Abstract

This paper improves the performance of convolutional codes on the CDMA forward link by providing more accurate channel state estimates to the Viterbi decoder. Channel state estimation determines the received amplitude of the desired signal and the variance of the interference and noise at the channel decoder input. This paper illustrates that the in-cell interference process at the mobile Rake receiver output is non-stationary. Simulations show that accounting for this non-stationarity when performing channel state estimation improves Viterbi decoder performance.

1 Introduction

This work improves convolutional code performance on the CDMA forward link by providing the Viterbi decoder with improved channel state estimates. Channel state estimation refers to determining the amplitude of each encoded symbol received by the mobile and the variance of the interference and noise corrupting those symbols.

A convolutional code can be represented as a trellis and an encoded information sequence as a unique path through that trellis [1]. Using the received signal, the Viterbi decoder selects the trellis path that most likely represents the transmitted information. This selection is based on comparing metrics associated with each path. If desired signal amplitude and interference variance changes during the encoded frame, these quantities must be estimated at the Viterbi decoder input and incorporated into the metric calculation [2].

In a CDMA mobile, the Viterbi decoder operates on samples of the signal at the mobile Rake receiver output. Therefore, channel state estimation requires desired signal amplitude, $\zeta(i)$, and interference plus noise variance, $\sigma^2(i)$, to be determined at the Rake output for each symbol interval $i$. However, interference level is most easily measured at the receiver input. As a result, $\sigma^2(i)$ at the Rake output is typically calculated using input interference levels. This calculation must be based on an appropriate model for CDMA forward link interference.

Most CDMA forward link channel code studies assume that all interference and noise can be modelled as a single, stationary Gaussian process at the receiver input [3, 4]. This is a reasonable model for out-of-cell interference and thermal noise. However, the in-cell component of the interference received by the mobile travels through the same radio channel as the desired signal and is partially cancelled due to the Walsh spreading codes used on the forward link [5]. The result is a non-stationary in-cell interference component that is considerably different than the stationary Gaussian process assumed by most channel code studies. When calculating $\sigma^2(i)$ at the Rake receiver output, the non-stationary nature of in-cell interference must be taken into account.

This paper compares two techniques for calculating $\sigma^2(i)$. The first technique assumes that all interference and noise can be modelled as a single, stationary Gaussian process. The second technique accounts for the non-stationary nature of the in-cell component of CDMA forward link interference. Accounting for non-stationary in-cell interference produces a more accurate estimate of $\sigma^2(i)$ and improves Viterbi decoder performance.

Section 2 presents a model for the CDMA forward link that characterizes forward link interference. Section 3 discusses the two channel state
estimation schemes compared in this paper. This section also explains how channel state estimates are incorporated into the Viterbi decoder trellis path metric calculation. Simulation results that show the performance improvement possible when channel state estimation is improved are presented in Section 4. Concluding remarks are made in Section 5.

2 CDMA Forward Link Model

Let \( X_i(n) \) be the spread spectrum waveform used by a CDMA base station to transmit the \( i \)th channel encoded symbol \( x_i \) to user 0 in a sector with \( K \) users. The waveform is expressed in discrete time at two samples per spreading code chip as \( X_i(n) = G_i x_i a_k(n - 2iR) \) where \( R \) is the number of spreading code chips per encoded data symbol, \( G_i \) is the forward link power control gain factor applied to \( x_i \) and \( a_k(n) \) is the complex spreading code waveform assigned to user \( k \). In the following, this derivation can be extended to complex valued symbols in a straightforward manner. The spreading code, \( a_k(n) \), is the product of a real valued Walsh code unique for each user and a complex valued PN spreading sequence that is common for all users in the sector.

The complex valued samples of the forward channel impulse response are written as \( c(n, l) \), \( l = 0, \ldots, L - 1 \), where \( n \) signifies time in half chip intervals and \( l \) signifies excess delay in half chip intervals. The number of impulse response samples with significant signal energy at time \( n \) is equal to \( L \). The excess delay of each multipath component in the channel impulse response is assumed to be an integer multiple of a half chip duration. In the following, the term \( c(l) \) will be used to refer to \( c(2iR, l) \), where the index \( 2iR \) is removed for brevity.

Fig. 1 illustrates a mobile Rake receiver with \( W \) fingers for tracking the strongest of the multipath components received from the base station. The signal components tracked by the Rake fingers are located at channel delays \( z_0, z_1, \ldots, z_W - 1 \), where \( 0 \leq z_w \leq L - 1 \). The fingers despread the multipath components of the received signal and combine them using maximal ratio combining. It is assumed that the channel remains constant during one encoded symbol interval.

The baseband equivalent desired signal component at the output of the Rake receiver during the \( i \)th symbol interval is \( S_i = \zeta(i)x_i \) where the signal envelope is

\[
\zeta(i) = \sqrt{RG_i \sum_{w=0}^{W-1} |c(z_w)|^2}. \tag{1}
\]

![Figure 1: Conventional Rake receiver.](image)

Out-of-cell interference and thermal noise is typically modeled as a single Gaussian process at the Rake receiver input. Accounting for the maximal ratio combining and despreading performed within the Rake receiver, the out-of-cell interference plus thermal noise affecting symbol \( x_i \) at the Rake receiver output is

\[
N_i = \sum_{w=0}^{W-1} c^*(z_w) \sum_{r=0}^{R-1} a_k(2r) N(2iR + z_w + 2r)
= \sum_{w=0}^{W-1} c^*(z_w) N_{w,i} \tag{2}
\]

where \( N(n) \) denotes the out-of-cell interference plus thermal noise process at the input to the Rake receiver in discrete time at two samples per chip resolution. Two samples per chip is two times oversampling of the received signal. Therefore, \( N(n) \) is modeled as a coloured complex Gaussian process with zero mean and variance \( \sigma_N^2 \) that becomes white when decimated to one sample per chip.

The despreading stage in each Rake finger does not alter the Gaussian distribution of the out-of-cell interference. Samples of a Gaussian process that are multiplied by a pseudo-random spreading code with real and imaginary components
equal to 1 or -1 retain a Gaussian distribution. The Gaussian process at the output of the normalized despreading summation block in Fig. 1 has the same variance as the Gaussian process at the input to the summation [1]. Therefore, \( N_{w,i} \) in (2) is a complex white Gaussian process with zero mean and variance \( \sigma_N^2 \). Due to the independence of \( N_{w,i}, w = 0, \ldots, W - 1 \), the variance of \( N_i \) can be written as

\[
\langle N_i^2 \rangle = \sigma_N^2 \sum_{w=0}^{W-1} |c(z_w)|^2. \tag{3}
\]

The composite forward link signal transmitted by the base station is represented in discrete time at two samples per chip as \( I(n) \). Assuming a large number of users, this signal is modeled as a coloured complex Gaussian process with zero mean and variance \( \sigma_I^2 \) that becomes white when decimated to one sample per chip. Since \( I(n) \) propagates through the forward link radio channel, the in-cell interference at the output of finger \( w \) can be written as

\[
I_{w,i} = c^*(z_w) \frac{1}{\sqrt{R}} \sum_{r=0}^{R-1} a_0(2r) c(l) I(2iR + z_w - l + 2r). \tag{4}
\]

Rake finger \( w \) will extract the desired signal from the component of \( I(n) \) arriving at delay \( z_w \). The Walsh codes used for spreading on the forward link allow the despreading performed by finger \( w \) to completely cancel the signals of the \( K - 1 \) interfering users that also arrive at delay \( z_w \). Therefore,

\[
I_{w,i} = c^*(z_w) \sum_{l=0 \atop l \neq z_w}^{L-1} c(l) I'_{z_{w-l},i} \tag{5}
\]

where the term \( I'_{l,i} \) is the normalized sum of \( R \) samples of the Gaussian process \( I(n) \) multiplied by the spreading code of user 0 with an offset of \( r \) during symbol interval \( i \). As was the case for out-of-cell interference, the despreading operation in (4) does not alter the Gaussian distribution of \( I(n) \). Therefore, \( I'_{l,i} \) is a complex white Gaussian random process with zero mean and variance \( \sigma_I^2 \).

Let the vector \( \mathbf{I}_i = [I_{0,i} \ldots I_{W-1,i}]^T \) represent the in-cell interference at the finger outputs during symbol interval \( i \). The covariance matrix \( \mathbf{R} = \langle \mathbf{I}_i \mathbf{I}_i^H \rangle \) represents the second order statistics of the interference where the elements of the matrix are

\[
r_{mn} = \sigma_I^2 \sum_{l=0}^{L-1} \sum_{q=0}^{L-1} c^*(z_m)c(l)c(z_n)c^*(q) \\
\cdot \delta((q - l) - (n - m)) \\
\cdot [1 - \delta(m - l)][1 - \delta(n - q)]. \tag{6}
\]

The total in-cell interference at the Rake receiver output is \( I_i = \sum_{w=0}^{W-1} c^*(z_w) \sum_{l=0 \atop l \neq z_w}^{L-1} c(l) I'_{z_{w-l},i} \). Using (6), the variance of \( I_i \) is given by

\[
\langle I_i^2 \rangle = \sum_{m=0}^{W-1} \sum_{n=0}^{W-1} r_{mn}. \tag{7}
\]

3 Viterbi Decoding with Channel State Estimates

The signal envelope estimate, \( \zeta(i) \), required by channel state estimation is calculated according to (1). There are two alternatives for calculating interference plus noise variance at the output of the mobile Rake receiver.

First, it can be assumed that all forward link interference and noise can be represented using a single, stationary Gaussian process at the Rake receiver input. This channel estimation scheme measures interference and noise at the Rake input and calculates \( \sigma^2(i) \) according to (3), where \( \sigma_N^2 \) in this equation represents the total interference and noise on the CDMA forward link. This method of estimating \( \sigma^2(i) \) is referred to as standard estimation.

The second approach separately accounts for in-cell and out-of-cell interference components when estimating \( \sigma^2(i) \). Interference variance at the mobile Rake output is calculated according to \( \sigma^2(i) = \langle I_i^2 \rangle + \langle N_i^2 \rangle \), where \( \langle I_i^2 \rangle \) is determined using (7) and \( \langle N_i^2 \rangle \) is determined using (3). The variance of the composite forward link signal at the channel input, \( \sigma_f^2 \), and the out-of-cell interference plus thermal noise level, \( \sigma_N^2 \), are assumed known. This method of calculating \( \sigma^2(i) \) is referred to as improved estimation.

Once estimates of \( \zeta(i) \) and \( \sigma^2(i) \) are determined, they are incorporated into the Viterbi decoder path metric calculation. A Viterbi decoder uses the sequence of received signal sam-
amples \( r = [r_0, \ldots, r_{N-1}] \) to find the transmitted encoded symbol sequence \( x = [x_0, \ldots, x_{N-1}] \) that maximizes the PDF \( p(r|x) = \prod_{i=0}^{N-1} p(r_i|x_i) \), where \( N \) is the number of encoded symbols in a frame. For white Gaussian noise, this is equivalent to maximizing a sum of log-likelihood metrics, \( \sum_{i=0}^{N-1} M(i) \), where \( M(i) = R(r_i)x_i \) and is referred to as the correlation metric \([1]\). The operation \( R(\cdot) \) indicates the real part of a complex number. For a wireless channel with non-stationary interference, the correlation metric is modified to be \( M(i) = \zeta(i)R(r_i)x_i/\sigma^2(i) \) \([2]\).

4 Simulation Results

The purpose of the simulation is to determine the transmitted energy per chip, \( E_c \), required by a mobile that uses forward link power control to maintain a Frame Error Rate (FER) of 1%. This value of \( E_c \) is normalized by \( \sigma_1^2 + \sigma_N^2 \) and plotted versus mobile velocity.

A forward link gain factor is applied to the desired signal before transmission. This gain factor is adjusted based on forward link power control commands transmitted by the mobile every 1.25 ms. The power control commands adjust the gain factor in steps of 0.5 dB in an attempt to maintain a received signal to interference ratio target, \( \gamma_t \), at the mobile. The mobile adjusts this target at the end of each received frame. If a frame error occurs, \( \gamma_t \) is increased by 0.3 dB. Otherwise, it is decreased by 0.003 dB. These adjustments ensure that the mobile average received FER remains at 1%.

As discussed in Section 2, the composite forward link signal at the channel input, \( I(n) \), is modeled as a Gaussian process with variance \( \sigma_1^2 \). Out-of-cell interference plus thermal noise is a Gaussian process with variance \( \sigma_N^2 \) that is added to the received signal at the input to the mobile receiver. Each simulation run is conducted for a specific ratio of \( \sigma_1^2 \) and \( \sigma_N^2 \), denoted \( R_{in} = \sigma_1^2/\sigma_N^2 \).

Simulations are conducted using a data rate of 9600 bps, a spreading rate of 1.2288 Mcps and frame lengths of either 20 ms or 80 ms. The convolutional code is a maximal free distance rate 1/2, K=3 code with soft decision Viterbi decoding. The channel state estimates used by the Viterbi decoder are calculated using either standard or improved channel state estimation. Perfect channel knowledge is assumed. Three different simulated Rayleigh channel models are considered: a three path model with average path energies of 0.642, 0.256 and 0.102, a two path model with average path energies of 0.5 and 0.5 and a five path model where all paths have average energies of 0.2.

Fig. 2 shows that using improved estimation provides the most benefit in hotspot scenarios. Out-of-cell interference plus thermal noise is a stationary Gaussian process that satisfies the assumptions made by standard estimation. Therefore, the performance difference between standard and improved estimation is most significant at high values of \( R_{in} \).

![Figure 2: Variable \( R_{in} \), 3 path channel, 20 ms frame.](image-url)
channel has more multipath components contributing to the in-cell interference at the Rake receiver output. This increase in terms results in a more stationary in-cell interference process. As a result, the benefit of using improved estimation to account for non-stationary interference is reduced for a channel with a large number of resolvable paths.

Figure 4: Two and five path channels, 20 ms frame, $R_{in}$ 25 dB.

5 Conclusion

This paper illustrates that convolutional code performance can be improved on the CDMA forward link by providing the Viterbi decoder with more accurate channel state estimates. This increased accuracy is a result of accounting for the non-stationary nature of CDMA forward link in-cell interference.

References


