Finger Management Schemes for RAKE Receivers with a Minimum Call Drop Criterion

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***Abstract*—We propose and analyze in this letter new finger management techniques which are applicable for RAKE receivers operating in the soft handover region. These schemes employ "distributed" types of generalized selection combining (GSC) and minimum selection GSC schemes in order to minimize the impact of sudden connection loss of one of the active base stations. By accurately quantifying the average error rate, we show through numerical examples that our newly proposed distributed schemes offer a clear advantage in comparison with their conventional counterparts.**

***Index Terms*—Fading channels, diversity techniques, RAKE receiver, generalized selection combining (GSC), minimum selection GSC, and performance analysis.**

I. Introduction

MULTI-PATH fading is an unavoidable physical phenomenon that affects considerably the performance of wireless communication systems. While usually viewed as a deteriorating factor, multi-path fading can also be exploited to improve the performance by using RAKE type of receivers [1, Section 9.5.1]. RAKE reception is a technique which uses several baseband correlators called fingers to individually process multi-path signal components. The outputs from the different correlators are coherently combined to improve the signal-to-noise ratio (SNR) and to therefore lower the probability of deep fades. Since they rely on resolvable multipaths to operate, RAKE receivers are used in conjunction with wideband systems. such as wideband code division multiple access (WCDMA).

In the soft handover (SHO) region, there is a large number of available resolvable paths coming from the serving base station (BS) as well as the target BS while the number of fingers in the mobile unit is very limited due to hardware and battery life time constraints. Hence, the RAKE receiver needs to judiciously select a subset of paths in order to achieve the required performance with a low complexity/processing-power consumption. For instance, with generalized selection combining (GSC) [2]–[4] which is a generalization of selection combining (SC), the receiver chooses a fixed number of paths with the largest instantaneous SNR from all available diversity paths and then combines them as per the rules of maximal ratio combining (MRC). As a power-saving implementation of GSC, minimum selection GSC (MS GSC) [5]–[7] was recently proposed and studied. With MS GSC, after examining and ranking all available paths, the receiver tries to raise the combined SNR above a certain threshold by combining in an MRC fashion the least number of the best diversity paths, and as such, MS GSC can save considerable amount of processing power by keeping less MRC branch active on average in comparison to the conventional GSC.

More recently, by considering macroscopic diversity techniques, the authors proposed and analyzed the performance of new finger assignment schemes that maintain a low complexity and reduce the SHO overhead [8], [9]. The main idea behind [8], [9] is that, in the SHO region the receiver uses the additional network resources only if necessary. It has been shown that these schemes can reduce the unnecessary path estimations, SNR comparisons, and the SHO overhead with a slight performance loss compared to the conventional GSC scheme when they operate in the SHO region.

Bearing in mind that our previous efforts focused on schemes that minimize the use of network resources, we consider in this letter other finger management schemes that are designed to minimize call drops by proposing two finger management schemes denoted by *distributed GSC* and *distributed MS GSC*. More specifically, we apply the conventional GSC scheme and the conventional MS GSC scheme to each BS by distributing the combined paths among the active BSs. The main idea behind these newly proposed schemes is that they try to "balance" SNR/paths among as many BSs as possible so that if the mobile unit ends up losing connection with one BS (due for example to the corner effect), we can keep a great proportion of the total initially combined SNR, and as such, minimize the possibility of call drops. The main contribution of this letter is to provide an analytical framework deriving the average error probability of our proposed schemes. Some selected numerical results show that our proposed schemes considerably outperform the conventional ones when there is a high chance of losing connection with a BS.

II. Finger Management Scheme

A. Channel and System Model

We focus on the receiver operation when the mobile unit is moving from the coverage area of its serving BS to that of a target BS. Note that in the SHO region the mobile unit is of roughly the same long distance from the serving and the

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target BSs. Thus, we assume first that the signals from all the resolvable paths experience independent and identically distributed (i.i.d.) Rayleigh fading conditions and that the receiver operates over a "perfect" uniform power delay profile provided by a multi-path searcher in a way that the multi-path components are correctly assigned to the RAKE fingers. In this channel model, we do not consider the effect of inter-symbol/channel interferences by assuming, for example, perfect spreading codes. As such, if we let γ denote the instantaneous received SNR of all the available resolvable paths, then γ follows the same exponential distribution with mean, $\overline{\gamma}$.

We consider a mobile unit which is equipped with an L_c-finger RAKE receiver and is capable of despreading signals from different BSs using different fingers in order to facilitate SHO. We further assume that there are L_1 and L_2 available paths from BS1 and BS2, respectively. In the SHO region, according to the mode of operation described in the next section, at most L_c out of the $L_1 + L_2$ available paths are used for RAKE reception.

B. Mode of Operation

We distinguish the combined SNRs from each BS by letting γ_{B_1} and γ_{B_2} be the combined SNRs of the paths from BS1 and BS2, respectively. In both schemes, we assume first that the receiver estimates all the resolvable paths.

1) Distributed GSC: With this scheme, the receiver selects and combines the L_{c_1} largest paths among L_1 ones and the L_{c_2} largest paths among L_2 ones, respectively, where $L_{c_1}+L_{c_2} = L_c\,(\leq L_1, L_2)$. Hence, γ_{B_1} and γ_{B_2} are the combined output SNRs of L_{c_1}/L_1-GSC and L_{c_2}/L_2-GSC, respectively.

2) Distributed MS GSC: With this scheme, the receiver selects the least number of the best paths such that the combined SNRs, γ_{B_1} and γ_{B_2}, are greater than the predetermined thresholds, γ_{T_1} and γ_{T_2}, respectively. More specifically, starting from the best path from BS1, the receiver tries to increase the combined SNR, γ_{B_1}, above the threshold, γ_{T_1}, by combining an increasing number of diversity paths. This process is performed until either γ_{B_1} is above γ_{T_1} or the best L_{c_1} paths out of L_1 ones are combined. In the later case, the receiver acts as a traditional L_{c_1}/L_1-GSC combiner. The same algorithm is applied to BS2 along with the chosen design parameters, L_{c_2} and γ_{T_2}, where $\gamma_{T_1}+\gamma_{T_2} = \gamma_T$ and γ_T is the final output threshold. Hence, γ_{B_1} and γ_{B_2} are the combined output SNRs of L_{c_1}/L_1-MS GSC and L_{c_2}/L_2-MS GSC, respectively.

It is important to note that, in both conventional and proposed distributed schemes, while it is of course clear that MS-GSC is always outperformed by GSC, MS-GSC will use on average less number of combined paths to reach a certain threshold, and as such, save the processing power on the mobile units receiving data on the down-link. In addition, in comparison to the conventional schemes, the proposed distributed schemes with minimum call drop criterion will show better performance when the signals coming from one BS are completely lost. In the next section, we investigate this issue by exactly quantifying the average error rate of the proposed schemes in terms of the probabilities of losing BSs.

III. Performance Analysis

In this section, we analyze the average error rate of the proposed schemes. If we assume that P_1 and P_2 are the probabilities of losing BS1 and BS2, respectively, which can be statistically characterized from the corner effect [1, Chapter 12], then the final combined SNR, denoted by γ_t, is mathematically given by

$$\begin{aligned}\gamma_t &= (1-P_1)(1-P_2)(\gamma_{B_1}+\gamma_{B_2}) \\ &\quad +(1-P_1)P_2\gamma_{B_1} + (1-P_2)P_1\gamma_{B_2} \\ &= (1-P_1)\gamma_{B_1} + (1-P_2)\gamma_{B_2}. \end{aligned} \tag{1}$$

Note that although we consider two BSs for the illustration purpose, an extension to multi-BS case is straightforward[1]. Since two random variables, $(1-P_1)\gamma_{B_1}$ and $(1-P_2)\gamma_{B_2}$, in (1) are independent, we can express the moment generating function (MGF) of γ_t as a product of the MGFs of these two random variables as

$$\begin{aligned}\mathcal{M}_{\gamma_t}(s) &= \mathcal{M}_{(1-P_1)\gamma_{B_1}}(s)\cdot\mathcal{M}_{(1-P_2)\gamma_{B_2}}(s) \\ &= \mathcal{M}_{\gamma_{B_1}}((1-P_1)s)\cdot\mathcal{M}_{\gamma_{B_2}}((1-P_2)s). \end{aligned} \tag{2}$$

The MGF-based method for the evaluation of the average error rate over fading channels can be used [10, Sec. 9.2.3]. For example, the average bit error rate (BER) of binary phase shift keying (BPSK) signals is given by

$$\begin{aligned}P_B(E) &= \frac{1}{\pi}\int_0^{\pi/2}\mathcal{M}_{\gamma_t}\left(\frac{-1}{\sin^2\phi}\right)d\phi \\ &= \frac{1}{\pi}\int_0^{\pi/2}\mathcal{M}_{\gamma_{B_1}}\left(\frac{P_1-1}{\sin^2\phi}\right)\mathcal{M}_{\gamma_{B_2}}\left(\frac{P_2-1}{\sin^2\phi}\right)d\phi. \end{aligned} \tag{3}$$

A. Distributed GSC

With the distributed GSC scheme, the MGFs, $\mathcal{M}_{\gamma_{B_1}}(\cdot)$ and $\mathcal{M}_{\gamma_{B_2}}(\cdot)$, in (3) are the MGFs of the L_{c_1}/L_1-GSC and L_{c_2}/L_2-GSC output SNRs, respectively. The general form of the MGF of GSC for i.i.d. Rayleigh case can be found in [3, Eq. (13)]. After substitution of [3, Eq. (13)] into (3) and some manipulations, (3) specializes to

$$\begin{aligned}P_B(E) &= \binom{L_1}{L_{c_1}}\binom{L_2}{L_{c_2}}\sum_{i=0}^{L_1-L_{c_1}}\sum_{j=0}^{L_2-L_{c_2}}(-1)^{i+j} \\ &\quad\times\binom{L_1-L_{c_1}}{i}\binom{L_2-L_{c_2}}{j} \\ &\quad\times\frac{1}{(1+i/L_{c_1})(1+j/L_{c_2})} \\ &\quad\times\frac{1}{\pi}\int_0^{\frac{\pi}{2}}\prod_{n=1}^{4}\left(\frac{\sin^2\phi}{\sin^2\phi+c_n}\right)^{r_n}d\phi, \end{aligned} \tag{4}$$

where

$$c_1 = \frac{(1-P_1)\overline{\gamma}}{1+i/L_{c_1}},\quad c_2 = \frac{(1-P_2)\overline{\gamma}}{1+j/L_{c_2}},$$
$$c_3 = (1-P_1)\overline{\gamma},\quad c_4 = (1-P_2)\overline{\gamma},$$

[1]For example, in the case of N BSs, $\gamma_t = \sum_{n=1}^{N}(1-P_n)\gamma_{B_n}$ where P_n is the probability of losing nth BS and γ_{B_n} is the combined SNR of the paths from the nth BS.

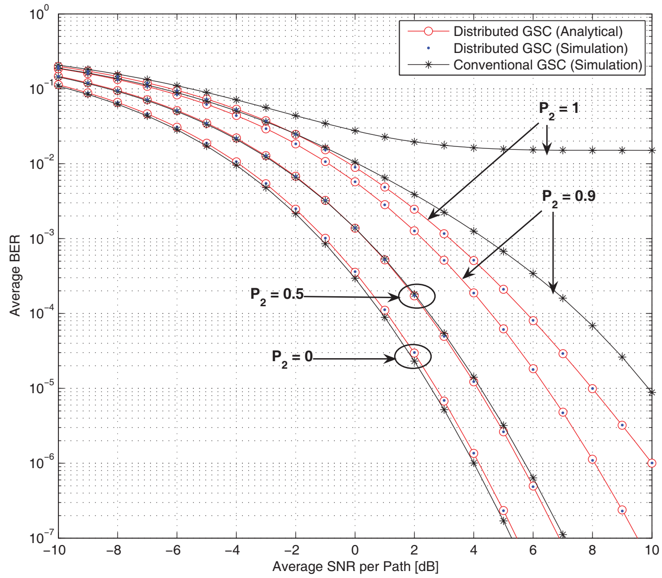

Fig. 1. Average BER of BPSK versus the average SNR per path, $\overline{\gamma}$, of distributed GSC and conventional GSC for various values of P_2 over i.i.d. Rayleigh fading channels when $L_1 = L_2 = 6, L_{c_1} = L_{c_2} = 2$, and $P_1 = 0$.

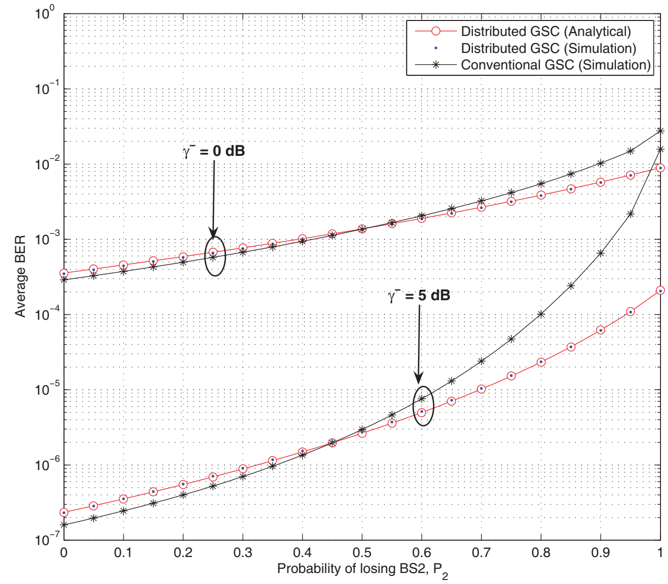

Fig. 2. Average BER of BPSK versus the probability of losing BS2, P_2, of distributed GSC and conventional GSC for various values of $\overline{\gamma}$ over i.i.d. Rayleigh fading channels when $L_1 = L_2 = 6, L_{c_1} = L_{c_2} = 2$, and $P_1 = 0$.

$$r_1 = 1, \quad r_2 = 1, \quad r_3 = L_{c_1} - 1, \quad r_4 = L_{c_2} - 1.$$

Since the integral in (4) can be found in closed form (see [10, Eq. (5A.74)]), (4) presents the final desired closed-form result for the average BER of the distributed GSC scheme.

Fig. 1 shows the average BER of BPSK of the proposed distributed GSC scheme as a function of the average SNR per path, $\overline{\gamma}$, over i.i.d. Rayleigh fading channels. Note that in all numerical examples, the simulation results verify our analysis. For comparison purpose, we also plot through computer simulations the average BER of the conventional GSC scheme. Note that the conventional GSC scheme acts as $L_c/(L_1+L_2)$-GSC where $L_c = L_{c_1}+L_{c_2}$ while the distributed GSC scheme uses the combinational form of L_{c_1}/L_1-GSC and L_{c_2}/L_2-GSC, and as such, a certain number of paths from one BS are always secured. Therefore, we can clearly see from this figure that by evenly[2] distributing paths to BSs, the distributed GSC scheme shows a comparable or better performance in comparison to the conventional GSC scheme especially when the probability of losing one BS is increasing. To better illustrate the benefit of our proposed scheme, we present in Fig. 2 the average BER in terms of the probability of losing BS2, P_2, for fixed values of $\overline{\gamma}$. We can observe from this figure that, for example, for our chosen set of parameters, the proposed distributed scheme outperforms the conventional scheme when $P_2 > 0.5$.

The outage probability which is another important standard performance criterion over fading channels is the probability that the instantaneous combined SNR, γ_t, falls below a certain specified threshold, x, or equivalently that the instantaneous error rate exceeds a specified value, i.e.,

$$P_{\text{Outage}} = \Pr[0 \leq \gamma_t \leq x] = \int_0^x f_{\gamma_t}(\gamma_t) d\gamma_t = F_{\gamma_t}(x), \quad (5)$$

[2]Note that if each BS has the different number of non-i.i.d. paths, the values of L_{c_1} and L_{c_2} should be chosen according to the quality of the paths from each BS.

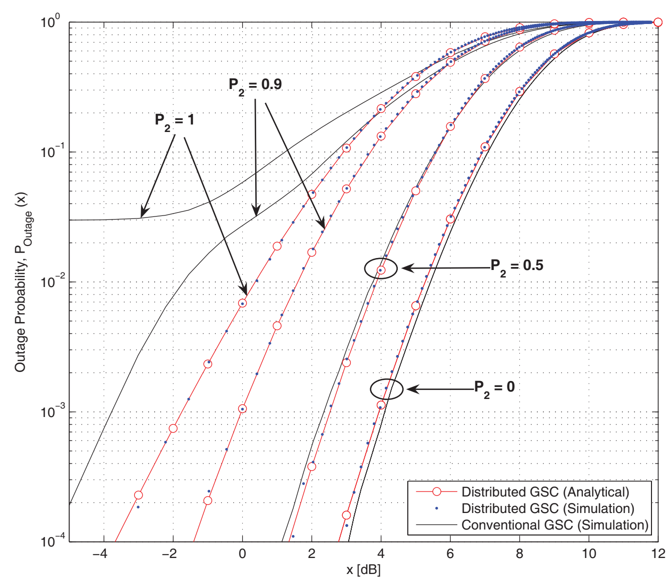

Fig. 3. Outage probability of distributed GSC and conventional GSC for various values of P_2 over i.i.d. Rayleigh fading channels when $L_1 = L_2 = 6, L_{c_1} = L_{c_2} = 2, P_1 = 0$, and $\overline{\gamma} = 0$ dB

where $f_{\gamma_t}(\cdot)$ and $F_{\gamma_t}(\cdot)$ are the probability density function (PDF) and the cumulative distribution function (CDF) of γ_t, respectively. Since it is very difficult to find the PDF of γ_t, we instead rely on the MGF-based numerical technique for the outage probability evaluation [11]. We present in Fig. 3 the outage probability of the proposed distributed GSC scheme with the conventional GSC scheme for different values of P_2. Note that the outage probability of the distributed GSC is obtained by using the result in [11, Eq. (11)] and verified by the computer simulation while for the conventional GSC, we just use the simulation results since no closed-form expression for the statistics of this scheme is available. We can see that the

$$
\begin{aligned}
\mathcal{M}_{MSGSC}(s) = {} & L\sum_{j=0}^{L-1}\binom{L-1}{j}(-1)^j\frac{e^{-\left(\frac{1+j}{\overline{\gamma}}-s\right)\gamma_T}}{1+j-\overline{\gamma}s}+\sum_{i=2}^{l}\binom{L}{i}\left[\sum_{m=0}^{i-1}\frac{(1-i)^m}{(i-1-m)!}\left(\frac{i\gamma_T}{\overline{\gamma}}\right)^{i-1-m}\right.\\
& \times\mathcal{G}_0(s)+\sum_{j=1}^{L-i}\binom{L-i}{j}(-1)^{j-i+1}\left(\frac{i}{j}\right)^{i-1}\left(\frac{e^{-\left(\frac{1+j/i}{\overline{\gamma}}-s\right)\gamma_T}-e^{-\left(\frac{1+j/i}{\overline{\gamma}}-s\right)\frac{i}{i-1}\gamma_T}}{1+j/i-\overline{\gamma}s}\right.\\
& \left.\left.-\sum_{k=0}^{i-2}\sum_{m=0}^{k}\frac{\left(\frac{i-1}{i}j\right)^m\left(-j\frac{\gamma_T}{\overline{\gamma}}\right)^{k-m}\mathcal{G}_j(s)}{(k-m)!}\right)\right]+\binom{L}{l}\left[\mathcal{F}_l(s)+\sum_{i=1}^{L-l}\binom{L-l}{i}\right.\\
& \left.\times(-1)^{l+i-1}\left(\frac{l}{i}\right)^{l-1}\left(\frac{1-e^{-\left(\frac{1+i/l}{\overline{\gamma}}-s\right)\gamma_T}}{1+i/l-\overline{\gamma}s}-\sum_{m=0}^{l-2}\left(-\frac{i}{l}\right)^m\mathcal{F}_{m+1}(s)\right)\right], \qquad (6)
\end{aligned}
$$

where

$$
\mathcal{G}_x(s) = e^{x\frac{\gamma_T}{\overline{\gamma}}}\frac{\Gamma[m+1,((1+x)/\overline{\gamma}-s)\,\gamma_T]-\Gamma[m+1,((1+x)/\overline{\gamma}-s)\,(i/(i-1))\,\gamma_T]}{m!(1+x-\overline{\gamma}s)^{m+1}},
$$

$$
\mathcal{F}_x(s) = \frac{\Gamma[x]-\Gamma[x,(1/\overline{\gamma}-s)\,\gamma_T]}{(x-1)!(1-\overline{\gamma}s)^x},
$$

outage performance observed from this figure is very similar to the BER performance in Fig. 1. For example, the proposed distributed scheme shows the lower outage probability than the conventional one as P_2 increases especially when $P_2 > 0.5$. These outage performance results provide us with the selection criterion between the conventional and the proposed schemes from the minimum call drop perspective.

B. Distributed MS GSC

Similar to the distributed GSC scheme, we just need to replace the MGFs, $\mathcal{M}_{\gamma_{B_1}}(\cdot)$ and $\mathcal{M}_{\gamma_{B_2}}(\cdot)$, in (3) with the MGFs of the L_{c_1}/L_1-MS GSC and L_{c_2}/L_2-MS GSC output SNRs, respectively. The general form of the MGF of l/L-MS GSC for i.i.d. Rayleigh case is given by [7, Eq. (35)] as shown in (6)[3] where $\Gamma[\cdot]$ and $\Gamma[\cdot,\cdot]$ are the complete and the incomplete gamma functions, respectively, defined in [12, Sec. 8.3]. Thus, substituting (6) into (3), we can obtain the average BER of the distributed MS GSC scheme.

In Fig. 4, we compare the average BER of the distributed MS GSC scheme with the conventional MS GSC scheme as a function of $\overline{\gamma}$ for different values of P_2. Note that, unlike conventional GSC, the conventional MS GSC scheme does not necessarily combine all the L_c best paths if the channel is of satisfactory quality compared to the output threshold. In some cases, for example, using only a few best paths out of all the available paths can be enough to meet our threshold. However, in this case, the conventional MS GSC scheme has the drawback of having a high chance of losing the few combined paths which can come from only one BS. Curves for the conventional MS GSC in Fig. 4 manifest indeed this phenomenon. For the distributed MS GSC scheme, we distribute the combined paths as well as the threshold between two BSs as evenly as possible, and as such, acquiring at least one best path from each BS is guaranteed. Hence, we can clearly see from this figure a great amount of performance improvement of the proposed scheme in comparison to the conventional scheme as P_2 increases. This performance gain comes at the cost of an increase in the processing power, which will be investigated in the next section. Also note that the outage probability can be routinely obtained by the same method used for the distributed GSC scheme. Because of space limitations, we omit in this letter the results for the outage probability of the proposed distributed MS GSC scheme.

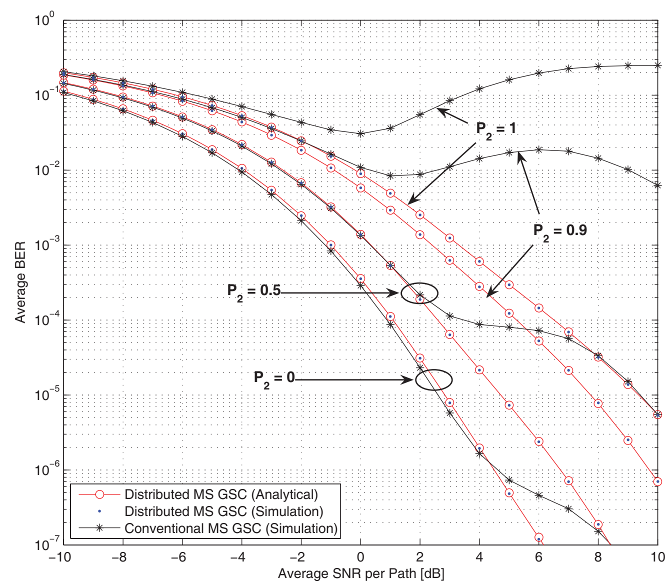

Fig. 4. Average BER of BPSK versus the average SNR per path, $\overline{\gamma}$, of distributed MS GSC and conventional MS GSC for various values of P_2 over i.i.d. Rayleigh fading channels when $L_1 = L_2 = 6, L_{c_1} = L_{c_2} = 2, P_1 = 0, \gamma_T = 10$ dB, and $\gamma_{T_1} = \gamma_{T_2} = \frac{\gamma_T}{2}$.

IV. Average Number of Combined Paths with Distributed MS GSC

As mentioned earlier, in comparison to the conventional GSC scheme, the conventional MS GSC scheme can save

[3] Note that Eq. (6) corrects some minor typos in [7, Eq. (35)].

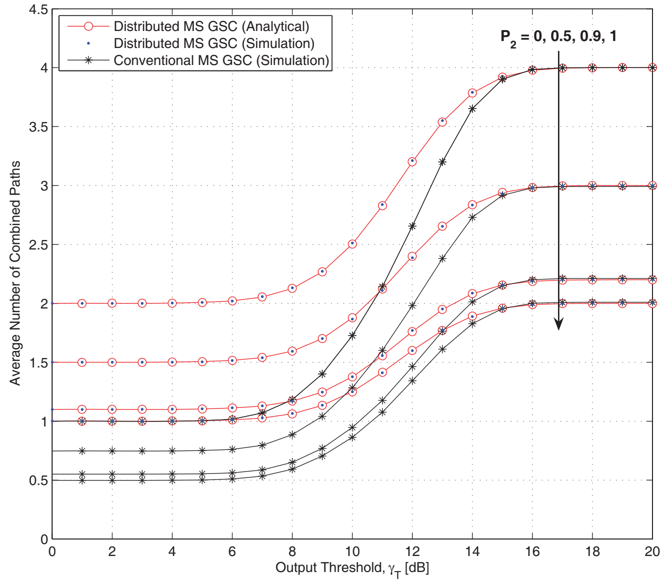

Fig. 5. Average number of combined paths versus the output threshold, γ_T, of distributed MS GSC and conventional MS GSC for various values of P_2 over i.i.d. Rayleigh fading channels when $L_1 = L_2 = 6, L_{c_1} = L_{c_2} = 2, P_1 = 0, \overline{\gamma} = 5$ dB, and $\gamma_{T_1} = \gamma_{T_2} = \frac{\gamma_T}{2}$.

receiver processing power by using the least number of combined paths while keeping the combined SNR above a predetermined output threshold. As a quantification of this power savings with MS GSC, the average number of combined paths was analyzed and given in [7, Eq. (16)]. Since we are distributing MS GSC selection algorithm to each BS, we can easily obtain the average number of combined paths with distributed MS GSC as

$$\overline{N}_{D-MSGSC} = (1 - P_1)\left(1 + \sum_{i=1}^{L_{c_1}-1} F_{\Gamma_{i:L_1}}(\gamma_{T_1})\right) + (1 - P_2)\left(1 + \sum_{i=1}^{L_{c_2}-1} F_{\Gamma_{i:L_2}}(\gamma_{T_2})\right), \quad (7)$$

where $\gamma_{T_1} + \gamma_{T_2} = \gamma_T$, $\Gamma_{i:j}$ is the sum of the i largest SNRs among j ones, and $F_{\Gamma_{i:j}}$ is the well-known CDF of i/j-GSC output SNR which can be found in [10, Eq. (9.440)].

Fig. 5 shows the average number of combined paths with the conventional and the distributed MS GSC schemes as a function of the output threshold, γ_T. As we can see, in both cases the average number of combined paths decreases as P_2 increases, but increases as the output threshold increases since the receiver has to combine more paths to raise the combined SNR above the output threshold. Considering Fig. 4 together with Fig. 5, we can observe the complexity tradeoff issue between the proposed and the conventional schemes . For example, if the output threshold is set to 10 dB, for $\overline{\gamma} = 5$ dB and $P_2 = 0.9$, the proposed scheme and the conventional scheme show 1.2×10^{-4} BER and 1.7×10^{-2} BER, respectively, while the proposed scheme requires on average only around 0.5 more combined paths than the conventional scheme.

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