HYBRID-SELECTION/OPTIMUM COMBINING

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Abstract

In this paper we propose and study hybrid-selection/optimum combining (H-S/OC). With this technique, L out of M diversity branches are weighted and combined to maximize the output signal-to-interference-plus-noise ratio. We first present computer simulation results for L=1, showing that selecting the antenna with the largest signal-to-interference power ratio (S/I), rather than the largest signal power, can significantly improve performance when a few strong interferers are present. Our results with equal-power interferers show that H-S/OC can greatly suppress more than L interferers when $M > L$. Finally, we present computer simulation results for an ANSI-136 TDMA cellular system which show a 7-fold increase in capacity for H-S/OC with L=1,M=12 or L=2,M=4. Thus, H-S/OC offers the potential for systems to operate with multiple strong cochannel interferers and obtain diversity gain with only a few receiver chains.

I. INTRODUCTION

In this paper we propose and study hybrid-selection/optimum combining (H-S/OC). With this technique, L out of M diversity branches are weighted and combined to maximize the output signal-to-interference-plus-noise ratio (SINR). This technique is an extension of hybrid-selection/maximum ratio combining (H-S/MRC), where L out of M diversity branches are weighted and combined to maximize the signal-to-noise ratio (SNR) (which has been extensively studied (see, e.g., [1])), to the case with cochannel interference. For the case where the diversity branches are antennas, these hybrid techniques have the advantage that they require fewer receiver RF chains and A/D converters (which is where much of the cost and power consumption of the receiver lies) than full MRC (or OC); yet, as shown in [1] for H-S/MRC, the performance can approach that of M-branch MRC even for L much less than M. However, the diversity gain against multipath fading becomes incrementally smaller with increasing M, i.e., most of the improvement is obtained with a few diversity branches, and thus the improvement of L out of M H-S/MRC over L-branch MRC rapidly approaches a limiting value as M and/or L increases. However, since OC can completely suppress M-1 interferers with M antennas [2], its gain can continue to grow substantially with M, e.g., in cellular systems capacity increases on the order of M-fold with M antennas may be possible [3]. Thus, a large M is more important with OC, and one would expect that H-S/OC would have even greater advantage than H-S/MRC in an interference-limited environment. (Note that the performance of H-S/OC is equal to that of H-S/MRC in a noise-only environment).

Now, L-branch OC can completely suppress K interferers (for $K < L$) and obtain an L-K diversity gain against multipath fading [3]. With $K \geq L$, only limited interference suppression is possible, but if the number of dominant interferers (out of K total interferers) is less than L, the performance gain with OC can still be large. For example, in field tests with ANSI-136 cellular systems, 2-branch OC has been shown to provide a 3-4 dB gain over 2-branch MRC in interference-limited environments, nearly doubling capacity. Furthermore, simulation results indicate that with 4-branch OC, frequency reuse in every cell is possible, resulting in a 7-fold increase in capacity [4]. With H-S/OC we would hope for even larger gains, an indication of which would be the ability of H-S/OC to significantly suppress K equal-power interferers when $K \geq L$. Note that this should be possible (if M is large enough) because the receiver can select the L antennas where the received channel vectors for the K interferers are nearly orthogonal to the desired signal channel vector. Therefore, below we study the performance of H-S/OC with K ($K \geq L$) equal-power interferers versus M. Then we study the performance of H-S/OC in a cellular environment, specifically ANSI-136, using a system simulation program similar to that used in [5].

Note that a variation of H-S/OC can be used in in multiple transmit/receive antenna (multiple input multiple output, MIMO) systems, where an L-fold increase in capacity can be achieved with L transmit/receive antennas [6,7]. In these systems, since additional transmit and/or receive antennas may be needed for diversity gain against multipath fading and for cochannel interference mitigation, H-S/OC could be useful in keeping the number of RF transmit and/or receive chains at a reasonable value. In particular for the transmit antennas, feedback from the receiver could be used to determine which transmit antennas to select that would maximize the SINR at the receiver, or, in duplex operation, the measured receive channels could be used to select the best antennas for transmission. Selection of transmit antennas in MIMO systems has been previously studied in [8].

In Section II we present computer simulation results for H-S/OC with equal-power interferers. A computer simulation model for cellular systems is described in Section III along with numerical results. A summary and conclusions are presented in Section IV.

II. SINGLE LINK RESULTS

With H-S/OC, L out of M antennas are selected and combined using OC to maximize the output SINR. Note that for L=1, H-S/OC is just selection diversity. However, previous analyses [9] for selection diversity have only considered the case of K=0 with selection of the antenna with the highest received desired signal strength, or the case of $K \geq 0$ with selection of the antenna with the highest desired signal plus interference power. For our H-S/OC system, though, since we consider optimum combining, we assume that we can distinguish the desired signal from the interference (e.g., with training sequences as in ANSI-136), and thus we can determine both the desired and cochannel interference power. In this case, the optimum selection criterion is to select the antenna with the highest SINR.

We used computer simulation to study the performance of H-S/OC with K equal-power interferers. We determined the receive SINR required for an average (averaged over the Rayleigh fading) BER of 10^{-2} with coherent detection of binary phase shift keying (BPSK) with independent Rayleigh fading at each diversity branch and K equal-power interferers. This required SINR was determined by the bisection technique, where the receive SINR was adjusted until a 10^{-2} BER was achieved with a receive SINR accuracy of 0.1 dB.

For a given receive SINR, the BER is calculated as follows. We average the BER by using Monte Carlo simulation with 20,000 iterations. For each iteration, we generate M independent Gaussian random variables for the desired signal channel and each of the K interferer channels (total of $(K+1)M$ independent Gaussian random variables). We then determine the BER for each of the $\frac{M!}{(M-L)!L!}$ possible selections of L diversity branches and find the minimum BER over these selections for use in the averaging over 20,000 iterations. For each selection of L diversity branches, the corresponding BER (BER_c) is given by

$$BER_c = \frac{1}{2} erfc(\sqrt{\mathbf{S}^{\dagger} \mathbf{R}_{I+M}^{-1} \mathbf{S}}) \quad , \tag{1}$$

where

$$\mathbf{S} = \left[S_1 S_2 \cdots S_L \right]^T \quad , \tag{2}$$

$$\mathbf{R}_{I+N} = \sigma^2 \mathbf{I} + \sum_{i=1}^{K} \mathbf{I}_i \mathbf{I}_i^{\dagger} \quad , \tag{3}$$

$$\mathbf{I}_i = \left[I_{i1} I_{i2} \cdots I_{iL} \right]^T \quad , \tag{4}$$

the superscripts $\dagger$ and T denote complex conjugate transpose and transpose, respectively, the S_i's are zero-mean, complex Gaussian random variables with variance 1, the I_{ij}'s are zero-mean, complex Gaussian random variables with variance $\frac{1}{KS/I}$ (note that S/I is the signal-to-*total*-interference-power ratio), $\mathbf{I}$ is an LXL identity matrix, and σ^2 is the noise power (given by $\frac{1}{S/N}$). Thus,

$$SINR = \frac{1}{S/N^{-1} + S/I^{-1}} \quad . \tag{5}$$

We set

$$S/N = \begin{cases} 40 \text{ dB for } K > 0 \\ SINR \text{ for } K = 0 \end{cases} \quad . \tag{6}$$

Figure 1 shows the required receive SINR versus M for $L=1$ and K=0, 1 and 2. As noted above, for $L=1$, H-S/OC is just selection diversity, but the diversity branch is selected based on the largest branch receive S/I rather than the typically-used S/N or signal strength S. However, for the $K=0$ case (which is the noise-only case or equivalently the $K=\infty$ case), the results are the same whether S/I, S/N, or S is used for selection. It can be seen from Figure 1 that selection based on S/I rather than S/N or S provides an increasing improvement as M increases. With M=10, S/I-based selection permits operation with an interferer that is more than 3 dB stronger than the desired signal, which is 5 dB higher than with S-based selection.

Figure 2 shows the required receive SINR versus M for L=1 to 4 and $K=L-1$, L, and $L+1$. Results for H-S/MRC (which is equivalent to H-S/OC with K=0) are also shown. With $K=L-1$, the receiver can operate with interferers that have a total power up to 40 dB higher than the desired signal (which corresponds to the S/N - note that the maximum I/S for an average BER of 10^{-2} is always approximately equal to the S/N) but with a loss of multipath diversity when $L=M$. However, for $M>L$, diversity gain is possible, with the improvement approaching that of selection diversity without interference. With $K=L$, for $L=M$, the performance of OC is only a few dB better than MRC. However, as M increases (for a given L) this difference becomes much larger, and the difference increases with L. For example, with $L=4$, H-S/MRC improves performance by only 3 dB for M = 10 versus 4, but H-S/OC improves performance by more than 20 dB for M = 10 versus 4. Thus, if there are a small number of interferers, additional diversity branches have a much greater benefit with H-S/OC than with H-S/MRC. Looking at the results for $K=L+1$ (where there are 2 more interferers than degrees of freedom in the receiver), note that the improvement with additional diversity branches is still large, and this improvement increases significantly with M even at large M.

III. CELLULAR SYSTEM PERFORMANCE

To study the performance of H-S/OC in a typical cellular system (specifically ANSI-136), we used a modified version of the computer simulation program of [5]. This program used Monte Carlo simulation based on a simulation program from Justin Chuang, which is an event-driven simulation using a model described in [10]. The cellular system consisted of hexagonal cells in a 7×14 grid with a frequency reuse (N) of 7 and a 6×6 grid with N = 4 (as in [5]), 3, and 1. The base stations were located at the center of each cell, and the users were uniformly distributed in each cell. Shadow fading with a lognormal distribution was used, with a loss exponent of 3.7 and a standard deviation of 8 dB.

The simulation was event driven based on arrivals and departures. At each event, it was first determined whether the event was an arrival or departure. The probability that the event is a departure is given by

$$P = \frac{\mu nact}{[\lambda(ntot - nact) + \mu nact]}\quad, \qquad (7)$$

where $nact$ is the number of active users, λ is the arrival rate, μ is the service rate (the inverse of the length of calls), and $ntot$ is the total number of subscribers in the system. For our simulation, we set $\frac{\lambda}{\mu}$ = .2 or 20% usage per user, e.g., an average call length of 3 minutes with a call every 15 minutes (note that our results in [5] did not vary significantly for $0.1 < \lambda/\mu < 0.4$). The total number of subscribers in the system depends on λ/μ, the number of sectors per cell ($nsector$), the number of channels available per sector ($nserver$), the number of cells in the system ($ncell$), the loading (occ), and the number of time slots (nts). Using typical cellular parameters, we considered a three sector system with 20 channels per sector, with 98 for N=7 and 36 cells for N = 4, 3, and 1, as described above. Note that 98 cells is comparable in size to the largest cellular system in current use. The probability of blockage due to no available channels is given by the Erlang B formula, and for this cellular system, a 2% blockage probability (which is a typical design goal) occurs at about 60% loading, and therefore this loading was used in the simulation. Now, the total number of subscribers is given by

$$ntot = \left[1 + \frac{\mu}{\lambda}\right] nserver \cdot nsector \cdot occ \cdot nts \cdot ncell\ . \qquad (8)$$

Thus, with the above parameters, $ntot$ = $6 \cdot 20 \cdot 3 \cdot 0.6 \cdot 3 \cdot ncell$= $648 ncell$, or 63,504 for N=7 and 23,328 for N = 4, 3, and 1.

Each simulation run begins with no active users. At the beginning, the events are mainly arrivals (note that the probability of departure is small when the number of active users is small). For each arrival, a random location is chosen for the user. The user then chooses the base station with the strongest signal (with shadow fading), and determines the sector for that base station. For that sector, we considered random channel (carrier) and time slot selection with carrier packing. That is, the user randomly chooses an empty time slot in a channel with at least one other user (for carrier packing). If no such time slot exists, then the user randomly chooses a time slot and channel among the unused channels for that sector.

For each departure, an active user is randomly chosen to depart, and the mean S/I as well as the desired and interfering signal powers on the uplink and downlink for that user are determined.

The average BER with H-S/OC is then determined using a method similar to that described above for the equal-power interferer case. Specifically, we average the BER by using Monte Carlo simulation with 2,000 iterations. For each iteration, we generate M independent Gaussian random variables for the desired signal channel and each of the K interferer channels (total of $(K+1)M$ independent Gaussian random variables). We then determine the OC output S/I ($\mathbf{S}^{\dagger}\mathbf{R}_{I+N}^{-1}\mathbf{S}$) for each of the $\frac{M!}{(M-L)!L!}$ possible selections of L diversity branches and find the minimum S/I over these selections for use in the averaging over 2,000 iterations. Since ANSI-136 uses DQPSK, we considered coherent detection of DQPSK. Thus, for each selection of L diversity branches, the corresponding BER (BER_c) is given by

$$BER_c = 2P_e - P_e^2 \quad , \tag{9}$$

where

$$P_e = \frac{1}{2} erfc(\sqrt{\mathbf{S}^{\dagger}\mathbf{R}_{I+M}^{-1}\mathbf{S}/2}) \quad . \tag{10}$$

To study the steady state performance of the system, the distribution of this departure uplink and downlink average BER is calculated after the time when the number of active users exceeds 90% of the steady state value, which is given by $occ \cdot ncell \cdot nserver \cdot nsector \cdot nts$ = 10584 for N=7 and 3888 for N = 4, 3, and 1. The simulation was run for 19,600 arrivals for N=7 and 7200 arrivals for N = 4, 3, and 1, to ensure an adequate number of samples at a 1% cumulative probability distribution of average BER (although some results are shown to 0.1%). For ANSI-136, we assume adequate performance at BER = $2X10^{-2}$ and therefore define the outage probability as the probability that the BER is below this value.

For ANSI-136, the downlink must be continuous, and thus interference occurs among all users in a channel at a base station and all users in the same channel at other base stations. This was also included in the computer simulation program.

Figures 3 and 4 show the outage probability versus M for the uplink and downlink, respectively, for H-S/OC. Results are shown for N = 7, 4, 3, and 1 with L=1, 2, and 3. The results for the uplink and downlink are similar, although the downlink has a slightly lower outage probability. With L=1, the outage probability on the uplink and downlink is less than 10% for N=7 and M=1, similar to current systems, while M=2 is required for a similar outage for N=4 and 3, and M=15 for N=1. On the downlink, a 10% outage probability with N=1 requires M=3 with L=2 and L=3, and a 1% outage probability requires M=7 and 5 for L=2 and 3, respectively. Also, the performance of OC with L=3 can be achieved with H-S/OC and L=2,M=4, or L=1,M=16. These results show that the outage probability can be dramatically reduced with H-S/OC.

IV. CONCLUSIONS

In this paper, we have proposed and studied H-S/OC and shown the large improvement of L out of M H-S/OC over H-S/MRC and L-branch OC. With K equal-power interferers, when $K < L$, H-S/OC provides near-complete cochannel interference suppression with an additional gain similar to selection diversity (without the interference). Furthermore, H-S/OC can greatly suppress even more equal-power interferers than the available degrees of freedom when M is greater than L, with the suppression increasing significantly with M even for $M >> L$.

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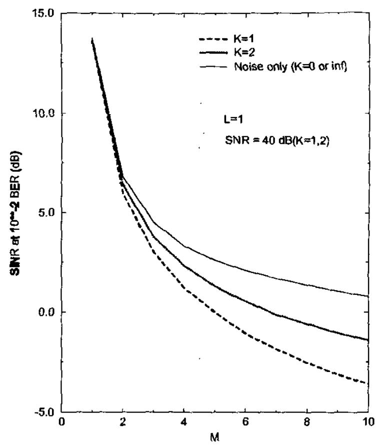

Fig. 1. Receive SINR for a 10^{-2} average BER versus M with L=1 for K=0, 1, and 2.

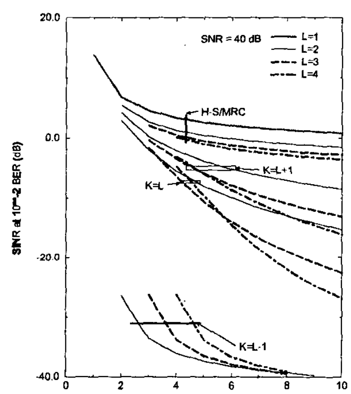

Fig. 2. Receive SINR for a 10^{-2} average BER versus M for H-S/OC and H-S/MRC with various K relative to L.

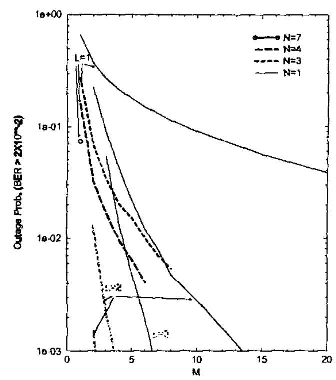

Fig. 3. The outage probability versus M for the uplink with H-S/OC.

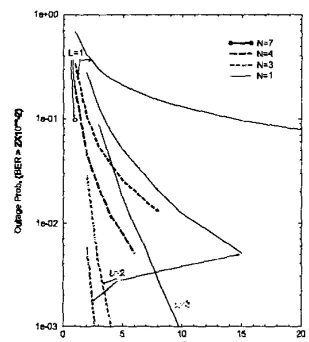

Fig. 4. The outage probability versus M for the downlink with H-S/OC.