International Symposium on Circuits and Systems, pp. 357-360, May 2003, Bangkok, Thailand

Minimum Selection GSC and Adaptive Low-Power Rake Combining Scheme

Suk Won Kim [1], Dong S. Ha[2], and Jeffrey H. Reed[3]

[1]System LSI Division, Device Solution Network
Samsung Electronics Co., Ltd.
San #24 Nongseo-Ri, Giheung-Eup
Yongin-City, Gyeonggi-Do, Korea 449-711

[2]VTVT Laboratory and [3]MPRG
Department of Electrical and Computer Eng.
Virginia Tech
Blacksburg, Virginia 24061 USA

E-mail: sukim4@samsung.co.kr, ha@vt.edu, and reedjh@vt.edu

ABSTRACT

In this paper, we investigate a new generalized selection combining (GSC) technique and an adaptive rake combining scheme to save the power consumption of mobile rake receivers for wideband CDMA systems. The new GSC technique called minimum selection GSC (MS-GSC) selects a minimum number of rake fingers, while maintaining the combined SNR larger than a given threshold. The proposed adaptive rake combining scheme dynamically adjusts the threshold value to maintain the desired BER. Therefore, our rake combining scheme can be integrated into any GSC, which select fingers based on a given threshold value. The proposed MS-GSC shows a low standard deviation in bit error statistics and is advantageous in practical implementation. Our experiments indicate that the proposed adaptive combining scheme reduces the power consumption of a mobile rake receiver up to 67.8 % by turning off unselected rake fingers.

1. INTRODUCTION

A rake receiver adopts multiple fingers to exploit diversity of multipath signals called diversity combining. In general, a larger number of fingers would improve the SNR (signal to noise ratio) at the cost of higher circuit complexity and larger power dissipation. In practice, the number of rake fingers is in the range of two to five. Since a rake receiver operates at the chipping rate, it is one of the most power consuming blocks of a baseband signal processor for a CDMA (code division multiple access) receiver.

Instead of selecting all the fingers as for the case of the maximal ratio combining (MRC), generalized selection combining (GSC) methods choose the best m fingers out of L fingers depending on the SNR or the signal strength [1]-[7]. The number of selected fingers m is decided *a priori* in [1]-[4], while it varies dynamically in [5]-[7]. Note that the MRC is a special case of a GSC, where the number of selected fingers m is fixed to L. For the latter approach in which m varies dynamically, an absolute threshold GSC (AT-GSC) selects fingers whose SNRs are greater than a given threshold [5],[6]. Alternatively, a normalized threshold GSC (NT-GSC) selects fingers whose relative SNRs to the maximum SNR among all fingers are greater than a given threshold [5],[7].

GSC methods intend to save hardware and/or power dissipation. If m is fixed and less than L, it reduces the circuit complexity of a rake receiver and hence the power dissipation. Since m changes dynamically in the range of 1 to L for the AT-GSC and the NT-GSC, the two schemes do not save hardware. In fact, hardware complexity increases to be able to change m. However, the AT-GSC and the NT-GSC can save power dissipation by turning off unselected fingers. Two major design considerations regarding the AT-GSC and the NT-GSC are:

(i) determination of threshold values, and
(ii) effectiveness of the two methods in terms of power and hardware implementation.

A threshold value should be set to meet the required QoS (quality of service) and to turn off a maximal number of fingers. BER (bit error rate) is often used as a metric for the QoS. For example, a BER of 10^{-3} may be necessary for voice communications and a BER of 10^{-6} for data communications. One practical approach to achieve the desired QoS is to maintain the combined SNR over a certain threshold, so that the BER is below a certain level.

In this paper, we propose a new GSC method called minimum selection GSC (MS-GSC) and an adaptive rake combining scheme to determine the threshold value for a GSC. Our MS-GSC selects a minimum number of fingers, while maintaining the combined SNR greater than a given threshold. Our proposed adaptive scheme for determination of the threshold value is applicable to the three GSC methods, the AT-GSC, the NT-GSC, and the proposed MS-GSC. Through simulation, we estimated the effectiveness of the proposed MS-GSC and the adaptive rake combining scheme for a mobile rake receiver of wideband CDMA (WCDMA) systems.

The paper is organized as follows. The proposed MS-GSC is presented in Section 2. An adaptive rake combining scheme for low-power dissipation is proposed in Section 3. Simulation results applied to a mobile rake receiver of WCDMA systems are presented in Section 4. Finally, Section 5 concludes the paper.

2. NEW GSC METHOD

Our method denoted as MS-GSC (T_m, L) selects a minimum number of fingers out of L fingers, while maintaining the combined SNR is larger than a given threshold T_m. The signal level or strength of a finger is usually used in actual implementation instead of the SNR (which is difficult to measure), in which the signal strength represents signal plus noise (S+N) value. Since the channel condition varies in time, maintaining a certain level of (S+N) value does not guarantee that a certain level of BER is being maintained. So that it is necessary for the MS-GSC to adjust the threshold level based on the estimated current BER. For details on the impact of the use of (S+N), refer to [8]. Hereafter, we use SNR and (S+N) interchangeably, but it is clear from the context which one is intended.

The operation of the MS-GSC (T_m, L) is as follows. The MS-GSC starts with a given threshold T_m and k rake fingers, where $k \le L$. The combined signal strength is periodically measured. If the combined signal strength is less than the threshold, then one more rake finger is activated in the next time frame. Since the signal with a smaller delay is stronger in general, the finger with the smallest delay is selected and activated. Note that the delay information is provided by a cell searcher. If the combined signal strength is sufficiently greater than the threshold, then a rake finger with the lowest signal strength is turned off in the next time frame. Otherwise, the current rake combining with k fingers is maintained.

Comparing with the AT-GSC and the NT-GSC, the proposed MS-GSC has two benefits. Since the combined signal strength in the MS-GSC is maintained close to the threshold value, the statistics of erroneous bits have a low standard deviation, which will be presented in Section 4. This may result in less burst errors, which leads to a better error correction for a channel decoder. The second benefit is that the MS-GSC turns on a finger with the smallest delay, so that it does not need to measure the signal strength of a finger before it is turned on. In contrast, the AT-GSC and the NT-GSC necessitate activation of each finger momentarily to measure the current signal strength, so that it can determine whether the finger should be turned on or remain turned off.

3. ADAPTIVE RAKE COMBINING SCHEME

To maintain a certain level of BER, a mechanism to dynamically adjust a threshold value to adapt to a time-varying channel condition is required. In this section, we propose an adaptive scheme to determine threshold values for the three GSC methods, the AT-GSC, the NT-GSC, and the proposed MS-GSC. Since we use the (S+N) value instead of the SNR value as a threshold, hereafter, we refer to an (S+N) threshold value as a threshold value. Threshold values of a GSC method should be adjusted dynamically to turn off a maximal number of fingers, while maintaining the required BER or equivalently QoS. When a Viterbi decoder is employed for a system, the error metric of the survived path at the end of the forward processing can be used to estimate the current BER. For the case of turbo decoders, the number of iterations or the rate of convergence may be used for the estimation. The block diagram of the proposed system is presented in Figure 1, in which the control logic adjusts the threshold value dynamically based on the inputs from the channel decoder.

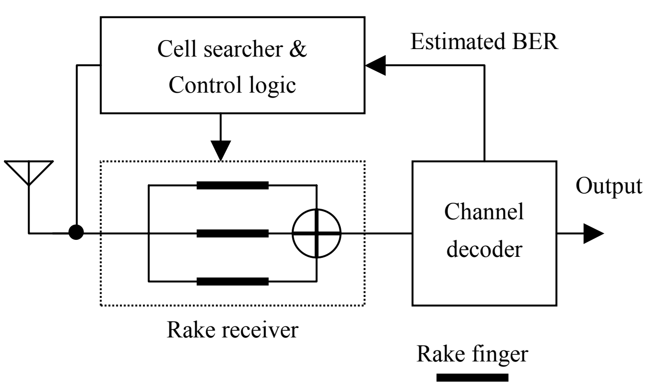

Figure 1. Block Diagram of the Proposed Adaptive Scheme

The proposed adaptive scheme consists of two loops, an outer loop and an inner loop. The outer loop adjusts the threshold value, and the inner loop dynamically changes the finger selection based on the threshold value provided from the outer loop.

Suppose that a set of N threshold values $\{T_1, T_2, \ldots T_i, \ldots T_N\}$ for a GSC has been determined using system simulation, and suppose that $T_1 > T_2 > \ldots > T_N$ for the AT-GSC and the NT-GSC and $T_1 < T_2 < \ldots < T_N$ for the MS-GSC. This implies that a GSC selects a larger number of fingers for a larger index i, which results in a lower BER. A larger N leads to, on average, a larger number of fingers turned off, but it results in more complex hardware and more frequent on and off operations of fingers. Therefore, a larger N does not guarantee more power saving due to more frequent switching operations.

The outer loop adjusts the threshold value as described next. Suppose that the current threshold of a GSC method is T_i. If the BER estimated at the end of each frame is higher than the required BER, then the threshold is changed to T_{i+1} to decrease the BER. If the BER is sufficiently lower than the required BER, then the threshold index is changed to T_{i-1}. Otherwise, the current threshold T_i is maintained. In practice, to avoid too frequent changes of the threshold value the current threshold is maintained if the BER lies in a certain range. The inner loop dynamically adjusts selection of fingers based on the new threshold value according to the selection strategy of the employed GSC scheme.

The power saving of the proposed adaptive scheme is highly dependent on the operating condition and the employed threshold set. The average number of rake fingers activated $\overline{m}$ is obtained as $\overline{m} = \sum_{i=1}^{N} A_i P_i$, where N is the number of threshold values $\{T_i\}$, A_i is the average number of rake fingers activated for a threshold value T_i, and P_i is the probability of the proposed adaptive scheme operating on the threshold value T_i. Then, the power saving with the proposed adaptive scheme over the MRC rake combiner is obtained as $\frac{L-\overline{m}}{L}$. The probability P_i depends on the channel condition and the power control strategy, so it is difficult to estimate the probability accurately and hence the power saving of the scheme. Analytical results under the assumption of the equal probability are available in [8].

4. SIMULATION RESULTS

The proposed adaptive combining scheme is integrated with three GSC methods and is simulated for a mobile rake receiver of a WCDMA system. System models and parameters considered in our simulation are typical for the 3GPP WCDMA system [9] except only one transmit antenna is used at a base station.

Eight users' signals with a spreading factor 32 and the common pilot channel (CPICH) signal with a spreading factor 256 are modulated, channelized, combined, scrambled, pulse-shaped, and transmitted through the channel. 20 % of the total transmitted power is allocated to the CPICH, and the remaining 80% of the power is allocated equally to each user signal. For the channel profile (such as delay and average power), the ITU (International Telecommunication Union) channel profiles described in [10] are applied. Four or six multipath signals (M) are generated in the wireless channel depending on the channel type. Each multipath signal is experienced an independent Rayleigh fading. For the Vehicular channel model, the mobile velocity is assumed to be 50 km/hr, which results in 99.1 Hz of maximum Doppler frequency for a 2.14 GHz carrier frequency. The mobile velocity for the

Pedestrian channel is assumed to be 3 km/hr, which results in 5.9 Hz of maximum Doppler frequency. The despread CPICH signal of each multipath signal is utilized to estimate the channel condition, i.e., the amplitude and the phase, and thus is used as a weighting factor of each rake finger to combine the selected rake finger outputs. To reduce the simulation time, channel encoding and decoding is not included. Thus, a hard decision is made at the output of rake combiner and the output is compared with the original data bits to evaluate the BER performance. This BER is fed back to the control logic for the proposed adaptive rake combiners.

4.1 MS-GSC, AT-GSC, and NT-GSC

First, we present the BER performances of the MS-GSC, the AT-GSC, and the NT-GSC under the ITU Pedestrian B channel profile. Figure 2 shows the BER performance of the proposed MS-GSC with a threshold set of δ = 0.5, where *δ is defined as the difference between the average numbers of rake fingers activated for two consecutive threshold values*. As shown in the figure, the MS-GSC (T_m, 5) performs better as the threshold T_m becomes large. The AT-GSC and the NT-GSC show almost the same BER performance as that of the MS-GSC with a threshold set of δ = 0.5.

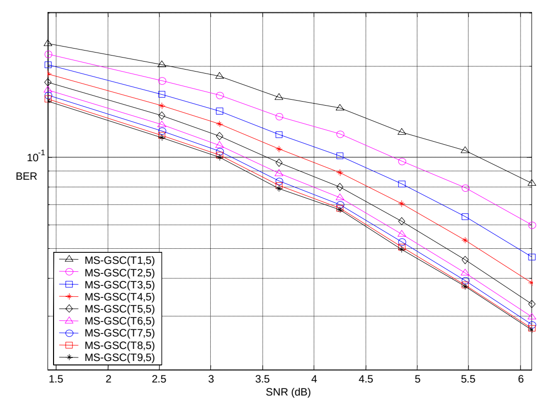

Figure 2. BER Performance with Pedestrian B Channel

Next, we present the BER performance under the ITU Vehicular A channel profile. The BER performance of the AT-GSC with a threshold set of δ = 0.5 is presented in Figure 3. As shown in the figure, the AT-GSC (T_a, 4) performs better as the threshold T_a becomes smaller. We observed that the MS-GSC with a threshold set of δ = 0.5 shows almost the same BER performance as that of the AT-GSC. The NT-GSC performs better than the AT-GSC and the MS-GSC using a threshold set such that the average number of rake fingers activated is same. When the Vehicular B channel profile is applied, each GSC method shows the same trend as for the case of the Vehicular A channel profile. The only difference lies in the combined SNR and the BER performance, since each channel profile has a different power profile.

4.2 Adaptive Rake Combiners

The BER performance as well as the power saving of the proposed adaptive scheme are presented next. To generate the feedback information for the outer loop of the proposed adaptive rake combiners, the current BER performance is estimated on every frame at the rate of 100 Hz. To adjust the number of rake fingers activated for the inner loop of the adaptive rake combiner, the combined signal quality is evaluated in order to check whether it meets the given threshold value provided from the outer loop at the pilot symbol rate of 15 kHz (= 3.84 MHz / 256). The control logic to evaluate the BER and the combined signal quality operates at a much lower frequency compared with the chipping rate (3.84 MHz), at which rake fingers operate. Hence, the power dissipation due to the control logic would be small when implemented in the CMOS technology. (Note that the power dissipation is roughly proportional to the operating frequency in the CMOS.) Thus, the power saving of the adaptive rake combiner can be represented as the average number of rake fingers deactivated.

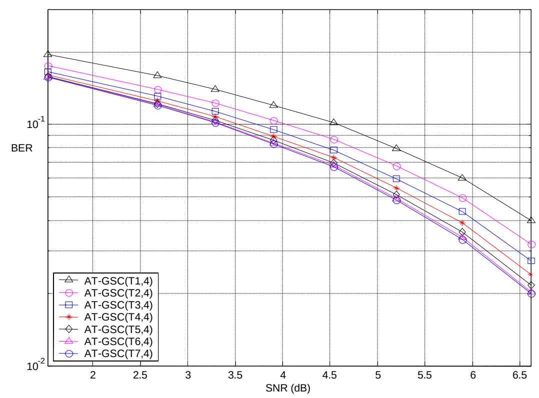

Figure 3. BER Performance with Vehicular A Channel

The performance of adaptive rake combiners under various conditions for the ITU Vehicular A channel profile with a fixed amount of noise is summarized in Table 1. The first column under "Condition" represents operating conditions, in which the desired target BER (TBER) and the average combined SNR with the MRC are presented. A fixed amount of noise is added to the received signal at the receiver, and we obtain an average combined SNR for four fingers with the MRC. The relative noise power to the signal power of the first multipath is –12.0 dB, –11.5 dB, -11.0 dB, and -10.5 dB, which yields 3.90 dB, 4.54 dB, 5.20 dB, and 5.89 dB of the combined SNR, respectively. The second column under "Perform" has three items such that an average BER, a normalized standard deviation of the BER (N-STD), and an average number of rake fingers deactivated (F-saving). The normalized standard deviation is computed as the ratio of standard deviation over the mean of erroneous bits. The column "MRC" represents the performance of the conventional MRC rake combiner. The last three columns (MS-GSC, AT-GSC, and NT-GSC) represent the performance of the adaptive rake combiner employing MS-GSC, AT-GSC, and NT-GSC, respectively. For brevity, we call them as MS-GSC, AT-GSC, and NT-GSC, respectively, in the following.

As presented in Table 1, all three GSCs achieve the required BER performance for the most cases except the AT-GSC under the target BER of 8 %. However, the deviation is less than 0.25 %, which may be insignificant for a channel decoder. The NT-GSC shows the best performance in terms of power saving. The power saving with the NT-GSC ranges from 44.5 % (= 1.78/4) to 67.8 % (= 2.71/4). The MS-GSC shows the smallest normalized standard deviation, which would result in the least burst errors. Meanwhile, the AT-GSC shows the largest normalized standard deviation. The simulation results under the ITU Pedestrian B channel profile with a fixed amount of noise show the same trend as that under the ITU Vehicular A channel profile.

To verify the ability of the proposed adaptive rake combiner to dynamically adapt to the environment, a variable amount of noise is also considered for the simulation. The result is almost the same as with a fixed amount of noise. Each adaptive rake combiner achieves the required BER performance for most cases. With the exception of a few cases, the maximum deviation is less than 0.5 %. The NT-GSC shows the best performance in terms of power saving, in which the maximum power saving is 65.8 % (= 2.63/4). Like for the case of a fixed amount of noise, the MS-GSC and the AT-GSC show the smallest and the largest normalized standard deviation, respectively. More numerical results are available in [8].

Table 1. Performance of Adaptive Rake Combiners (Vehicular A)

Condition		Perform	MRC	MS-GSC	AT-GSC	NT-GSC
TBER	SNR					
10 %	3.90 dB	BER	8.48 %	9.67 %	9.93 %	9.59 %
		N-STD	22.19 %	21.86 %	27.25 %	25.21 %
		F-saving	0	1.88	1.91	2.12
	4.54 dB	BER	6.63 %	8.98 %	8.96 %	8.76 %
		N-STD	23.48 %	21.58 %	26.57 %	23.95 %
		F-saving	0	2.62	2.54	2.67
8 %	4.54 dB	BER	6.66 %	7.65 %	8.02 %	7.68 %
		N-STD	23.61 %	22.94 %	29.27 %	27.09 %
		F-saving	0	1.84	1.90	2.13
	5.20 dB	BER	4.89 %	7.05 %	7.05 %	6.87 %
		N-STD	28.27 %	25.93 %	31.87 %	28.95 %
		F-saving	0	2.66	2.58	2.71
6 %	5.20 dB	BER	4.88 %	5.27 %	5.71 %	5.35 %
		N-STD	27.44 %	26.91 %	35.86 %	31.59 %
		F-saving	0	1.39	1.50	1.78
	5.89 dB	BER	3.41 %	4.97 %	5.15 %	4.94 %
		N-STD	30.13 %	28.57 %	36.88 %	31.89 %
		F-saving	0	2.55	2.48	2.68

In summary, the simulation results indicate that the proposed adaptive scheme works well with all GSC methods to maintain the required BER performance. The adaptive scheme with the NT-GSC shows good performance in terms of finger saving, and the power saving is as high as 67.8 %. The adaptive scheme with the MS-GSC shows the smallest normalized standard deviation for the all cases, which is somewhat expected.

5. CONCLUSION

In this paper, we propose a new generalized selection combining (GSC) technique and an adaptive low-power rake combining scheme to save the power consumption of mobile rake receivers for a WCDMA system. The new GSC technique called minimum selection GSC (MS-GSC) selects a minimum number of rake fingers as long as the combined SNR is larger than a given threshold. Since the MS-GSC tries to maintain the combined signal strength at a certain level, the normalized standard deviation of the BER is the lowest among all the GSCs considered. This results in better error correction when a channel decoder is applied. In addition, the MS-GSC is advantageous in terms of power saving.

The proposed rake combining scheme adaptively adjusts the threshold value to maintain the desired BER, in which each GSC dynamically selects *m* rake fingers among *L* rake fingers to meet the given threshold condition, while turning off unselected fingers to save the power dissipation. The simulation results indicate that the proposed adaptive scheme works well with all GSC methods to maintain the required BER performance. The adaptive scheme with the NT-GSC shows good performance in terms of finger saving. The proposed scheme reduced the power consumption of a mobile rake receiver up to 67.8 %.

REFERENCES

[1] N. Kong, T. Eng, and L. B. Milstein, "A Selection Combining Scheme for RAKE Receivers," *IEEE International Conference on Universal Personal Communications*, pp. 426-430, November 1995.

[2] M. Z. Win and J. H. Winters, "Virtual Branch Analysis of Symbol Error Probability for Hybrid Selection/Maximal-Ratio Combining in Rayleigh Fading," *IEEE Transactions on Communications*, Vol. 49, No. 11, pp. 1926-1934, November 2001.

[3] M.-S. Alouini and M. K. Simon, "An MGF-based Performance Analysis of Generalized Selection Combining over Rayleigh Fading Channels," *IEEE Transactions on Communications*, Vol. 48, No. 3, pp. 401-415, March 2000.

[4] C. M. Lo and W. H. Lam, "Approximate BER Performance of Generalized Selection Combining in Nakagami-*m* Fading," *IEEE Communications Letters*, Vol. 5, No. 6, pp. 254-256, June 2001.

[5] L. Yue, "Analysis of Generalized Selection Combining Techniques," *IEEE Vehicular Technology Conference*, pp. 1191-1195, May 2000.

[6] A. I. Sulyman and M. Kousa, "Bit Error Rate Performance of a Generalized Diversity Selection Combining Scheme in Nakagami Fading Channels**,"** *IEEE Wireless Communications and Networking Conference*, pp. 1080-1085, September 2000

[7] M. K. Simon and M.-S. Alouini**,** "Performance Analysis of Generalized Selection Combining with Threshold Test per Branch (T-GSC)," *IEEE Global Telecommunications Conference*, pp. 1176-1181, November 2001.

[8] Suk Won Kim, **"**Smart Antennas at Handsets for the 3G Wideband CDMA Systems and Adaptive Low-Power Rake Combining Schemes," Ph. D. Dissertation, Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, July 2002.

[9] http://www.3gpp.org/.

[10] ITU ITU-R M.1225, "Guidelines for Evaluations of Radio Transmission Technologies for IMT-2000," 1997.