Non-Parametric Interference Cancellation for CDMA Uplink System

Wei Zhang, Sharad Sambhwani
Corporate Research and Development
QUALCOMM Incorporated
San Diego, USA
{wzhang, sharads}@qualcomm.com

Abstract—**Uplink capacity of a code division multiple access (CDMA) system is limited by the mutual interference among users. It is well known that interference cancellation can significantly increase the CDMA uplink capacity. In this paper, we present a new interference cancellation scheme based on non-parametric channel estimation and waveform reconstruction. Compared with the traditional parametric scheme, the new scheme can effectively solve the model mismatch problem caused by a multipath channel. We also propose channel estimation cleaning methods to further improve the performance.**

Keywords-CDMA; uplink; interference cancellation; parametric model; non-parametric model; channel estimation; Rake ; Correlator; waveform reconstruction

I. INTRODUCTION

The uplink in a CDMA system is a typical non-orthogonal multiple access channel [1]. Users are mutually jammed by the signals (interference) from the co-existing users in the system. The uplink capacity is limited by the amount of multi-user interference observed by the base station. A single user matched filter receiver is suboptimal in dealing with interference. Receivers with advanced multi-user detection (MUD) algorithms can significantly increase the system capacity [2]. Among these advanced algorithms, interference cancellation is an effective approach for jointly decoding users on a multiple access channel. With interference cancellation, the cellular network can operate at a higher interference level since the effective interference can be reduced after cancellation. The increased interference level can directly translate to system gains in terms of the number of simultaneously supported users or cell throughput.

It was shown in [3] that successive decoding interference cancellation can achieve the sum-rate capacity for a CDMA uplink. In successive decoding, the receiver first decodes the user's data, then reconstructs the user's signal from the decoded data, and finally subtracts the user's signal from the received signal. An architecture for successive decoding interference cancellation was proposed for a CDMA EV-DO reverse link in [4]. The link-level model and network performance was studied in [5] and [6], respectively. A parametric channel estimation and waveform reconstruction model was used in the aforementioned scheme. It assumes that the received signal from each discrete physical path can be resolved by channel estimation and reconstructed with the estimated parameters. To fulfill this parametric model, a matched filter structure (a.k.a. Rake) was considered in both channel estimation and waveform reconstruction. However, in reality, the individual physical paths are absorbed into the composite channel response including the transmitter and receiver filters. Furthermore, in a rich scattering environment such as a dense urban area, the physical paths are hard to be resolved from the received signal. So the parametric model is inherently mismatched with reality. To overcome this problem, we propose a non-parametric interference cancellation scheme in this paper. To avoid resolving the individual physical paths, we estimate the channel impulse response and reconstruct the interference waveform with a Nyquist sampling rate.

This paper is organized as follows. We first describe the interference cancellation system architecture. We also give a summary of the parametric model used in the previous study and analyze its deficiencies. Then we present the non-parametric model. The channel estimation, channel estimation cleaning, and waveform reconstruction algorithms used in the non-parametric model are described in detail. Finally, we study the performance of non-parametric interference cancellation in terms of short-term cancellation efficiency and make comparisons with its parametric counterpart.

II. SYSTEM DESCRIPTION

A. Receiver Structure for Interference Cancellation

The structure of a general successive decoding interference cancellation receiver is shown in Figure 1. The samples r_n of received signal $r(t)$ are stored in a buffer. The receiver processes users in a successive manner. The top part of the receiver is the chain for demodulation and decoding. The choice of demodulator is independent of the interference cancellation scheme. It could employ a matched filter (Rake) or an equalizer. The success or failure of decoding can be verified with the aide of a cyclic redundancy check (CRC) on the packet. If the CRC passes, the decoded data are encoded again and passed to the reconstruction chain. The encoded data is modulated and spread to chip sequence c_k. The channel response is estimated with the aide of the known chip sequence. Finally, the waveform $\hat{y}_n$ of this specific user is reconstructed and subtracted from the sample buffer. The interference cancelled waveform $\tilde{r}_n$ is written back to the buffer. As a result, there will be less interference when the receiver processes the next user.

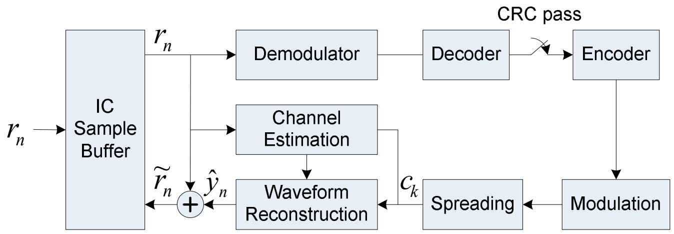

Figure 1 Receiver Structure for Successive Decoding Interference Cancellation

Next we describe the baseband signal processing of the interference cancellation system. At the transmitter, the chip sequence c_k passes through the transmitter filter $g_T(t)$ and the wireless channel $h(t)$. The multipath channel response $h(t)$ is given by

$$h(t) = \sum_{l=1}^{L} h_l \delta(t - \tau_l)$$

where τ_l and h_l are the delay and gain of the l-th path. At the receiver side, the receiver filters the received signal with filter $g_R(t)$. The output from the receiver filter is sampled for the subsequent digital processing. The channel impulse response (CIR) $g(t)$ seen by the receiver is the convolution of the transmitter filter, wireless channel, and receiver filter.

$$g(t) = \sum_{l=1}^{L} h_l g_{RC}(t - \tau_l)$$

where

$$g_{RC}(t) = g_T(t) * g_R(t)$$

The received signal can be written in continuous-time form as

$$r(t) = \sum_k c_k \sum_{l=1}^{L} h_l g_{RC}(t - \tau_l - kT_c) + z(t)$$

where $z(t)$ is the interference seen by the interested user. The discrete samples are given by

$$r_n = \sum_k c_k \sum_{l=1}^{L} h_l g_{RC}(nT_s - \tau_l - kT_c) + z_n$$

To meet the Nyquist sampling criteria, a common choice of the sampling rate is often two times of the chip rate. Now the task is to reconstruct the user's noiseless signal, i.e.,

$$y_n = \sum_k c_k \sum_{l=1}^{L} h_l g_{RC}(nT_s - \tau_l - kT_c)$$

B. Parametric Model for Interference Cancellation

The parametric model tries to resolve physical paths from the channel observation. The identification of physical paths is performed by a searcher. Then channel estimation is done by a Rake front-end [7], in which each finger tracks one physical path and estimates the parameters such as the path gain $\hat{h}_l$ and delays $\hat{\tau}_l$. Without loss of generality, let the Rake front-end estimate the gain $\hat{h}_m$ of the m-th path. We assume that the delay estimate $\hat{\tau}_m$ is already known. The Rake finger first interpolates the samples at time $t = nTc + \hat{\tau}_m$ from the samples in the buffer.

$$\begin{aligned} r_n^{(m)} &= r(t)\big|_{t=nT_c+\hat{\tau}_m} \\ &= \sum_k c_k \sum_l h_l g_{RC}(nT_c + \hat{\tau}_m - \tau_l - kT_c) + z_n^{(m)} \end{aligned}$$

Then the Rake finger correlates the interpolated samples with the known chips. The correlator output is given by

$$\begin{aligned} \hat{h}_m &= \frac{1}{N}\sum_{n=0}^{N-1} c_n^* r_n^{(m)} \\ &= \sum_l h_l g_{RC}(\hat{\tau}_m - \tau_l) \\ &+ \frac{1}{N}\sum_{n=0}^{N-1} c_n^* \sum_{k\neq n} c_k \sum_l h_l g_{RC}(nT_c + \hat{\tau}_m - \tau_l - nT_c) + w_m \end{aligned}$$

where N is the processing gain of the correlation. Further processing can be employed to refine the rough channel estimate $\hat{h}_m$. With the known chip sequence c_k, the parametric model will reconstruct the received signal with the estimated path gains and delays. The reconstructed signal is given by

$$\hat{y}_n = \sum_k c_k \sum_l \hat{h}_l g_{RC}(nT_s - \hat{\tau}_l - kT_c)$$

A finger based operation can be employed in waveform reconstruction if we exchange the order of summation in $\hat{y}_n$ and treat the inner sum as one finger.

However, this parametric model is prone to several defects. First, the searcher could miss weak paths and never reconstruct them. Second, errors in delay estimates and fat path effect cause the Rake finger to drift away from the true delay. Third, the path gain estimates are inaccurate if the delay estimates have errors. Finally, even if the delay estimates are perfect, the path gain estimates are biased due to the CIR. This can be explained with the following analysis. The correlator output $\hat{h}_m$ consists of three terms. We can show that the last two interfering terms are both zero mean and can be suppressed by filtering. However, the expectation of the estimate, i.e., the first term, is not the true h_m but the CIR at time $t = \hat{\tau}_m$. Thus the path gain estimate is inherently biased.

$$\overline{\hat{h}}_m = \sum_l h_l g_{RC}(\hat{\tau}_m - \tau_l) = g(\hat{\tau}_m) \neq h_m$$

Due to the error in delay estimation and the bias in path gain estimation, the subsequent waveform reconstruction is also erroneous. We can show the reconstruction error in the following example. Assume the channel has two equal paths. The second path has one chip delay relative to the first path. The transmitter and receiver filters are both root raised cosine filter with rolloff factor 0.22. In Figure 2, the two pulses generated by the two paths are plotted in blue and black, respectively. The composite channel response (red) is the supposition of these two pulses. We can see the two pulses merge into one fat pulse. Often in this case, the receiver can not resolve the two physical paths. Assume the searcher exactly finds the peak of the composite channel response. With the parametric approach, the receiver will reconstruct the waveform as if it is generated by a physical path located at the delay of the peak. Then a model mismatch happens since one fake path is reconstructed instead of two physical paths. We can see there is a large error between the composite channel pulse and the Rake reconstructed pulse (green).

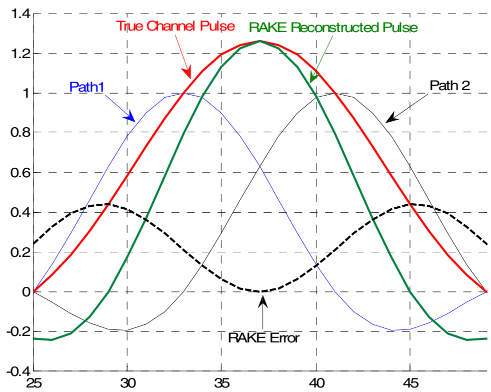

Figure 2 Example of Reconstruction Error in Parametric Model

C. *Non-parametic Model for Interference Cancellation*

1) *Channel Estimation*

The parametric model suffers from inaccurate parameter estimation and, more seriously, channel model mismatch. To overcome these problems, we propose a new model that relies on non-parametric estimation of the channel impulse response (CIR). In essence, the channel response is modeled as a fractional chip spaced transversal filter with K taps. The CIR taps are given by

$$g_i = g(t)\big|_{t=iT_s} = \sum_{l=1}^{L} h_l g_{RC}(iT_s - \tau_l)$$

Without loss of information, we assume the sampling rate is two times of the chip rate (chipx2) in the following derivation. In the non-parametric model, we only need to estimate the CIR taps. This avoids resolving the physical paths and abstracting the parameters associated with them.

The non-parametric interference cancellation scheme consists of a front-end, a back-end, and a waveform reconstruction block. In the front-end, the Rake fingers are replaced by a correlator bank for chip-level processing. The back-end includes channel estimation and cleaning functions for each channel tap. The waveform reconstruction uses a different structure than the parametric model to reconstruct the signals. The block diagram of non-parametric scheme is shown in Figure 3.

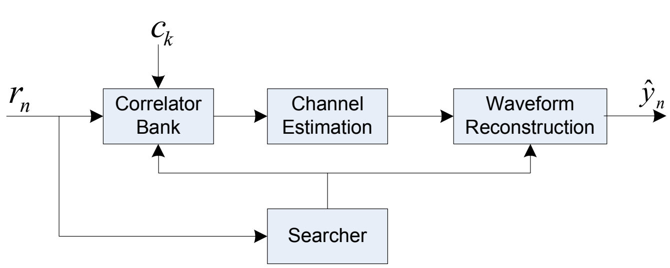

Figure 3 Non-parametric IC

The correlator and channel estimation filter are illustrated in Figure 4. The correlator in the correlator bank performs chip-level processing such as despreading similar to a Rake finger. The correlator uses the same half-chip sampling timing as the sample buffer so that interpolation is not required anymore. The correlation delay is in unit of ½ chips. This means the minimum offset between the correlators is ½ chip. In contrast, Rake fingers are usually much farther away from each other to overcome the fat path effect. Also Rake fingers typically need interpolators for finer resolution, usually up to 1/8 chip. The correlators can be placed with aide from the searcher, for which the correlators are only placed in clusters around physical paths identified by the searcher. For example, we can place correlators to cover the delay [-2, +2]-chips around each physical path. Alternatively, the placement of correlators can be window based. After identifying the first path, we can place consecutive correlators to cover a wide delay window starting from the first path. An example of correlator placement is shown in Figure 5.

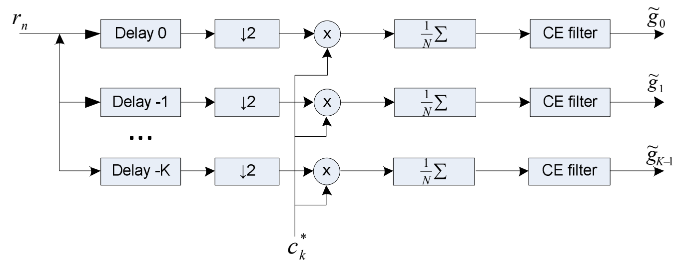

Figure 4 Correlator bank and channel estimation

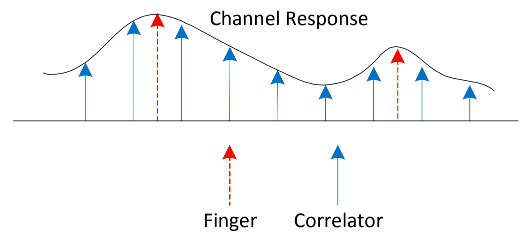

Figure 5 Example of Correlator Placement

Assume there are K correlators with correlation delays $0, 1, \ldots, K\text{-}1$ in unit of ½ chips. The i-th correlator output

$$\begin{aligned}\hat{g}_i &= \frac{1}{N}\sum_{n=0}^{N-1} c_n^* r_{2n+i} \\ &= \sum_{l} h_l g_{RC}(iT_s - \tau_l) \\ &\quad + \frac{1}{N}\sum_{n=1}^{N} c_n^* \sum_{k\neq n} c_k \sum_{l} h_l g_{RC}(nT_c - iT_s - \tau_l - kT_c) + w_i\end{aligned}$$

These correlator outputs are coarse channel estimates. We can show that they are unbiased estimates of channel response. To improve the channel estimation quality, a channel estimation filter is applied on the coarse channel estimates. The channel estimation filter is denoted as function $f(\cdot)$. The refined channel estimates are given by

$$\tilde{g}_i = f(\hat{g}_i), i = 0, 1, \ldots, K-1$$

2) *Channel Estimation Cleaning*

The channel response on some taps may be very weak since it is generated by the side lobes of the physical paths. The channel estimates on these weak taps are usually very noisy. Sometimes it's better not to reconstruct the taps at all. So we design two cleaning mechanisms to purify the channel estimates. The first one is the MMSE cleaning. The MMSE cleaning algorithm is described below:

1. The signal power on each tap is calculated as

$$\hat{p}_i = |\tilde{g}_i|^2, i = 0,1,...,K-1$$

2. We further use filter $F(\cdot)$ to filter the power on each tap

$$\tilde{p}_i = F(\hat{p}_i)$$

3. Estimate the noise power σ_i^2 on each tap. A very simple method to estimate the noise power is given below:
   - Find the M smallest filtered tap powers (M<<K)
   - Use the mean of these M values as noise power

2. Calculate a ratio between the filtered tap power and the noise power. The ratio is actually a signal to noise ratio on the tap

$$\eta_i = \frac{\tilde{p}_i}{\sigma_i^2}$$

3. Compare the ratio with a threshold
   - If η_i > Threshold, then keep this tap in the channel response estimate.
   - If η_i < Threshold, then discard this tap from the channel response estimate.

The second cleaning method is MMSE scaling. The idea of MMSE scaling is to scale the channel estimates according to the tap SINR. The algorithm is described as below:

1. The signal power on each tap is calculated as

$$\hat{p}_i = |\tilde{g}_i|^2, i = 0,1,...K-1$$

2. We further use filter F to filter the power on each taps

$$\tilde{p}_i = F(\hat{p}_i)$$

   For example, we can use an IIR filter for this purpose.

3. Estimate the noise power σ_i^2 on each tap
4. Compute the scaling factor as

$$\alpha_i = \frac{G \cdot \tilde{p}_i}{G \cdot \tilde{p}_i + \sigma_i^2}$$

   where G is the processing gain on channel estimation.

5. The scaled channel estimates are

$$\bar{g}_i = \alpha_i \tilde{g}_i$$

Similar to the idea of MMSE cleaning, we can also apply a threshold on the scale factor to eliminate the taps with very small scale factor.

3) Waveform Reconstruction

The waveform is reconstructed based on the chipx2 CIR $\bar{g}_i$, *i=0,1,...,K-1*. The reconstruction is accomplished by convolving the chip sequence with the cleaned channel response. Since the channel response is chipx2 sampling rate, the convolution can be done by a polyphase filter with two phases. The even phase and odd phase of the filter are given by

$$\bar{g}_i^{(e)} = \bar{g}_{2i}$$

$$\bar{g}_i^{(o)} = \bar{g}_{2i+1}$$

The even and odd samples are reconstructed by

$$y_n^{(e)} = c_n * \bar{g}_n^{(e)}$$

$$y_n^{(o)} = c_n * \bar{g}_n^{(o)}$$

Then the even and odd samples are time multiplexed to form the chipx2 waveform.

Another method for waveform reconstruction is the delay-and-sum method. It is done in three steps:

1. Upsample the chip sequence c_k two times by inserting zeros
2. For the *i*-th channel tap, delay the upsampled chip sequence by *i* samples and multiply it with $\bar{g}_i$
3. Then add the samples for all channel taps together

III. Performance of Non-parametric Interference Cancellation

In a multi-path environment, the power of received signal from the *i*-th user is given by

$$E_c = \sum_{l=1}^{L} |h_l|^2$$

where we assume that the chip energy is normalized to one. The instantaneous *SINR* of the *i*-th user is defined as

$$SINR = E_c / N_t$$

where N_t is the interference power, including all other users' power and thermal noise. Naturally the quality of interference cancellation can be measured from the residual interference power normalized by the interference power itself. We define *cancellation efficiency* as

$$\beta = 1 - E\left[|y_n - \hat{y}_n|^2\right] / E\left[|y_n|^2\right]$$

For successive decoding interference cancellation, the cancellation efficiency mainly depends on channel estimation quality, which is ultimately determined by the instantaneous SINR during channel estimation. Using link-level simulation, we can obtain the average cancellation efficiency as a function of instantaneous SINR [5]. This function *β(SINR)*, also referred to as cancellation efficiency short-term curve, is used to measure the interference reduction [6].

We simulate the parametric and non-parametric interference cancellation schemes on AWGN and several ITU fading channels. We use WCDMA uplink modulation and spreading format [8], in which the chip rate is 3.84 MHz and root-raised cosine filter with rolloff factor 0.22 is used as transmitter filter. For both Rake fingers and correlators, the correlation length is 256 chips and a 10-tap moving average filter is used to refine the rough channel estimates. For the parametric scheme, we assume the RAKE fingers are placed at the true physical channel delay, i.e., ideal delay estimation. For non-parametric scheme, we assume the correlators cover a range of [+2,-2] chips around the physical paths. The short-term cancellation efficiency is calculated on a period of 256 chips. The simulation results are plotted in Figure 6 to Figure 10. The non-parametric scheme is worse than the parametric scheme for an AWGN channel, which is ideal for the parametric model but often unrealistic in the field. For other multipath channels, the non-parametric scheme has 10%~20%

gain of cancellation efficiency over the parametric scheme when E_c/N_t>-20dB. If the system maintains the same interference level after cancellation, higher cancellation efficiency allows users to transmit at higher data rates. The parametric scheme suffers from a cap on cancellation efficiency due to deficiencies discussed before. And in low SINR region, MMSE scaling can greatly improve the performance of the non-parametric scheme. This is because MMSE scaling can significantly reduce the noise introduced by the weak channel taps.

IV. CONCLUSION

In this paper, we present a new non-parametric model for successive decoding interference cancellation in a CDMA uplink channel. We also analyze the deficiencies of the traditional parametric model. The non-parametric model is shown to outperform the parametric model in simulations. Nowadays the demand for higher uplink data rates is shifting the operating point to the high SINR region. For example, 16QAM modulation was introduced for the WCDMA enhanced uplink in Release 7 [9]. Given this trend, the non-parametric scheme is particularly favored over the parametric scheme.

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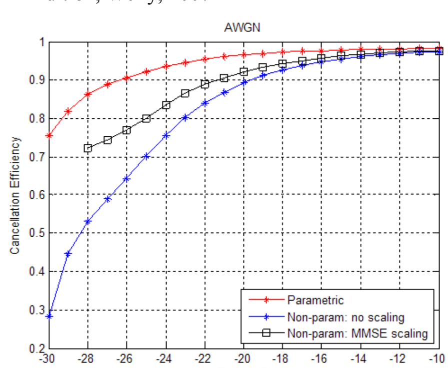

Figure 6 Simulation Results: AWGN Channel

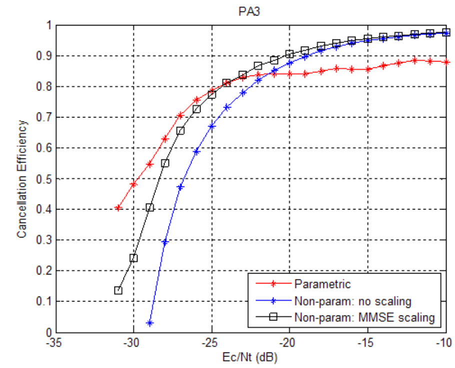

Figure 7 Simulation Results: ITU PA3 Channel

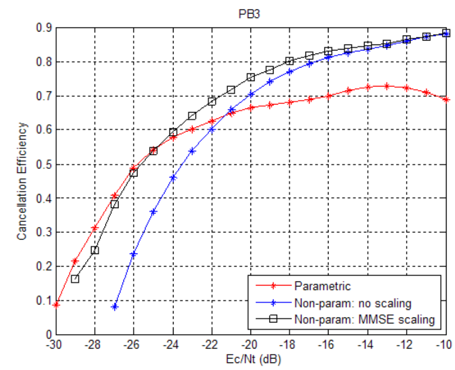

Figure 8 Simulation Results: ITU PB3 Channel

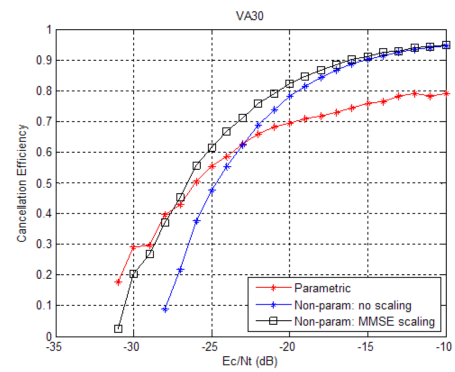

Figure 9 Simulation Results: ITU VA30 Channel

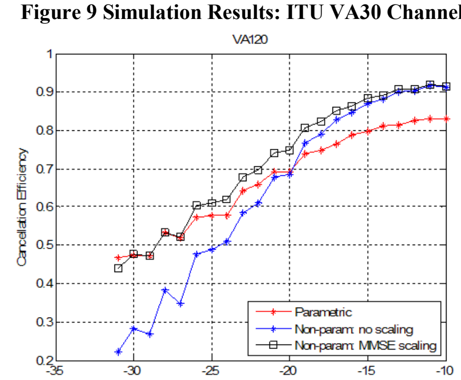

Figure 10 Simulation Results: ITU VA120 Channel