assigned to an adjacent cell or even to a cell that is two layers away. But it obviously cannot notch for all of the narrowband users in the system, as that would likely constitute the entire system bandwidth, nor does it need to. As a result of the shadowing, there will be in some cases narrowband users near to the CDMA mobile that are not significantly degraded by the CDMA signal, and hence a notch is not necessary for them. This also holds for a significant percentage of the users that are not near to the CDMA mobile, due both to shadowing and propagation loss.
The total CDMA interference seen by a narrowband user depends on the CDMA signals' received powers, phases, and on the $V_k$ variables. When deciding whether or not a notch is necessary, the power can be estimated and the information exchanged between base stations, but the phases and the $V_k$ obviously will be unknown. Hence a specific criterion that will be used is that a CDMA signal must be notched if the narrowband-to-CDMA power ratio at the narrowband receiver is less than a given threshold $T$.

The CDMA capacity results are shown in Figure 1 for $T = 7, 9, 11$ dB. In contrast to the 0.75 CDMA users/cell that was achievable in the unfiltered case, it is possible that with $T = 9$ dB, 19 users/cell can be tolerated by the narrowband system when filtering is employed, a tremendous increase in capacity. As the threshold is raised to $T = 11$ dB, and hence a CDMA user is more likely to need a notch, the amount of CDMA loading that can be tolerated by the narrowband system increases substantially to 29 users/cell, a level at which the CDMA system itself probably cannot function. And if it is reduced to $T = 7$ dB, the possible loading drops to 13 users/cell. In the next section, the capacity limit will be looked at based on how much notching the CDMA system can handle.

It is also important to look at how much notching must be done. Omitting the details, which may be found in [4], we present in Figure 2 a plot showing the probability that a CDMA user at a distance $d$ from its closest base station (not necessarily the one to which it is assigned) must notch for a narrowband user that is assigned with equal probability to any of the base stations within the previously described 19-cell area. Thus an upper bound on the number of notches required in the CDMA signal would be a binomial random variable dependent on the total number of narrowband users assigned to the base stations in the 19-cell area and on the notch probability. It is an upper bound because it is possible that two of the narrowband users for which the CDMA user must notch would perhaps themselves be located several cells apart and would occupy the same channel.

**III. CDMA PERFORMANCE**

In the previous section, it was shown that a tremendous advantage is afforded to the narrowband system when the CDMA users notch their signals so as to avoid narrowband users. The corresponding effect that the notching has on the CDMA system will be looked at in this section.

A cellular overlay system with a frequency reuse of 1/7 was simulated for an AWGN channel. The CDMA system had a processing gain of 32 chips/bit, an $E_b/N_0$ value of 10 dB, and used the DFT-based filtering method with 8 bits of zero-padding when filtering was necessary. The narrowband users' and CDMA users' data rates were set equal, meaning that there could be 32 narrowband users in the equivalent bandwidth of the CDMA system. For a system with a frequency reuse of 1/7, each cell would have at most 4-5 narrowband users.

The CDMA users employed the minimum mean-squared error (MMSE) receiver [5]-[8], and were assumed to have converged to the ideal Wiener solution at steady state. The system capacity in CDMA users/cell was determined to be the maximum density for which the following blocking criterion was satisfied:

$$Pr((P_{e,CDMA} > 0.05) \cup (# \text{ notches} > 10)) < 0.02 \quad (3)$$

In this criterion, a CDMA user will be blocked if its bit error rate is too high, or if it needs more than 10 notches. As the sampling rate of the system is $1/T_c$, the range in which notching can be done is actually $-0.5/T_c < f < 0.5/T_c$. Any frequency locations outside of this range must be notched in the appropriate location mirrored around $\pm 0.5/T_c$. Thus with a processing gain of 32, there are effectively only 16 notching locations. With more than 60% of the CDMA signal notched out, the user must be dropped.

A two-dimensional capacity plot is shown in Figure 3 for notching thresholds of $T = 7, 9, 11$ dB. The notching threshold may affect the capacity criterion of equation (3) in two ways. First, as more notching becomes necessary, it is more likely that the desired user will have more than 10 notches and will be dropped. Also, it should be more difficult to demodulate the desired user's signal as more notches are added, and hence the probability of error should be higher on average.

Notice that when the narrowband system is lightly-loaded, there is little difference in the amount of CDMA loading possible for each threshold. It was observed that when the loading was at most 1.5 narrowband users/cell, no drops occurred as a result of excessive notching, i.e. more than 10 notches. However, there would be more notching when the threshold is higher, and the fact that the threshold had little effect at these loading levels suggests that the notching has a minimal effect on the bit error rate.

As the narrowband loading increases beyond 1.5 users/cell, the effects of having users dropped due to excessive notching begins to show. Notice that the CDMA system is constrained by the fact that for a high enough narrowband loading, the probability that a CDMA user requires more than 10 notches, and is therefore dropped, is greater than 2%, and the criterion of equation (3) cannot be satisfied for any amount of CDMA loading. From Figure 3, this occurs at 3.5, 2.8, and 2.3 narrowband users/cell respectively for $T = 7, 9, 11$ dB.
The results of Figure 3 characterize the capacity limits of the overlay system as dictated by the CDMA system. In conjunction with the limits resulting from considerations of the narrowband system as shown in Figure 1, it is clear that the notching threshold $T = 9$ dB is the best choice, as its limits according to each of the two systems are relatively close. From Figure 1, about 19 CDMA users/cell can be tolerated by the narrowband system, and from Figure 3, if the narrowband system is about half-loaded with 2 users/cell, then the CDMA system itself can support about 15 users/cell. This is a significant capacity improvement which would be very useful as mentioned previously in the transition from a narrowband cellular system to a CDMA cellular system.

It would also be of interest to investigate separately the effects of notching and the effects of narrowband noise on the CDMA system. This was done by fixing the number of narrowband users assigned to the desired user's cell at 0, 1, 2, 3, or 4, while the number of notches in the desired user was varied, and the CDMA density was found according to only the bit error rate part of the criterion of equation (3). The narrowband-to-CDMA near-far ratio was fixed at 20 dB, which is relatively high. The results are shown in Figure 4.

In going downward from curve to curve, it is seen that the effect of an additional narrowband user is to decrease the CDMA capacity by about 4 users/cell, which is significant. However, for a fixed number of narrowband users, the performance does not degrade significantly as the number of notches in the desired user's signal increases, even up to the point where there are 8 notches, or 25% of the CDMA signal is notched. This again corroborates the previous finding that the presence of narrowband noise is more detrimental to the CDMA performance than is the notching.

IV. CONCLUSION

In this paper, we have looked at applying CDMA overlay to the cellular case, as narrowband cellular systems by design only use a fraction of the system bandwidth in each cell. The CDMA overlay, if not very lightly-loaded, was shown to have an adverse effect on the existing narrowband system. The use of notch-filtering at the CDMA transmitters to avoid active narrowband users can greatly increase the amount of loading that the narrowband system can tolerate. Simulations showed that while the CDMA signals may at times require a large amount of notching to avoid narrowband users located throughout the cellular coverage region, the performance degradation is not severe. It was observed that the CDMA system is much more sensitive to the presence of strong narrowband interference than it is to notching. The results indicate that CDMA overlay is very promising for cellular systems, particularly as a means of transition from a system which exclusively supports narrowband service to one which supports CDMA service but can still meet previous commitments to narrowband subscribers.

REFERENCES


Figure 1: Maximum CDMA loading tolerable to NB system. Processing gain is 32 chips/bit. CDMA user notched if NB-to-CDMA power ratio is less than the notching threshold.

Figure 2: Notching probability as a function of a CDMA user’s distance $d$ to its closest base station. Notching thresholds are $T = 7, 9, 11$ dB.

Figure 3: Capacity plot for processing gain of 32 chips/bit, and for $E_b/N_0$ of 10 dB for the CDMA system. Notching thresholds are $T = 7, 9, 11$ dB.

Figure 4: CDMA users/cell vs. number of notches in desired user. Processing gain is 32 chips/bit. $E_b/N_0$ of CDMA system is 10 dB. NB-to-CDMA near-far ratio is 20 dB.