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Maximum Ratio Combining for a WCDMA Rake Receiver

By Kim-Chyan Gan

Wideband CDMA (WCDMA), a widely accepted third-generation interface, is based on direct-sequence (DS) CDMA technology. To minimize distortion of the signals in a DS-CDMA system, a rake receiver is used. A signal transmitted through the wireless channel may be severely distorted due to co-channel interference, adjacent channel interference (or multiple access interference), thermal noise, and multipath fading. The most severe distortion comes from fading, which changes the bit error rate (BER) curve from an exponential to a linear curve. One technique the rake receiver employs to combat these distortions is diversity. There are different diversity techniques, including frequency, time, and space. This application note explains how the DS-CDMA rake receiver employs multipath diversity techniques to minimize distortion.

CONTENTS

1 System Model

In the diversity scenario are different combining schemes, including the following:[1]

- *Selection diversity (SD)*. When L multipath signals are received, the combining scheme selects the paths with the higher signal-to-noise ratio (SNR) and discards the L-1 paths. Selection diversity is used in reverse-link of IS-95, where multiple base stations receive the signal from the mobile, but only the basestation that receives the strongest signal is chosen to serve the mobile.
- *Equal gain combining (EGC)*. The receiver corrects the phase rotation of the received signals caused by the fading channel and combines the received signals of different paths with equal weight.
- *Maximum ratio combining (MRC)*. The optimum way (in the sense of the least BER) to use information from different paths to achieve decoding in an additive white gaussian channel (AWGN) [1].[2] The receiver corrects the phase rotation caused by a fading channel and then combines the received signals of different paths proportionally to the strength of each path. Since each path undergoes different attenuations, combining them with different weights yield an optimum solution under an AWGN channel.

In a Rayleigh fading channel, the MRC performance is the best, followed by EGC, and then SD. The performance of MRC is the same as that of EGC if signals from each path are of equal strength. In a DS-CDMA communications system, the received signal from the base station to the handset can be expressed as follows:

Equation 1

$$r(p) = \sum_{l=1}^{L} c_l(p)a\left(p - \left[\frac{\tau_l}{T_c}\right]\right) + n(p)$$

Where:

- *p:* discrete time index
- *r(p)*: the received baseband signal after match filter
- *L*: the number of fading paths
- $c_l(p)$*:* discrete complex channel coefficient of the l^{th} path
- $a_k(p)$*:* discrete transmitted data
- τ_l*:* delay of the l^{th} path
- T_c: chip period
- *[x]:* rounding of x
- *n(p):* thermal noise plus inter-channel interference

The path searcher finds the exact delay of each path, and the channel estimation finds the fading channel coefficient.With this information, the received signal, r(p), can be decoded, as follows.

Equation 2

$$r\left(p + \left[\frac{\tau_i}{T_c}\right]\right)c_i^*\left(p + \left[\frac{\tau_i}{T_c}\right]\right) = \beta a(p) + \sum_{l=1, l \neq i}^{L} c_l\left(p + \left[\frac{\tau_l}{T_c}\right]\right)c_i^*\left(p + \left[\frac{\tau_i}{T_c}\right]\right)a\left(p - \left[\frac{\tau_l}{T_c}\right] + \left[\frac{\tau_i}{T_c}\right]\right) + n\left(p + \left[\frac{\tau_i}{T_c}\right]\right)\left(c_i^*\left(p + \left[\frac{\tau_i}{T_c}\right]\right)\right)$$

[1] See Lee, J. S., Miller, L.E., *CDMA Systems Engineering Handbook*, Artech House mobile communication library, 1998. See also the TIA/EIA/IS-95-A, Mobile Station-Base Station Compatibility Standard for a Dual-Mode Wideband Spread Spectrum Cellular System.

[2] See Stuber, G. L., *Principles of Mobile Communication*, 1st ed. Kluwer Academic Publishers, 1996

The first term on the right-hand side (R.H.S.) is the transmitted data weighted by the strength of the fading channel (β). The second term is inter-path interference (IPI). The last two terms (second and term term) can be combined and modeled as a single AWGN noise. As the noise from last two terms increases, the probability of error increases. If the fading channel is a Rayleigh distribution, β becomes an exponential distribution. If β is less than 1, the distance between the symbols in signal constellation shrinks, and the error in decoding becomes more likely than in a normal AWGN channel. In other words, fading shortens the distance in the signal constellation, changing the BER curve to linearly decrease as SNR goes up.

To achieve better diversity, the signals from different paths should be totally uncorrelated. If the signals from different paths are correlated, performance deteriorates because duplicate information is extracted from each path. In a real environment, the signals from different paths are almost correlated.

The strengths of different paths also affect the probability error curve. If total power is constant, it is desirable to allocate power equally to signals of all the paths to achieve better diversity. In a real-time transmission, the strength of the signal depends on the environment.

2 Chip/Symbol Rate Combining

There are two ways to achieve combining: at the chip level and at the symbol level. Symbol-level combining, as its name implies, combines the signals of different paths at the symbol level. The descrambling and despreading are performed before combining in order to convert chip-level signals into symbol-level signals. **Figure 1** shows the block diagram for combining at the symbol level. Chip-level combining performs combining followed by descrambling and despreading. **Figure 2** shows the block diagram for combining at the chip level.

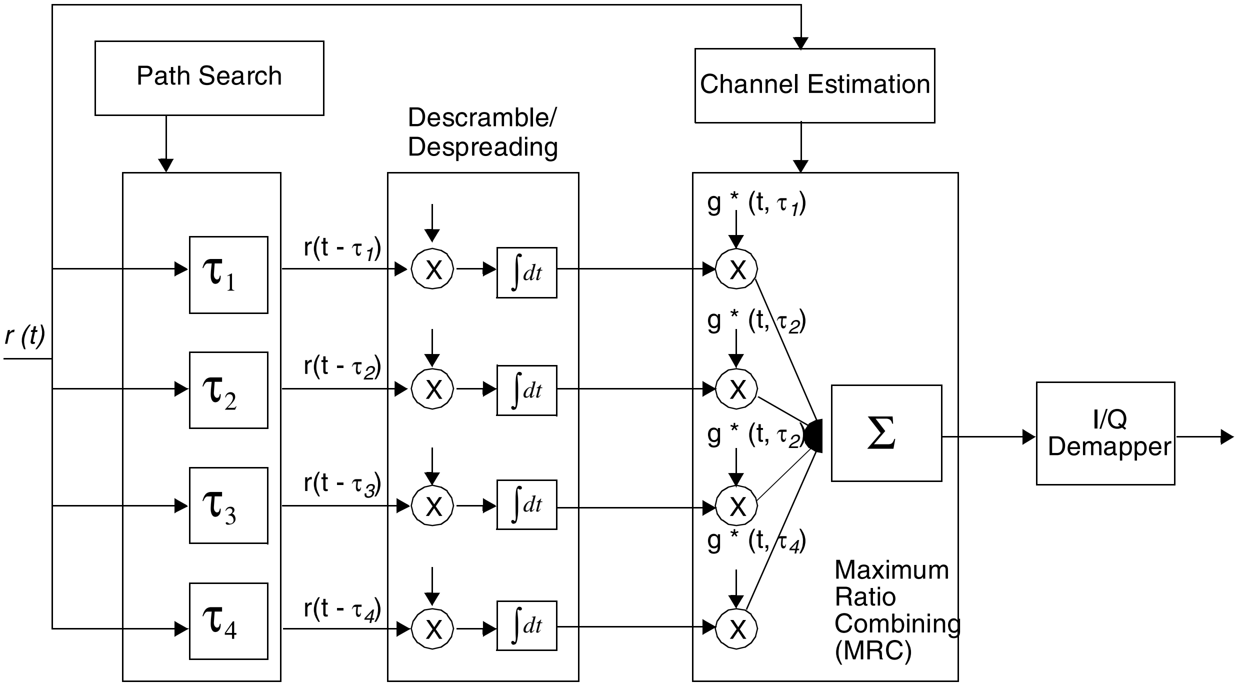

Figure 1. Block Diagram Rake Receiver (Symbol-level Combining)

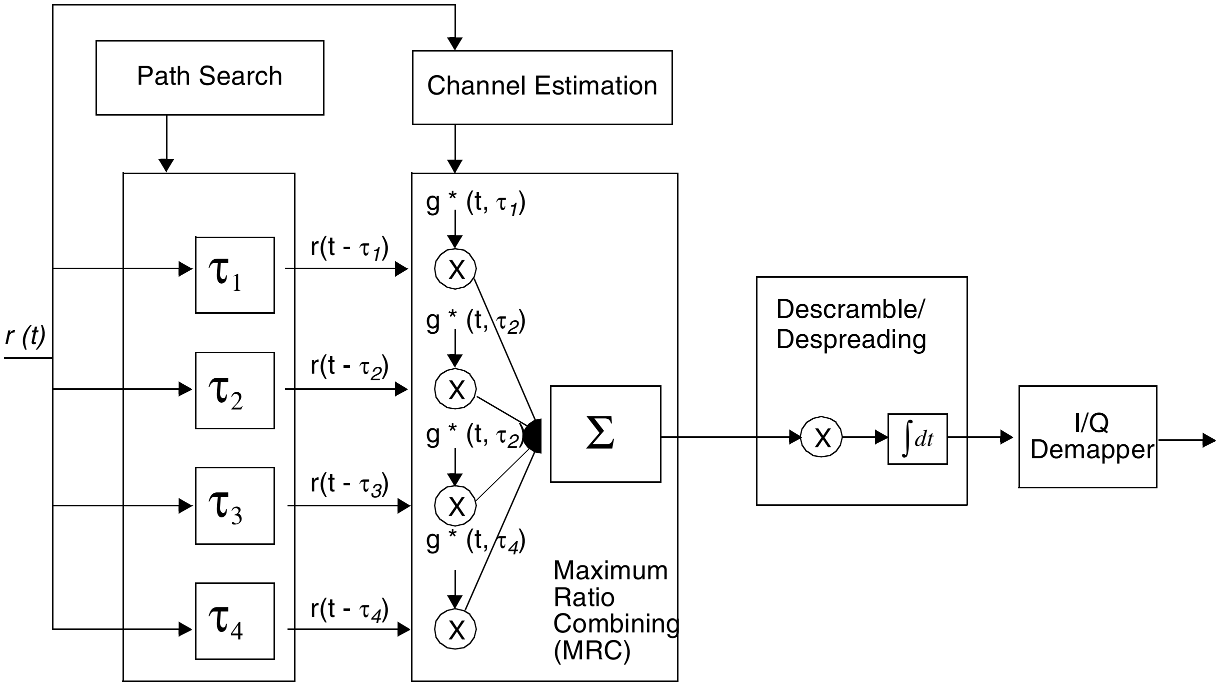

Figure 2. Block Diagram Rake Receiver (Chip-level Combining)

The performance of both combining schemes is the same under perfect channel estimation and path searching, assuming that the fading channel is constant over a symbol period. **Table 1** shows the estimation of the computational loads of both combining schemes for one channel. The descrambling and despreading are combined and occur in one step. It is assumed that the scrambling code and the spreading code do not change during the transmission.[3]

Table 1. Complexity of Chip-Level Versus Symbol-Level Combining in One Channel

Number of Finger(s)	Spreading Factor	Chip-Level Combining			Symbol-Level Combining		
		Number of Real MACs in MRC	Number of Real MACs in Descramble/ Despread	Total MACs	Number of Real MACs in Descramble/ Despread	Number of Real MACs in MRC	Total MACs
1	4	153600	153600	307200	153600	38400	192000
1	512	153600	153600	307200	153600	300	153900
2	4	307200	153600	460800	307200	76800	384000
2	512	307200	153600	460800	307200	600	307800
3	4	460800	153600	614400	460800	115200	576000
3	512	460800	153600	614400	460800	900	461700
4	4	614400	153600	768000	614400	153600	768000
4	512	614400	153600	768000	614400	1200	615600
5	4	768000	153600	921600	768000	192000	960000

[3] If the spreading or the scrambling code changes, the new composite scrambling/spreading code needs to be generated.

Table 1. Complexity of Chip-Level Versus Symbol-Level Combining in One Channel (Continued)

Number of Finger(s)	Spreading Factor	Chip-Level Combining			Symbol-Level Combining		
		Number of Real MACs in MRC	Number of Real MACs in Descramble/ Despread	Total MACs	Number of Real MACs in Descramble/ Despread	Number of Real MACs in MRC	Total MACs
5	512	768000	153600	921600	768000	1500	769500
6	4	921600	153600	1075200	921600	230400	1152000
6	512	921600	153600	1075200	921600	1800	923400

In the rake receiver, symbol-rate combining rather than chip-rate combining is used in the simulation because symbol-rate combining requires fewer computations, especially when the spreading factor goes up. Channel estimation is hard to achieve in chip-level combining. Usually, it is estimated at the symbol level and interpolated to the chip level. Therefore, symbol-level channel estimation requires fewer cycles than chip-level estimation since the interpolation (even the simplest repetition or first-order hold) requires some cycles. The symbol and chip rate combining are compared in term of memory usage. In chip rate combining, one path is stored, but the stored data is in chip-rate, which is as many as 38400 samples. In symbol rate combining, the data of multiple paths is stored. However, each path is in symbol level. The total number of samples is (38400/SF) * L. The discrepancy of memory usage between chip and symbol combining is as follows:

Equation 3

$$\Delta = 38400 - \frac{38000}{SF}L$$

where L is the number of fingers (ranging from 2 to 8) and SF is the spreading factor (ranging from 4 to 512). If **Equation 3** is positive, chip-rate combining requires more memory than symbol-rate combining. Since SF is larger than L most of the time, and **Equation 3** is positive, symbol-rate combining uses less memory than chip-rate combining.

3 Implementation in StarCore

A four-finger rake receiver is considered for implementation. MRC is just a complex multiplication with a channel coefficient in each finger, followed by addition of the results from the different fingers. These steps can be combined using multiply-accumulation (MAC) instructions. Optimization techniques used in an MRC routine are as follows:

- *Software pipelining*. Loads both the input and output data. Thus, the first input is executed at the end of the loop while the data output occurs at the beginning of the loop.
- *Scheduling*. Allows two combinings to proceed concurrently. In the SC140 core, there are four Data Arithmetic Logic Units (DALUs). One symbol combining occupies two DALUs, one for real and another for imaginary calculation. Thus, two combinings use up all the DALUs.
- *Loop unrolling*. The inner kernel is unrolled four times because the outer kernel is executed very frequently. This technique saves the cycles of setting up the loop at the expense of memory size.

Chip-level or symbol-level combining does not affect the MRC implementation. Only the loop counter must be changed. The MRC in this application note is valid for both combining schemes. For chip-level combining, N is 38400, and for symbol-level combining, N is 38400/SF (SF is the spreading factor).

Example 1. Maximum Ratio Combining (Four Fingers)

```
       move.l #N/2,d0                ; N/2
       dosetup0 combine4path doen0 d0
     [ move.4f (r0)+,d0:d1:d2:d3     ; ri(1,1),rq(1,1),ri(1,2),rq(1,2)
       move.4f (r8)+,d4:d5:d6:d7     ; gi(1,1),gq(1,1),gi(1,2),gq(1,2)
     ]
       falign
     loopstart0
combine4path:
     [ mpy d0,d4,d8                  ; ri(1,1)*gi(1,1)
       mpy d1,d4,d9                  ; rq(1,1)*gi(1,1)
       mpy d2,d6,d10                 ; ri(1,2)*gi(1,2)
       mpy d3,d6,d11                 ; rq(1,2)*gi(1,2)
       moves.4f d8:d9:d10:d11,(r7)+  ; output, first 4 are dummies
     ]
     [ mac d1,d5,d8                  ; rq(1,1)*gq(1,1)
       mac -d0,d5,d9                 ; ri(1,1)*gq(1,1)
       mac d3,d7,d10                 ; rq(1,2)*gq(1,2)
       mac -d2,d7,d11                ; ri(1,2)*gq(1,2)
       move.4f (r1)+,d0:d1:d2:d3     ; ri(2,1),rq(2,1),ri(2,2),rq(2,2)
       move.4f (r9)+,d4:d5:d6:d7     ; gi(2,1),gq(2,1),gi(2,2),gq(2,2)
     ]
     [ mac d0,d4,d8                  ; ri(2,1)*gi(2,1)
       mac d1,d4,d9                  ; rq(2,1)*gi(2,1)
       mac d2,d6,d10                 ; ri(2,2)*gi(2,2)
       mac d3,d6,d11                 ; rq(2,2)*gi(2,2)
     ]
     [ mac d1,d5,d8                  ; rq(2,1)*gq(2,1)
       mac -d0,d5,d9                 ; ri(2,1)*gq(2,1)
       mac d3,d7,d10                 ; rq(2,2)*gq(2,2)
       mac -d2,d7,d11                ; ri(2,2)*gq(2,2)
       move.4f (r2)+,d0:d1:d2:d3     ; ri(3,1),rq(3,1),ri(3,2),rq(3,2)
       move.4f (r10)+,d4:d5:d6:d7    ; gi(3,1),gq(3,1),gi(3,2),gq(3,2)
     ]
     [ mac d0,d4,d8                  ; ri(3,1)*gi(3,1)
       mac d1,d4,d9                  ; rq(3,1)*gi(3,1)
       mac d2,d6,d10                 ; ri(3,2)*gi(3,2)
       mac d3,d6,d11                 ; rq(3,2)*gi(3,2)
     ]
     [ mac d1,d5,d8                  ; rq(3,1)*gq(3,1)
       mac -d0,d5,d9                 ; ri(3,1)*gq(3,1)
       mac d3,d7,d10                 ; rq(3,2)*gq(3,2)
       mac -d2,d7,d11                ; ri(3,2)*gq(3,2)
       move.4f (r3)+,d0:d1:d2:d3     ; ri(4,1),rq(4,1),ri(4,2),rq(4,2)
       move.4f (r11)+,d4:d5:d6:d7    ; gi(4,1),gq(4,1),gi(4,2),gq(4,2)
     ]
     [ mac d0,d4,d8                  ; ri(4,1)*gi(4,1)
       mac d1,d4,d9                  ; rq(4,1)*gi(4,1)
       mac d2,d6,d10                 ; ri(4,2)*gi(4,2)
       mac d3,d6,d11                 ; rq(4,2)*gi(4,2)
     ]
     [ macr d1,d5,d8                 ; rq(4,1)*gq(4,1)
       macr -d0,d5,d9                ; ri(4,1)*gq(4,1)
       macr d3,d7,d10                ; rq(4,2)*gq(4,2)
       macr -d2,d7,d11               ; ri(4,2)*gq(4,2)
       move.4f (r0)+,d0:d1:d2:d3     ; ri(1,1),rq(1,1),ri(1,2),rq(1,2)
       move.4f (r8)+,d4:d5:d6:d7     ; gi(1,1),gq(1,1),gi(1,2),gq(1,2)
     ]
     loopend0
       moves.4f d8:d9:d10:d11,(r7)+  ; output, first 4 are dummies
```

4 Results

Table 2 shows the approximate cycles per WCDMA frame for MRC and the code size.

Table 2. Code Size and Approximated Cycle Count

Function	Cycles/Combining	Code Size (Bytes)
Maximum Ratio Combining (four fingers)	4	212

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Freescale Semiconductor
Technical Information Center, CH370
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+1-800-521-6274 or +1-480-768-2130
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Europe, Middle East, and Africa:
Freescale Halbleiter Deutschland GMBH
Technical Information Center
Schatzbogen 7
81829 München, Germany
+44 1296 380 456 (English)
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+33 1 69 35 48 48 (French)
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Japan:
Freescale Semiconductor Japan Ltd.
Headquarters
ARCO Tower 15F
1-8-1, Shimo-Meguro, Meguro-ku,
Tokyo 153-0064, Japan
0120 191014 or +81 3 5437 9125
support.japan@freescale.com

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