TWO DIFFERENT PHILOSOPHIES IN CDMA - A COMPARISON

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ABSTRACT

There has been considerable interest recently in the subject of multiuser interference cancellation techniques for CDMA wireless systems. It is widely believed that a system design using interference cancellation techniques has considerably better capacity than the design methodology adopted in the IS-95 CDMA cellular standard [2], which does not use such techniques. In this paper, we examine this issue, and in particular focus on linear interference cancellation techniques. Linear techniques [3, 4] are simpler and require fewer assumptions, such as accurate knowledge of amplitude and phase information of the users to be canceled, than nonlinear interference cancellers. However, linear interference cancellation techniques require a fundamentally different CDMA system design philosophy than IS-95. In IS-95, the coding gain from error control codes bears the burden of handling interference, while a linear canceller uses dimensional separation of users. This paper compares and contrasts the two design philosophies. Our comparison is based on overall user capacity (defined as the number of users per Hz per unit area) as well as robustness and fairness. The focus of the paper will be the mobile-user to base station reverse link which is modeled by the classical many-to-one multiple-access problem.

1. INTRODUCTION

Interference cancellation techniques for CDMA wireless systems is a topic of intense research. One major motivation to study them is to attain further improvements in capacity (defined as the number of users/Hz/cell) of cellular CDMA. These techniques in CDMA can be classified into two basic categories. The first class of techniques is nonlinear in nature, and they use the principle of decision feedback. There are several variants of this principle [7, 8, 9], depending on the number of iterative stages of decision feedback, whether hard or soft decisions are made, whether error control coding is used etc. Broadly speaking, in such a receiver, in order to demodulate a user, a tentative decision is made of the bits of interferers to this user. These interferers are then subtracted out. It is possible to implement this in an iterative or multistage fashion [8, 9].

In a coded system, it is not desirable to make decisions at the code symbol level because the symbol SNR is too low, both due to the coding gain of the code and because the symbol energy is a fraction of the bit energy. Hence it is necessary to employ the technique of *successive decoding*. In [7] a design approach is presented in which the users employ very low rate orthogonal convolutional codes and are allocated powers in a geometric progression. The strongest user is decoded first and then re-encoded, remodulated and subtracted out from the received signal. Demodulation and decoding proceeds to the next stronger user. It is shown that this method can asymptotically achieve the Shannon capacity of the band-limited AWGN channel.

In either case, the use of decision feedback techniques requires accurate knowledge (or estimates) of amplitudes, phases and delays of all the users and hence is suitable mainly in AWGN channels without impairments such as fading, multipath, shadowing, frequency and phase variations etc. Cellular channels suffer from all of these degradations and hence nonlinear interference cancellers are not practical in such channels. Indeed, most of the literature on interference cancellation addresses only AWGN channels. The IS-95 CDMA system has been specifically designed to be robust to these impairments. It is possible to use decision feedback based interference cancellation along with the IS-95 system, but for the aforementioned reasons, performance is likely to be good only in AWGN channels. Hence in this paper we focus on the second class of interference cancellers based on linear techniques. There have been some major advances in such receivers [3, 4, 6]. They are simpler to implement, can be made adaptive, and require fewer assumptions about the channel. However, these techniques are not applicable to the IS-95 system, and a fundamentally different system design is required. In the sequel, we compare and contrast the

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two designs.

2. R-CDMA AND D-CDMA DESIGN PHILOSOPHIES

In IS-95, each user is encoded and modulated, and spread with a very long pseudo-random (PN) sequence lasting trillions of users' bits. In [1] we called such a design R-CDMA (which stands for (pseudo) Random CDMA). This approach is intrinsically unsuitable for linear interference cancellers, which require that each user occupy a unique dimension (or switch among a small number of dimensions) in signal space. In [1] we termed this second approach of assigning a unique dimension to each user as D-CDMA (which stands for Deterministic CDMA, and as explained subsequently it could also stand for dimension-limited CDMA). Hence D-CDMA uses PN sequences that have a period of one bit or code symbol of a user. The sequences assigned to different users are designed to have low cross-correlations.

The difference is not merely in the period of the PN sequences employed. Multi-access interference is treated differently in the two approaches. R-CDMA is fundamentally a minimax approach to system design. It is well known from information theory that when the variance of an additive interferer is constrained, the worst case additive interference to any user is white Gaussian noise [5]. Hence a robust design methodology is to make multi-user interference look like AWGN through careful system design. This is accomplished by assigning users extremely long pseudo-random spreading sequences. Powerful error control coding techniques are used to mitigate this multi-access noise. The coding gain of the error control code translates directly into higher capacity for the system and hence one would want to maximize the coding gain subject to constraints of complexity and delay. In practice, coding gains of the order of 3-6 dB are obtained for the AWGN channel; even greater gains are achieved for fading channels, when appropriate interleavers are employed. Since each user is a white noise source from the perspective of other users, it is important that the transmit power of the users be controlled. Such a power control mechanism also has the benefit of having each user transmit the minimum power necessary to meet the quality of service objectives.

The error control codes employed in R-CDMA are typically low rate (1/2 or 1/3) codes. In order to avoid having to track the phase in a rapid fading environment, noncoherent or partially coherent demodulation techniques are employed. For example, in the IS-95 reverse link, in addition to the rate 1/3 convolutional code, there is 64-ary orthogonal modulation, also acting as a block code, which is suitable for noncoherent demodulation. The result is a system that is very robust in a fading channel, rather than being optimized for the idealized AWGN channel. While decision feedback based interference cancellation is possible in R-CDMA, wide fluctuations in amplitude and phase over short intervals of time render such techniques impractical. The low rate codes employed make it challenging to use these techniques even in the benign AWGN channel, due to the very low SNR prevalent at the code symbol level. Linear interference cancellation is all but impossible in R-CDMA, because of the extremely long PN sequences employed.

In contrast to the minimax approach above, D-CDMA assigns a unique dimension in the signal space to each user, much like FDMA or TDMA. The signature sequences of the different users are weakly correlated, and multi-user receivers are employed to combat the mutual interference among the users. While our focus will be on linear cancellers, many of the points we make are applicable to both linear and nonlinear cancellers in the D-CDMA system model. In linear cancellation schemes, the dimensional separation of users is exploited in order to reduce the interference, unlike in R-CDMA where the coding gain of the error control code makes the system interference tolerant. Redundancy due to error control codes reduces the effective dimensionality available for user-separation though it also reduces the signal to interference ratio (SIR) necessary to achieve a given bit error rate. The reduced SNR available at the symbol level due to error control coding conflicts with the SNR requirements for speed of adaptation of linear interference cancellers. Most of the literature on D-CDMA does not address the issue of error control coding, and since the assumption of an uncoded system is favorable from the view point of an adaptive receiver, we will make the same assumption for D-CDMA.

3. COMPARISON

In an R-CDMA system, the capacity is limited by the total power of the interference. The number of interferers is irrelevant, as is the actual received power of each interferer. This robustness to the detailed configuration of interferers means that we can exploit the burstiness of the users (due to varying levels of voice activity) as well as the attenuation of signals with distance, in order to provide higher capacity. Thus the operation of the law of large numbers ensures that the system can be designed for *average* interference characteristics, rather than the worst case. Voice activity is exploited relying on the fact that not all of the users are simultaneously active. Same frequency is reused in all the cells, relying on the fact that on average, users in one cell arrive attenuated at another cell. Similarly, sectored-antenna or beam-forming techniques that spatially separate different users' are directly beneficial in capacity, to the extent that they reduce the interference levels. Universal frequency reuse also makes possible the technique of soft hand-off, which has considerable capacity and coverage benefits as well. These triple benefits of voice activity, universal frequency reuse and sectorization are the key to the superior capacity of IS-95. Such benefits are very hard if not impossible to achieve in TDMA, FDMA or as we will explain shortly, D-CDMA. In the interest of space, we refer the reader to [10, 11, 1], for detailed capacity estimates for an R-CDMA system based on IS-95. As a quick summary, the system can accommodate about 85 voice users (average rate of 4 kbits/sec and a peak rate of 9.6 kbits/sec) per cell per 1.25 MHz of bandwidth, for a *fully-loaded, multicell* system. This number has been verified through numerous field trials and takes into account impairments such as fading, multipath and shadowing as well as imperfections in power control.

In D-CDMA, since linear multiuser receivers require that the waveforms assigned to the users be linearly independent, the number of users is constrained to be less than or equal to the number of dimensions, which is determined by the total bandwidth, the per-user bit rate, the error control coding redundancy and the number of bits per modulation symbol of each user. This last parameter can in principle be arbitrarily high by using multi-level modulation [4]. But problems such as amplifier nonlinearities and fading channels limit the number of levels in the modulation scheme in cellular systems. In practice BPSK or QPSK is almost always employed. The dimensional limitation on the capacity of D-CDMA, which is similar to FDMA or TDMA was the basis of the capacity estimates made in [1]. Hence the single cell capacity of D-CDMA in an AWGN channel is not greater than that of FDMA or TDMA.

In practice, the number of users has to be much less than the number of dimensions, especially in an asynchronous system. Unlike in R-CDMA, where multipath energies if harnessed effectively result in negligible capacity degradation, in D-CDMA interference cancellation is affected because any particular interferer will appear in multiple dimensions, thereby increasing the perceived number of users. Also, because there is no randomization of interference, a subset of users suffer poor performance even before the overall dimensional limit is reached. Such poor performance persists until the relative time offsets of the signature sequences change, which could take a fairly long time compared to the span of the FEC code used. This effect imposes a smaller limit on the capacity of D-CDMA systems than is implied by the hard dimensional limit.

This dimensional crowding phenomenon has been observed in [6], which considers an asynchronous system with 64 linearly independent signature sequences, with random phase offset between users. The performance of a blind adaptive MMSE detector deteriorates at around 48 users, in an ideal AWGN channel with no impairments such as fading. This gives a bandwidth efficiency of 0.75 bits/sec/Hz for a one-cell system.

In order to illustrate the dimensional crowding problem, we performed the following simulation in an ideal AWGN channel. For simplicity and clarity, we assume a real baseband system in which all the users are synchronous. The real baseband assumption is equivalent to assuming that all the users arrive in phase synchronism at the receiver[1]. The users are assumed to be BPSK modulated and use unique signature sequences to spread their signals. The signature sequences are picked at random, in order to model the effects of randomly arriving multipath and asynchronism. The period of the signature sequences is one bit (or code symbol, in a coded system) interval of the user. There are 128 chips per bit of each user and 80 users are assumed in the system. Each user is assumed to have signal to thermal noise (SNR) per bit of 20 dB, which is quite high. Our performance measure is the signal to interference ratio, achieved at the output of the MMSE receiver. The SIR per bit achieved by each user at the output of the MMSE receiver is shown in figure 1, for some typical realization of signature sequences. In figure 2, we plot the histogram of the SIR's achieved, collected over 100 realizations of the random sequences for each user. The wide variation in SIR achieved by the different users is apparent. The expected number of users who fail to achieve 6 dB SIR is 7.9 which is about 10% of the total number of 80 users. As the number of users increases to 90 and the SNR per bit doubled to 23 dB for each user, the expected number of users who fall short of 6 dB SIR is 12.2 which is 13.5% of the users. Clearly the capacity of the system can be no more than 80, because of the unacceptable number of users who fail to achieve required performance above this level. Optimistically multiplying this by a factor of 2 to account for phase randomness of different users (and hence the consequent reduction in interference seen by any particular user), we get a total *single*

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[1] If the phases of the users are assumed random, the effective interference seen by each user will be reduced by a factor of 2 on average. This improves the SIR and hence the capacity but due to the unequal SIR achieved by the various users, the capacity increase is much less than factor of 2.

cell capacity of less than 160. This corresponds to a bandwidth efficiency of $160/128 = 1.25$ bits/sec/Hz in a single cell system, as compared to the 0.75 bits/sec/Hz reported in [6] in a more practical configuration.

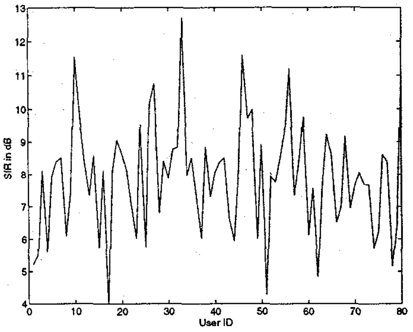

Figure 1: SIR achieved by each user

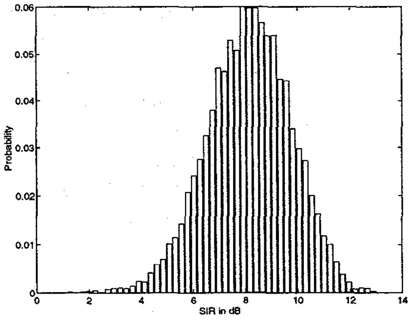

Figure 2: Histogram of SIR

Due to this dimensional crowding in D-CDMA, performance measures such as average bit error rate, where the average is taken over all the users, mask wide variations in user performance, even if all the users are received with equal powers. Interestingly, equalizing the performance of the various users requires a very complex power control strategy. The reason is that the MMSE detector depends on the received SNR's of the users, and hence in order to achieve a target SIR for each user, we need an iterative algorithm that adjusts the transmit powers and then finds the MMSE detector for this particular configuration of powers, and use the resultant SIR to drive the transmit powers. The adjustment of transmit powers clearly cannot happen faster than the speed of adaptation of the MMSE detector. This situation contrasts with the the simple power control scheme in R-CDMA which aims to keep the received powers of all the users equal. When received powers are equal in R-CDMA, the performance achieved by all the users is statistically the same. One key rationale cited for doing interference cancellation is to eliminate or reduce the need for power control. What we have shown is that maximizing capacity in D-CDMA requires the use of a more complex power control algorithm. The convergence of such an algorithm is not clear.

In a multiple cell situation, the total dimensionality of all of these interferers must satisfy the constraint shown above. Even so, one cannot have ideal interference cancellation due to the generally lower received SNR of the other-cell interferers at the cell of interest. This means that the capacity figure of 160 users applies to a cluster of adjacent cells taken as a whole. This is very similar to the frequency reuse patterns common in narrow-band cellular systems, except that here we have *dimension reuse.* Assuming a very optimistic reuse pattern of 3, the per cell capacity drops to about 53 users, under ideal AWGN channel conditions, and assuming the ideal MMSE receiver. Similarly sectorization (as performed with practical antennas) only reduces the total amount of interference, but does not increase the number of available dimensions. Hence it does not increase D-CDMA capacity.

In addition, due to the dimensional limitation, voice activity cannot be easily exploited in D-CDMA, unless very rapid switching of users among dimensions can be accomplished. This is more complicated than time-slot reassignment in TDMA because the reassignment algorithm has to take into account the effect of the reassignment on all the other users.

Note that in the above analysis of D-CDMA capacity, we have assumed an ideal AWGN channel employing the theoretical MMSE receiver. No fading, shadowing or multipath effects were assumed, nor the degradation due to the adaptive MMSE receivers that have to be employed in practice. In the presence of the severe channel impairments, the performance of multiuser receivers suffers and the capacity will be much less than the figures quoted above. Realistic simulations with adaptive MMSE receivers show that the number of users is only about half the dimension limit [6], even when carrier phase randomness of different users is taken into account (which provides for a halving of average levels of interference). Hence our estimates are very loose upper bounds.

Instead of attempting to cancel the other cell interferers, it is possible to randomize them completely and treat them as noise, as is done in R-CDMA. In such a case, same cell interferers will be treated as cancelleable multiaccess interference while other cell users will be treated as noise. Such a hybrid system is possible only if all the users in one cell use the same long random sequence that is different from the long random sequence employed by the users in adjacent cells. This calls for user synchronization in the reverse link. If the burden of synchronization is assumed, we might as well allocate orthogonal spreading codes to the users, exactly as done in IS-95 forward link. The rationale for incurring the complexity of interference cancellation disappears in this case.

4. ROBUSTNESS

As mentioned earlier, R-CDMA is an inherently robust design methodology. It can tolerate all manner of channel impairments with very graceful degradation in performance. The surprise is that this degree of robustness is achieved while simultaneously attaining high levels of bandwidth utilization. In contrast, the robustness of a D-CDMA based system design that uses multiuser receivers is open to question. Adaptive algorithms need a high SNR to converge, and yet in a fading channel the SNR may exhibit momentary fluctuations of 10 dB or more. In a highly loaded D-CDMA system, the unequal performance attained by users, with the same received powers, calls for complex power control strategies, the robustness of which are open to debate. Another important factor is the sensitivity of these receivers to frequency errors [6]. In high Doppler environments that prevail in satellite systems, this has serious implications.

5. CONCLUSION

There is a widespread perception that wireless CDMA systems should be designed in order to exploit interference cancellation techniques which are thought to dramatically increase capacity. It is our contention that an R-CDMA system like IS-95 clearly outperforms a D-CDMA system both in terms of per cell capacity and robustness. The key difference between the systems is the way the law of large numbers averages out interference and performance for all the users in R-CDMA. Due to this averaging effect, voice activity, universal frequency reuse and sectorization gain become possible in R-CDMA. D-CDMA design, due to its dimensional limitations, does not enjoy these benefits. The role of error control coding is also very critical to the performance of R-CDMA systems, a fact overlooked by most proponents of interference cancellation techniques. We believe that the directions for further capacity improvements in CDMA lie in spatial signal processing techniques and possibly also better error control codes.

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