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Parallel and successive interference cancellation in a digital front end of SDR receiver

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ABSTRACT

Software Defined Radio (SDR) is a radio technique that has the capability of replacing several receivers with a single universal receiver. It includes a Digital Front-End (DFE) with the ultimate goal to implement all processing in digital domain. As the receiver has to adapt to various communication standards with different characteristics, the objective is to develop an optimum detection algorithm to combat Multiple Access Interference (MAI). Subtractive Interference Cancellation (IC) detectors like SIC and PIC are proposed and are employed in both uplink and downlink transmissions. Suitability of linear detectors like MRC and MMSE based MUD is being analyzed in multistage receiver.

Introduction

In Code-Division Multiple Access (CDMA) all the users share the available bandwidth at the same time using the orthogonal codes allotted for them. The idea is to increase the geographical re-use of frequencies.It is the most promising method for 3G and 4G wireless mobile communication systems because of its high frequency utilization and suitability for handling multimedia services. As number of subscriber increases, the performance can be severely degraded.

A conventional DS/CDMA (Direct Sequence CDMA) system treats the desired signal as the signal of interest with the other users signal being considered as either interference or noise. IC techniques allow an existing receiver to operate with higher levels of co-channel interference. The IC principle is, to detect the information of the interfering users by Single User Detector (SUD) techniques. The interfering contribution is then reconstructed and cancelled from the received signal by performing a weighted selective cancellation of the co-channel interfering signal; detection of the desired user is finally performed.

In Multi User Detection (MUD) algorithms the presence of other signal is usually referred to as MAI and is used in the detection process. The main benefit of applying MUD techniques to CDMA systems is to increase the spectral efficiency. Thus MUD improves the capacity of the system to handle more users. It increases the overall throughput of the system while maintaining the data rate of the system.

Literature Review

Schneider (1979) and Kohno et al (1983) outlined the CDMA interference cancellation techniques based on Mean Square Error and Maximum Likelihood estimation. Verdu (1986) introduced and analyzed the optimum MUD for asynchronous Gaussian channels. It was very difficult to measure accurately in a real-time environment using this algorithm. Lupas and Verdu (1989) proposed a linear suboptimal detector for synchronous CDMA. The general structure has a bank of matched filter and linear memory less transformation on matched filter output. MUD algorithm and their variants were well covered by Juntti (1997). The residual error in the linear MMSE estimator was approximately Gaussian and from this assumption the posterior probability was obtained as pointed out by Poor and Verdu (1997). This property was very useful in the performance analysis of MMSE detector. However, it was reliably supported by few users. Catovic and Tekinay (2001) and Kapur and Varanasi (2003) studied extensively, the suboptimal detection for CDMA communication systems.

Multiple Access Techniques

Multiple access schemes allow many users to simultaneously share the fixed bandwidth radio spectrum. Three major methods of sharing the available bandwidth with multiple users in a wireless system are

- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)
- Code Division Multiple Access (CDMA)

CDMA is a multiple access technique in which each user is assigned with identical code. The unique code called spreading is applied to the information before transmitting it through the common medium. By applying the same code at the receiver, the transmitted signal of individual user is recovered. CDMA channels can handle an unspecified number of users and requires less frequency planning. But as all users can access the channel at all times, their signal interfere with each other.

Multiple Access Interference

Users in a CDMA system are distinguished by assigning a signature sequence. This sequence of one user is orthogonal to other users sequence. Due to user’s asynchronicity and hostile

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wireless channel effects, it is difficult to maintain orthogonality. As a result, there exists interference from other users, which is called the Multiple Access Interference (MAI).

Even in the case of ideal orthogonality, in the wireless propagation environment, signals originate from disparate geographical locations and propagate through distinct paths. The result is that the desired signal of each user is contaminated not only by thermal additive noise but also by the signals from other users called MAI.

The amount of MAI depends on two factors: signal strength of each individual user and the cross-correlation properties of the spreading codes. Many advanced techniques like Multiuser detection, Spatial diversity schemes and Source and channel coding have been proposed to combat MAI.

Multiuser Detection (Mud)

MUD is defined as a class of algorithms or methods in a communication receiver that exploit the considerable structure of the multiuser interference in order to increase the efficiency with which channel resources are employed S.Verdu [1998].

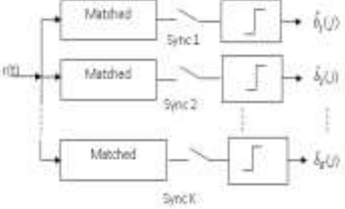

Figure 1: Conventional Multiuser Detector

MUD receivers may be classified as optimal, while using maximum likelihood sequence detection and suboptimal, employing either joint detection or subtractive interference cancellation. The optimum MUD employs Maximum Likelihood (ML) sequence estimation to jointly detect all users' data. Unfortunately, this detector is too complex for practical CDMA systems when the number of users is high. Therefore, most of the related research has focused on suboptimal MUD solution.

Suboptimum approach can be classified into two types namely, linear and non linear. Linear detectors include Decorrelating and Minimum Mean Square Error. Non linear suboptimal detectors include interference cancellers like Successive Interference Cancellation (SIC) and Parallel Interference Cancellation (PIC).

System Model

The base station receiver for the asynchronous uplink and downlink CDMA channel with QPSK modulation is being considered. User data is transmitted in blocks, with a block length M. It is assumed that the channel parameters remain constant in one block. The phase shifts and spreading codes of all users are known at the receiver. Initially the time delays are assumed to be exactly known at the receiver.

In Figure 2, MC-CDMA system, let $a_k^{(u)}$ denote the input data symbols of user u, N_{SF} the spreading factor and $c_m^{(u)}$ the spreading sequence of user u, selected from a set of orthogonal codes. The data symbols are spread by repeating each symbol $a_k^{(u)}$, N_{SF} times multiplied by the user specific spreading sequence, then suitably scaled by an amplitude factor $A^{(u)}$ and finally serial to parallel converted. The chip period T_{chip} is related to the symbol period T by $T_{chip} = T/ N_{SF}$. In this module the number of OFDM sub-carriers M equals the spreading factor, $(M = N_{SF})$ and one input symbol is transmitted per OFDM symbol. OFDM is implemented by using the Inverse Discrete Fourier Transform (IDFT).

The use of a suitable cyclic prefix removes both intersymbol and interchannel interference (ISI and ICI). This reduces the complexity of the receiver. The resulting signal $s_n^{(u)}$, transmitted over a radio channel $g_C^{(u)}$, is corrupted by the contribution of other users. In case of downlink transmissions, the channel $g_C^{(u)}$ is same for all users, while for uplink transmissions it is different. Let U indicate the number of active users.

When applying orthogonal spreading codes like Walsh-Hadamard codes, the maximum number of active users corresponds to the spreading coding length. In down link case, transmission is synchronous, while for uplink transmissions it is quasi-synchronous transmissions. The channels are time-invariant during atleast one OFDM symbol.

The received signal in the generic ith sub-carrier, after cyclic prefix removal and OFDM demodulation, implemented by the Discrete Fourier Transform (DFT), is given by

$$X_k[i] = \sum_{v=0}^{U-1} G_{c,k}^{(v)}[i] c_i^{(v)} A^{(v)} a_k^{(v)} + W_k[i] \qquad (1)$$

where $G_{c,k}^{(v)}[i]$ -complex coefficient that represents the flat fading channel of user *v* for sub-carrier i of length N_c. It is given by the DFT of channel impulse response,

$$G_{c,k}^{(v)}[i] = \sum_{p=0}^{Nc-1} g_{c,k}^{(v)}[p] e^{-j2\pi(ip)/M} \qquad (2)$$

i=0,1,……M-1

where $W_k(i)$ - noise on sub-carrier.i

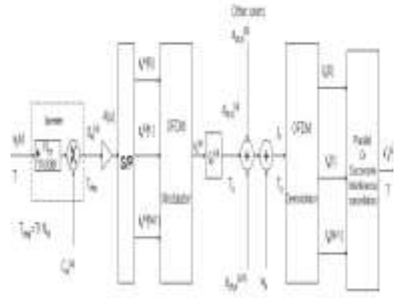

Figure 2: Block diagram of a MC-CDMA system using parallel or successive interference cancellation techniques at the receiver

$$W_k[i] = \sum_{M-1}^{P=0} w_k[p] e^{-j2\pi(ip)/M} \qquad (3)$$

where w_n - additive wide Gaussian noise (AWGN) at the receiver input with power spectral density N_0 and variance σ_w^2

Referring to the generic user u, the received signal in the ith subcarrier can be written as

$$x_k[i] = G_{C,k}^{(u)}[i] A^{(u)} c_i^{(u)} a_k^{(u)} + v_k^{(u)}[i] + W_k[i] \qquad (4)$$

The received signal $x_k[i]$ can be expressed using a vectorial notation as

$$x_k = [x_k[0], x_k[1], \text{-------} x_k[M-1]]^T \qquad (5)$$
$$= G_{C,k}^{(u)} A^{(u)} a_k^{(u)} c^{(u)} + v_k^{(u)} + W_k$$

where superscript ^{T} denotes the transpose

$G_{C,k}^{(u)}$ - diagonal channel matrix for user u.

It is given by

$$G_{C,k}^{(u)} = \mathrm{diag}[G_{C,k}^{(u)}[0], \text{---} G_{C,k}^{(u)}[M-1]] \qquad (6)$$

$c^{(u)}$-spreading sequence of user u, expressed as

$$c^{(u)} = [c_0^{(u)}, c_1^{(u)}, \text{--------} c_{NSF-1}^{(u)}]^T \qquad (7)$$

$v_k^{(u)}$ - interference vector of user u, given by

$$v_k^{(u)} = \sum^{U-1} G_{C,k}^{(v)}[i] A^{(v)} c^{(v)} a_k^{(v)} \qquad v=0, v \neq u \qquad (8)$$

and finally

$$W_k = [W_k[0], W_k[1], \text{----} W_k[M-1]]^T \qquad (9)$$

Maximal-Ratio Combining (MRC)

Maximal ratio combining is based on correcting the phase and weighting amplitude of each sub-carrier. It is a method of diversity combining in which the signals from each channel are added together, the gain of each channel is made proportional to the RMS signal level and inversely proportional to the mean square noise level in that channel, and the same proportionality constant is used for all channels. It is also known as ratio-squared combining and selective combining.

$$K^{(u)}[i] = G_{C,k}^{(u)*}[i] \qquad (10)$$

MRC produces an output SNR which is equal to the sum of each individual. The individual signals must be co-phased before being summed hence it requires an individual receiver and phasing circuit for each antenna element. Most of the CDMA mobile receivers are implementing MRC due to its low cost and reliable performance. Figure 3 delineates a block diagram of the MRC.

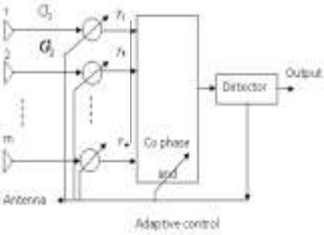

Figure 3: Maximal Ratio Combiner

Minimum Mean Square Error Per Carrier Combining (MMSE)

In the MMSE per carrier criterion, the coefficients $K^{[u]}[i]$ are adjusted to minimize, for each sub-carrier, the mean-square value of the error between the received and the desired signal. Signals are combined linearly based on the minimum mean square error (MMSE) principles, which only uses the knowledge associated with the desired user, MMSE receiver is known for its robustness against mismatched power.

$$K^{(u}[i]=\frac{M_a A^{(u)} G_{C,k}^{(u)*}[i]}{M\sigma_w^{2} + M_a \sum_{v=0}^{U-1} (A^{(u)})^2 \left| G_{C,k}^{(u)}[i] \right|^2} \qquad (11)$$

where M_a is the constellation power.

MMSE detector is an improved linear approach by assuming to have knowledge of strength on each users received signal. MMSE works by applying a linear transformation that has minimized the mean-squared error between the outputs and the data, i.e., min $|d - f(y)|^2$,where $f(.)$ is the function that maps y to d, and is chosen as to minimize the expected mean-squared error.

Parallel Interference Cancellation

PIC is a MUD technique which lends itself to a multistage implementation where the decision statistics of the users from the previous stages are used to estimate and cancel the MAI in current stage, and a final decision statistics is obtained at the last stage. This method is to estimate the interference and subtract simultaneously the signals originating from all the interfering users from the target user's signals M. K. Varanasi and B. Aazhang [1990]. The PIC receiver performs quite well when all the users are of equal strength.

Performance of PIC can be alleviated by properly weighing the MAI estimates before cancellation. A key question is how to choose the weights for different cancellation stages. An intuitive approach is to keep the value of the weight low at the early stages and large at the later stages, because the MAI estimates can be more reliable in the later stages, since much of the MAI would have been cancelled by then. A more formal approach is to obtain appropriate functions which when optimized will give the optimum weights. PIC is executed in the following two stages:

Stage-0:

For each user u, u = 0,……….,U-1

$$\hat{a}_k^{(u)[0]} = Q\{c^{(u)H}K^{(u)[0]}x_k\} \qquad (12)$$

where the superscript ^{H} denotes the conjugate transpose and the quantization operation Q{.} assigns to each value of $c^{(u)H}K^{(u)[0]}x_k$ an element of the data symbol alphabet.

Stage-1:

Estimate at stage-0 of the interference vector,

$$v_k^{(u)[0]} = \sum_{v=0,v\neq u}^{U-1} G_{C,k}^{(v)} c^{(v)} A^{(v)} \hat{a}_k^{(v)[0]} \qquad (13)$$

Final detection is given by

$$\hat{a}_k^{(u)[1]}=Q\{c^{(u)H}K^{(u)[1]}(x_k-v_k^{(u)[0]})\} \qquad (14)$$

The advantages of PIC is, its complexity grows linearly with the number of users, small delay compared to SIC and not required power estimates of all users, which is to be updated after each cancellation stage.

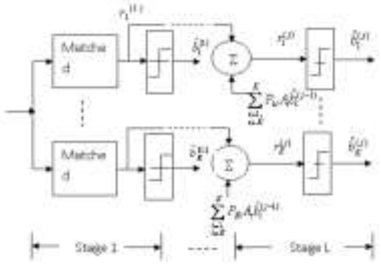

Figure 4: Structure of Parallel Interference Cancellation

Successive Interference Cancellation

In SIC approach, users are detected one after the other. The interference can be canceled on a user by user basis leading to serial or successive interference cancellation. At the receiver end, users are ranked according to their received power in order to detect the strongest user first, since this user can be detected with the most fidelity. After the demodulation of the strongest user, the second strongest user will be detected on the modified received signal without interference from the strongest user. The procedure is continued until all users are detected.

In terms of MAI, the received signal can be described as,

y_k = desired signal +MAI due to stronger users (1, . . . , k − 1) + noise (15)

This actually means that the strongest user often interferes with the desired user to the maximum extent. The strongest user is also least affected by MAI (P. Patel and J. Holtzman [1994]).

The SIC method works as follows :

In SIC all the users have been ranked according to their received signal power, with the highest power user being labelled as user 1 and the lowest power user being labelled as user K .

Stage-0

Let $x_k^{(1)[0]}= x_k$ for v=1,…,U-1

$$\hat{a}^{(p(v))[0]}= Q\{c^{(p(v))}K^{(p(v))[0]}x_k^{(v)[0]}\}$$

$$x_k^{(v+1)[0]}=x_k^{(v)[0]}[G_{c,k}^{(p(v))}[c^{(p(v))}A^{(p(v))}\hat{a}^{(p(v))[0]}] \qquad (16)$$

Stage-1

$$\hat{a}^{(p(0))[1]}= Q\{c^{(p(0))H}K^{(p(0))1]}X_k^{(U)[0]}\} \qquad (17)$$

Both PIC and SIC techniques at stage-1 detection of the useful user is based on a signal wherein estimate of all the U-1 interference has been cancelled from the input signal.

Simulations have been carried out for a MC-CDMA system with M = 16 sub-carriers, each being a QPSK signal. Users having different Walsh-Hadamard sequences and perfect channel knowledge are assumed at the receiver. Signals are being passed over a Rayleigh fading channel. The main objective of the results is to compare PIC and SIC receivers, both for downlink and uplink transmissions. The possibility of using different IC techniques in various PIC and SIC stages is being considered.

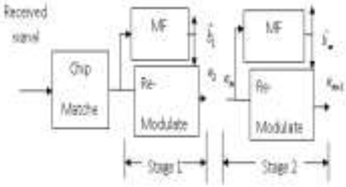

Figure 5 Structure of Successive Interference Cancellation

Simulation and results

Simulations have been carried out for a MC-CDMA system with M = 16 sub-carriers, each being a QPSK signal. Users having different Walsh-Hadamard sequences and perfect channel knowledge are assumed at the receiver. Signals are being passed over a Rayleigh fading channel.

The main objective of the results is to compare PIC and SIC receivers, both for downlink and uplink transmissions. The possibility of using different IC techniques in various PIC and SIC stages is being considered.

Performance comparison of PIC receiver in uplink, using different SUD techniques are considered with all users having same transmission power, since variation in each user receiver power is already created by the different propagating fading channels.

We observe that SIC out performs PIC receiver, even if the most powerful MMSE technique is used. For uplink transmissions (from mobile transmitter to base station) shown in figure 6, base station receives interfering signal designed for other terminals through the different channel as the desired signal. Since the channel is different, signals received will be with different power levels.

For downlink transmissions (from base station to mobile transmitter) shown in figure 7, a terminal receives interfering signals designed for other terminals through the same channel as the desired signal. Since the channel is the same, only if a dynamic power control is applied at the base station user signals can be received with different power levels. The simulation results shows that also when the power of received user signal is the same, performance of PIC and SIC can be different depending on technique.

In particular, when system is sensitive to MAI, technique such as MRC, is applied to both stages. Here SIC outperforms PIC for all number of users (comparing SIC 0MRC 1MRC and PIC 0MRC 1MRC). When more effective method such as MMSEC is used, PIC and SIC yield the same results. (Comparing SIC 0MMSEC 1MMSEC and PIC 0 MMSEC 1 MMSEC). Performance of PIC and SIC is also compared by combining the various technique between stage 0 and stage 1.

A performance comparison of parallel (PIC) and successive (SIC) IC techniques is presented, under dispersive channel conditions.Results from computer simulations show that, in many situations SIC receivers greatly outperform PIC receivers.

Following are some of the comparisons got from the plots in downlink and uplink transmission:

- With the single stage receiver, MMSEC performs better than the MRC.
- In PIC with multistage implementation shows

a) PIC 0 MMSEC 1 MRC is better than PIC 0MRC 1MMSE
b) PIC 0 MRC 1 MRC is better than PIC 0MMSE 1MMSE

- In SIC with multistage implementation

a) SIC 0 MRC 1 MMSE Is having comparable performance as that of SIC 0 MMSE 1 MRC
b) SIC 0 MMSE 1 MMSE is having comparable performance as that of SIC 0MRC 1 MRC

- Always SIC out performs PIC in all the cases.

SIC is both simpler and more robust than PIC with respect to error propagation, since users can be ranked according to their signal-to-interference plus noise ratio (SINR) and decoded in sequence. Hence focusing on SIC scheme:

- With the single stage receiver, MMSEC is preferred over MRC.
- In PIC with two identical stage implementation MRC is better than MMSE
- In PIC with two-stage implementation MMSE is better than MRC at the first stage.
- In SIC with two-stage implementation MRC is better than MMSE at the first stage.
- In SIC with two identical stage implementation MRC and MMSE have comparable performance.

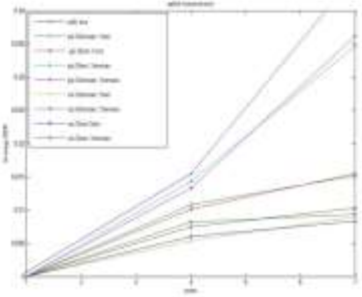

Figure 6: Comparison of PIC and SIC receiver at uplink transmission at SNR=5 dB.

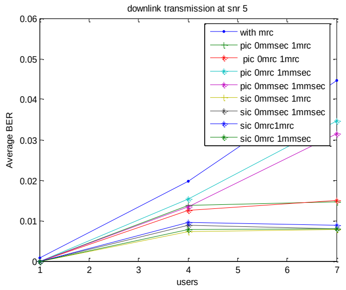

Figure 7: Comparison of PIC and SIC receiver at downlink transmission at SNR=5 dB.

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