Fast Viterbi Decoding Methods for the Co-channel Interference Cancellation on Cellular DS/CDMA Systems

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SUMMARY Capacity of Cellular DS/CDMA systems depends on an amount of co-channel interference (CCI). One of the effective schemes to eliminate the CCI and improve the capacity is CCI cancellers which remove the CCI by subtracting all the regenerated signals of the interfering users. These cancellers, however, suffer from the residual interference due to the symbol errors in the initial decision. Therefore, a canceller which employs error correction in the initial decision has been proposed. In this system, two Viterbi decoders per one user are needed. Therefore, the amount of calculation increases and this causes additional signal processing delay which is not preferable, especially for voice transmission. Here we propose three fast decoding methods by simplifying the second Viterbi decoder which is used for decoding after the cancellation. Method-1 uses information of the first Viterbi decoder. Method-2 utilizes information of the second correlator instead of that of the first Viterbi decoder. Method-3 is the combination of method-1 and method-2. It uses information from both the first Viterbi decoder and the second correlator. The results obtained from the computer simulation show that the ACS reduction ratio reaches up to 80% within 0.5 dB degradation in E_s/N_0.

key words: Viterbi decoder

1. Introduction

In cellular mobile communications, DS/CDMA (Direct Sequence Code Division Multiple Access) has some advantages such as increasing the capacity of wireless cellular communications and preventing cawedropping by third parties[1],[2]. In DS/CDMA, each user is interfered by the other users which occupy the same frequency band. This interference is called CCI (Co-Channel Interference). Therefore, the receiver at the base station has to eliminate the CCI and detect multiple users’ information accurately. To increase CDMA capacity, detection schemes which utilize received signals of multiple users have been developed for more than ten years. These detection schemes are called multiuser detection. The optimum detector (minimum error probability detector) was proposed by Verdu[3]. Although notable performance gains are obtained, its complexity grows exponentially with the number of users. Therefore, the decorrelating detector which performs multiuser detection based on the inverse cross-correlation matrix has been proposed[4],[5]. Its performance is close to the optimum while it is less complex than the optimum detector. A receiver with the decorrelating detector, however, must calculate the inverse cross-correlation matrix and the large amount of calculation is required if truncated PN sequences are employed.

To eliminate the CCI without the large amount of calculation, CCI cancellers were proposed[6],[7]. These cancellers regenerate the CCI based on the initial decision and remove it from the composite received signals. They don’t require knowledge of the cross-correlation and their complexity grows linearly with the number of users. However, there is residual interference due to symbol errors in the initial decision. It is then important to minimize the error in the initial decision. Therefore, a canceller which corrects the errors in the initial decision by a Viterbi decoder was proposed[8]–[10] and it increased the CDMA capacity. In this canceller, however, two Viterbi decoders per one user are needed. The first Viterbi decoder is used for the initial decision, and the second one is used for decoding after the cancellation. Therefore, the amount of the calculation for decoding doubles and this causes additional signal processing delay which is not preferable, especially for voice transmission.

To apply this CCI canceler at the base station to voice transmission, it is necessary to reduce the signal processing delay due to the Viterbi decoders. There are several methods for fast decoding, such as a SST type Viterbi decoder[13]–[15], which is using both pre-decoding and M-algorithm[16]–[18]. In these methods, fast decoding is achieved by reduction of the number of ACS (Add Compare Select) operations which occupy a dominant part of decoding. In the Viterbi decoder, path metrics of survival paths are calculated and new survival paths are selected by ACS operations. Reduction of the number of ACS operations is useful to realize fast decoding.

Here we propose three fast decoding methods by simplifying the second Viterbi decoder.

Method-1) Using information of the first Viterbi decoder. The information of the survived path in the first Viterbi decoder
is forwarded to the second Viterbi decoder examines only the paths which are likely to be correct.

Method-2) Using information of the second correlator. The second Viterbi decoder is simplified based on this information.

Method-3) Combination of the method-1 and the method-2.

In Sect. 2 the CCI canceler is defined. The proposed system is explained in Sect. 3. Section 4 shows the results of the computer simulation and Sect. 5 presents our conclusions.

2. CCI Canceler

2.1 System Model

The system which is assumed in this paper is the same as the system in [8]. Figure 1 shows the model of the transmitter. Each user's signal is encoded by the orthogonal convolutional encoder and converted to one of orthogonal codes generated by a Walsh function. After being interleaved and combined with a part of the long PN sequence which is unique for each user, the encoded signal is transmitted. Here, it is assumed that the noise is AWGN (Additive White Gaussian Noise) and every user's signal is transmitted synchronously on the uplink.

Figure 2 shows the model of the receiver at the base station with the CCI canceler proposed by Sanada et al. [8]. In Fig. 2, the received signal is despread and put to the correlator. The signal is then decoded once by the Viterbi decoder. These signals are re-encoded, interleaved and re-spread. Through these processes, every user's spread signal is regenerated. All the signals from the interfering users are subtracted from the received signal which is stored in the memory. Then the signal from the desired user is despread and decoded.

2.2 Performance Analysis

As mentioned above, each user encodes its data using an orthogonal convolutional code. Assuming that the code rate is $r = 1/m (M = 2^m)$ and the code has constraint length $n_A$. Depending on the output of the convolutional code, one of $M$ orthogonal sequences is chosen by the orthogonal convolutional encoder as one coded symbol [8]. The resulting symbols are then interleaved and modulated with a part of the long PN sequence which is unique for each user and separates one user from another in direct sequence spreading. The processing gain is $GP = T_S/T_C$, where $T_S$ is the symbol duration and $T_C$ is the chip duration of the PN sequence. The received signal at the base station is then

$$y(t) = \sum_{i=1}^{K} \sqrt{P_i} W^r(t - \tau_i)C_i(t - \tau_i) + n(t)$$

where $W^r(t)$ is one of the orthogonal sequences referred to as the $r$-th symbol, $r = 1, \ldots, M, C_i(t)$ is the long PN sequence for the $i$-th user whose period is much larger than $GP$ [15], $P_i$ is the signal power for $i$-th user (for simplicity, we subsequently assume $P_i = P$ for all $i$), $\tau_i$ is the time delay for the $i$-th user ($0 \leq \tau_i \leq T_S$) and $n(t)$ is the AWGN with power spectral density $N_0/2 W/Hz$.

At the base station, every user's received signals are first despread and decorrelated with a bank of correlators. The output of the $d$-th correlator of the $k$-th user is then given by

$$Z_k(u) = \frac{1}{\sqrt{T_S}} \int_0^{T_S} y(t)c_k(t - \tau_k)W^r(t - \tau_k)dt$$
\[ \begin{align*}
\text{SNR}_{n1} &= \frac{1}{K - 1} \frac{N_0}{GP + 2E_s} \\
\text{SNR}_{n2} &= \frac{2P_{en} \cdot K}{2P_{en} \cdot K - 1} \\
\text{Pd}_{n1} &= \frac{d \cdot SNR_{n1}}{2} \\
\text{Pd}_{n2} &= Q \left( \sqrt{\frac{d \cdot SNR_{n2}}{2}} \right)
\end{align*} \]

where \( SNR_{n1} \) is the signal to noise ratio at the correlator output. From Eqs. (5), (6), (7), it is given by

\[ \text{SNR}_{n1} = \frac{1}{K - 1} \frac{N_0}{GP + 2E_s} \]  

where \( K \) is the number of users, \( Q(t) \) is the standard Gaussian upper cumulative distribution function which is

\[ Q(t) = \frac{1}{\sqrt{2\pi}} \int_t^{\infty} \exp \left( -\frac{x^2}{2} \right) dx. \]

Then the average symbol error probability after the reencoding is

\[ P_{en} \approx \sum_{d=d_{free}+3}^{d_{free}+3} d \cdot A_d \cdot P_{d_{n1}}. \]

Therefore, \( SNR_{n2} \), the signal to noise ratio after the cancellation, is

\[ \text{SNR}_{n2} = \frac{1}{2P_{en} \cdot K - 1} \frac{N_0}{GP + 2E_s}. \]

From \( SNR_{n2} \), the approximate error probability after the cancellation is

\[ P_{en} = \sum_{d=d_{free}} B_d \cdot P_{d_{n2}} \]

where \( B_d \) is the total number of nonzero information bits on all weight \( d \) paths, \( d_{free} \) is the minimum free distance and \( P_{d_{n2}} \) is obtained from \( SNR_{n2} \) as

\[ P_{d_{n2}} = Q \left( \sqrt{\frac{d \cdot SNR_{n2}}{2}} \right). \]

3. Proposed System

The system described in Sect. 2 requires two Viterbi decoders per user. Thus, the delay due to decoding doubles compared to a receiver without the CCI canceller. This is not preferable for voice transmission. To make this decoding delay shorter, here, three kinds of fast decoding methods are considered.

Method-1 uses only the information of the first Viterbi decoder. The output of the encoder in the transmitter corresponds to one of the orthogonal codes generated by a Walsh function. Therefore, from (11), the probability density of the output of the first correlator (initial decision) is Gaussian, as shown Fig. 3. The mean of the output for the correct signal is normalized to 1 while the mean for the incorrect signal is equal to 0. The variance is given from Eq. (9). In Fig. 3, the threshold (Th1) is defined as the point where the probability density function of the incorrect signal is close to
0. This is expressed as \( P(Z_k(u) > Th1 | u + r) \approx 0 \). In other words, if the output is over the threshold, \( Z_k(u) \) is judged to be the output of the correct signal. The first Viterbi decoder examines all the metrics of the paths on the trellis diagram and memorizes which state transition of the decoded path is reliable by checking the outputs of the first correlator. This means that if \( Z_k(u) > Th1 \) then it is assumed that \( u = r \) on Eq. (4). Figure 4 is the example of the trellis diagram in the first Viterbi decoder. Assuming that the output of the correlator suggests the correct path should be from the state 01 to 10 between the time sequences \( t_5 \) and \( t_6 \). Then, in the second Viterbi decoder, the state transitions corresponding to 00, 10, 11 at \( t_5 \) and the state 00, 01, 11 at \( t_6 \) are examined no more. Also, if the path from the state 10 to 00 between \( t_5 \) and \( t_6 \) is reliable, the states 01, 10, 11 at \( t_7 \) on the trellis diagram in the second Viterbi decoder are not investigated. Thus, no ACS operation is taking place during the time sequences from \( t_5 \) to \( t_6 \).

The probability density of the output of the second correlator is Gaussian the same as the output of the first correlator. The variance given by Eq. (12), however, is smaller than that of the first correlator output because the cancellation process reduces the CCI (Fig. 5). In method-2, a threshold (Th2) is determined as the probability density of the correct signal is close to 0. Therefore, \( P(Z_k(u) < Th2 | u + r) \approx 0 \). This means that the output of the correlator below this threshold is considered as unreliable. Therefore, it is considered that if \( Z_k(u) < Th2 \) then \( u + r \) in Eq. (4). If a path includes the unreliable output, it is eliminated. For example, on Fig. 6, if the output of the correlator corresponding to the signal 01 does not exceed the threshold, between \( t_4 \) and \( t_5 \) the state transition which corresponds to the signal 01 is eliminated. In this way, the number of the ACS operations is reduced.

Method-3 is a combination of method-1 and method-2. It uses both the information of the first Viterbi decoder and the second correlator. In the second Viterbi decoder, a part of the decoded path is determined by using the information of the fast Viterbi decoder. As in method-2, if a path corresponds with the second correlator output that is below Th2, it is eliminated.

The proposed system is shown in Fig. 7. The eliminated paths are decided in the ACS controller based on the information of the first Viterbi decoder (in the initial decision) and the second correlator (after the can-
An ACS reduction ratio is defined as

$\frac{\text{(ACS reduction ratio)}}{\text{(The number of executed ACS operations)}} = \frac{1}{\text{(The number of all ACS operations)}}$ (15)

where the number of ACS operations is the number of comparison at the merged state. The number of all ACS operations is the maximum amount of calculation (using conventional methods) and is given as

$\frac{\text{(The number of all ACS operations)}}{\text{(The number of states)}} \times \text{(The number of bits per one packet)}$ (16)

4. Simulation Result

4.1 Results of the AWGN Channel

Table 1 shows the parameters of the computer simulation. The carrier frequency is 1.6 GHz. An AWGN channel and a Rayleigh fading channel are both considered. The performance of method-1 and method-2 on an AWGN channel is shown in Figs. 8 and 9. Figure 8 shows the BER vs. the threshold. The threshold for method-1 is the distance from the mean of the incorrect signal of the probability density and the threshold for method-2 is the distance from the mean of the correct signal. If the threshold is larger, the BER performance approaches the conventional system. Figure 9 shows the ACS operations are reduced by changing the threshold. From Figs. 8 and 9, the high ACS reduction ratio is achieved with the large BER degradation on both method-1 and method-2.

The ACS reduction ratio vs. the $E_s/N_0$ is shown in Fig. 10. Method-3 employs values of the Th1 and the Th2 which maintain the BER and reduce the number of ACS operations as much as possible. From Fig. 8, the Th1 and the Th2 are set to 1.6 and 1.5 when the number of users is 7. Also, the Th1 and the Th2 are set to 2.3 and 1.5 when the number of users is 27. Figure 11 shows the BER vs. $E_s/N_0$. BER degradation is within 0.3 dB from this figure. Method-3 achieves the largest ACS reduction ratio though the BER degradation is also the largest. However, there is not significant differences on the BER performance among three methods. Method-1 achieves higher ACS reduction ratio than method-2 in

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<thead>
<tr>
<th>Table 1 Simulation parameters.</th>
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<td>Constraint Length</td>
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Fig. 8 BER vs. threshold ($E_s/N_0 = 5$ dB).

Fig. 9 ACS reduction ratio vs. threshold ($E_s/N_0 = 5$ dB).

Fig. 10 ACS reduction ratio vs. $E_s/N_0$. 
4.2 Results on a Rayleigh Fading Channel

In Figs. from 12 to 16, a Rayleigh fading channel is assumed and its Doppler frequency is 5 Hz. It is assumed that each user's signal is influenced by the different fading waveforms. Figure 12 shows the BER vs. $E_s/N_0$ under closed loop power control. The power control interval is every 12 bits. It is clear from Fig. 12 that the dynamic range of 10 dB is enough to alleviate the influence of the Rayleigh fading channel.

Figures 13 and 14 show the BER vs. the threshold and the ACS reduction ratio vs. the threshold. The BER performance is inferior to the case of an AWGN channel. In the case of 7 users, the smaller threshold increases the BER more quickly than with method-2. Therefore, the fast decoding is difficult in this case.

On Fig. 13, the Th1 and the Th2 are set to 1.5 and 1.7 for method-3 when the number of users is 7. Also, the Th1 and the Th2 are set to 2.2 and 1.7 when the number of users is 27. The ACS reduction ratio vs. the $E_s/N_0$ is shown in Fig. 15. Comparing to the case of the AWGN channel, the ACS reduction ratio is improved and faster decoding is achieved. The ACS reduction ratio reaches up to 80%. In these methods, from Fig. 16, the fast Viterbi decoding is achieved within 0.5 dB degradation. However, for method-3, the BER degradation is larger than the other methods with 7 users. This is because, as mentioned before, the fast decoding is difficult with method-2 (7 users) and method-3 is largely influenced by the performance degradation due to method-2.

Method-3 achieves the largest ACS reduction ratio. However, the BER degradation is also the largest.
value (about 0.5 dB) among these three methods. In method-1, the ACS reduction ratio is a little smaller than method-3 though the BER degradation is smaller (about 0.3 dB). Method-2 achieves less ACS reduction ratio. Thus, method-2 is not preferable for a Rayleigh fading channel. As a result, method-1 and method-3 are both useful on a Rayleigh fading channel.

5. Conclusion

In this paper, we have proposed the three fast Viterbi decoding methods for the CCI cancellers. Method-1 uses the information of the first Viterbi decoder, method-2 uses the information of the second correlator and method-3 is the combination of method-1 and method-2. From the results obtained through computer simulation, the amount of calculation is reduced up to 80% within the 0.5 dB degradation in $E_s/N_0$. Decoding is faster on a Rayleigh fading channel than a AWGN channel.

References

Yukitoshi Sanada was born in Tokyo in 1969. He received his B.E. degree in electrical engineering from Keio University, Yokohama, Japan, and his M.A.Sc. degree in electrical engineering from the University of Victoria, B.C., Canada, in 1992 and 1995, respectively. He is now a Ph.D. student at Keio University. His current research interest is in spread spectrum communications.

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