Bit Error Rate Performance Analysis of a Threshold-Based Generalized Selection Combining Scheme in Nakagami Fading Channels

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The severity of fading on mobile communication channels calls for the combining of multiple diversity sources to achieve acceptable error rate performance. Traditional approaches perform the combining of the different diversity sources using either the conventional selective diversity combining (CSC), equal-gain combining (EGC), or maximal-ratio combining (MRC) schemes. CSC and MRC are the two extremes of compromise between performance quality and complexity. Some researches have proposed a generalized selection combining scheme (GSC) that combines the best $M$ branches out of the $L$ available diversity resources ($M \leq L$). In this paper, we analyze a generalized selection combining scheme based on a threshold criterion rather than a fixed-size subset of the best channels. In this scheme, only those diversity branches whose energy levels are above a specified threshold are combined. Closed-form analytical solutions for the BER performances of this scheme over Nakagami fading channels are derived. We also discuss the merits of this scheme over GSC.

Keywords and phrases: diversity systems, generalized selection combining, threshold-based GSC, mobile communications, Nakagami-$m$ fading.

1. INTRODUCTION

Diversity techniques are based on the notion that errors occur in reception when the channel is in deep fade—a phenomenon more pronounced in mobile communication channels. Therefore, if the receiver is supplied with several replicas, say $L$, of the same information signal transmitted over independently fading channels, the probability that all the $L$ independently fading replicas fade below a critical value is $p^L$ (where $p$ is the probability that any one signal will fade below the critical value). The bit error rate (BER) of the system is thus improved without increasing the transmitted power [1]. This is traditionally referred to as the diversity gain of the system. Most diversity considerations have always assumed that the spatial separations among the (multiple) diversity antennas are large enough so that the diversity branches experience uncorrelated fading, and therefore the signals received from the different diversity antennas are independent. In some practical mobile systems, however, large antenna spacings are not feasible, and therefore the fading statistics of the diversity branches in such cases may be correlated. The impact of fading correlation on the performance of diversity systems has been well studied in the literature (see, e.g., [2, 3] and references therein). The general conclusion from these studies is that the diversity gain of the system is reduced when the diversity branches are correlated. The severity of this performance gain reduction is usually in correspondence with the level of the fading correlations among the diversity channels [2, 3]. In this work, however, we focus mainly on the case of uncorrelated diversity branches.

A crucial issue in diversity systems is how to combine the available diversity branches in order to achieve optimum performance within acceptable complexity. The three
The authors have proposed a threshold-based generalized selection combining (T-GSC) scheme that overcomes the aforementioned shortcomings [8]. The T-GSC scheme combines all the strong diversity branches available at any time instant, discarding only the weak ones. The proposed scheme is more suitable for mobile channels, which frequently and intermittently improve and degrade during usage, and where power resource savings are critically important and must be made without compromising performance quality. The BER performance of T-GSC was simulated over a Nakagami fading environment, and compared with M-GSC. Apparently, the system in [8] has attracted other researchers [9, 10]. In [10], Simon and Alouini analyzed the system for Rayleigh fading channels with a slight modification to the threshold definition.

In this work, we extend our work in [8] by providing a detailed analysis of the BER performance of T-GSC over Nakagami fading channels. The rest of the paper is organized as follows. In Section 2, we review the combining rules of T-GSC. Detailed analysis of the BER performance of the system is furnished in Section 3. Some results are presented and discussed in Section 4. A comparison between T-GSC and M-GSC is provided in Section 5. Main conclusions of this work are finally summarized in Section 6.

2. PROPOSED T-GSC SCHEME

The proposed scheme combines diversity branches based on a criterion which we call “branch relative strength” (BRS). The BRS is the ratio of the SNR of each branch to the SNR of the best branch at the same instant of time [8]:

\[ \text{BRS}_i = \frac{y_i}{y_{\text{max}}}, \quad i = 1, 2, \ldots, L, \]  

(1)

where \( y_{\text{max}} = \max\{y_1, y_2, \ldots, y_L\} \) is the maximum SNR received at each time instant, and \( y_i \) is the SNR in the \( i \)th branch, \( i = 1, 2, \ldots, L \). The combining rule is then stated as follows: if the BRS, \( \gamma_{th} \), is larger than or equal to a specified threshold \( T \) (where \( 0 \leq T \leq 1 \)), the branch is combined; otherwise, it is discarded. Equivalently, one could compare each \( y_i \) to \( y_{th} \), where \( y_{th} = T \cdot y_{\text{max}} \).

The T-GSC scheme thus combines only the significant branches at any time, discarding the weak ones whose energy are below the threshold value. Processing resources, notably power, are therefore not dissipated in combining very weak branches that have no appreciable contribution to the total combined SNR—extending battery life for mobile units. Significant branches for different mobile situations can be selected by proper choice of \( T \) suitable for the fading environment and the mobile scenario concerned. A novel advantage here is that if all the branches’ SNRs meet the specified threshold (i.e., they are all strong), they are all combined and no useless information is “thrown off.” It is then obvious that \( M \), the number of branches combined at each time instant, will not be fixed but varies in correspondence to the channel fading level. Performance gains due to improvements in
channel conditions will thus be reflected in the system performance all the time. The scheme is as illustrated in Figure 1 for \( L = 5 \). In the figure, only branches 1, 2, and 4 are above threshold, and are therefore combined.

Next we derive the BER performance for the above scheme. Nakagami \( m \)-fading is assumed for the channel fading model [11]. The \( m \)-distribution proposed by Nakagami [12] is a general fading statistics from which other fading statistics approximating the mobile communication environments can be modeled by setting the Nakagami parameter \( m \) to an appropriate value. We recall that \( m = 1 \) corresponds to Rayleigh, and as \( m \) is increased, the fading becomes less severe. Binary PSK signal is used throughout the analysis.

3. BER PERFORMANCE: ANALYTICAL DERIVATION

Given \( L \) available diversity branches at the receiver, each branch having instantaneous SNR per bit, \( \gamma_l = \alpha^2 E_b/N_0 \), \( l = 1, \ldots, L \), where \( \alpha \) is the fading coefficient and \( E_b/N_0 \) is the transmitted bit-energy-to-Gaussian-noise spectral density ratio. The T-GSC receiver searches for the branch with the maximum SNR \( \gamma_{\text{max}} \) and chooses a threshold based on it.

In contrast to \( M \)-GSC in which a fixed number of diversity branches \( M \) is combined, the number of diversity branches to be combined in the T-GSC scheme is a random variable \( I, l \in \{1, L\} \). Using the theorem on total probability [13], the average BER for T-GSC can be derived as a weighted sum of the average BER for the \( M \)-GSC corresponding to \( M = 1, 2, \ldots, L \). Hence,

\[
P_{b,T}(E) = \sum_{l=1}^{L} \Pr(M = l) \cdot P_{b,M}(E|M = l),
\]

where \( P_{b,M}(E|M = l) \) is the average BER for the \( M \)-GSC given that the number of branches combined, \( M \), is equal to the variable \( l \).

\( \Pr(M = l) \) denotes the probability of the event that \( l \) branches have their SNRs equal to or exceed \( \gamma_{th} \) and are combined, while \( L - l \) branches have their SNRs lower than \( \gamma_{th} \) and are thus discarded. The probability of this event is given by [13]

\[
\Pr(M = l) = \frac{\binom{L-1}{l-1}}{\int_{0}^{\gamma_{\text{max}}} \gamma^{L-1} \cdot \int_{0}^{\gamma_{th}} p_{\gamma}(\gamma) d\gamma} \text{ max}_{l} \int_{0}^{\gamma_{th}} p_{\gamma}(\gamma) d\gamma \Lbracket^{L-l} .
\]

For Nakagami-\( m \) branch fading coefficients, each branch’s SNR, \( \gamma_l \), is a gamma random variable with pdf given as [1]:

\[
p_{\gamma}(\gamma) = \left( \frac{m}{\gamma} \right)^{m} \frac{\gamma^{m-1}}{\Gamma(m)} \exp \left\{ -\frac{m}{\gamma} \right\} ,
\]

where the lowercase letter \( m \) refers to the Nakagami parameter, and \( \gamma = E[\alpha^2] E_b/N_0 \). Substitution of (4) in (3) and making use of the reduction formula [14] in evaluating the integrals in the resulting expression, we arrive at

\[
\Pr(M = l) = \frac{\binom{L-1}{l-1}}{- \exp \{ (-m\beta_{\gamma_{\text{max}}}) \sum_{n=0}^{m-1} \frac{(m-1)!}{(m-1-n)!} (m\beta_{\gamma_{\text{max}}}^{m-1-n} + (m-1)!)^{L-l} \}
\]
\[
\cdot \left\{ - \exp \{ (-m\beta_{\gamma_{\text{max}}}) \sum_{k=0}^{m-1} \frac{(m-1)!}{(m-1-k)!} (m\beta_{\gamma_{\text{max}}}^{m-1-k}) \}
\}
\]
\[
+ \exp \{ (-m\beta_{\gamma_{th}}) \sum_{k=0}^{m-1} \frac{(m-1)!}{(m-1-k)!} (m\beta_{\gamma_{th}}^{m-1-k}) \}^{L-l} \}
\]
\[
\cdot \left\{ - \exp \{ (-m\beta_{\gamma_{th}}) \sum_{q=0}^{m-1} \frac{(m-1)!}{(m-1-q)!} (m\beta_{\gamma_{th}}^{m-1-q} + (m-1)!) \}^{L-l} \}
\]
where $\beta_{\text{max}} = \gamma_{\text{max}} / \gamma$ and $\beta_{\text{th}} = \gamma_{\text{th}} / \gamma$. Note that the solution in (5) for Nakagami fading is valid only for integer values of the Nakagami parameter $m$.

Substitution of (5) into (2) gives the desired result for the average BER of T-GSC, $P_{b,T}(E)$, over Nakagami-$m$ fading channels, in terms of the average BER of M-GSC, $P_{b,M}(E|M)$. Expressions for $P_{b,M}(E|M)$ over Rayleigh fading and Nakagami fading channels can be obtained from works in [15, 16], respectively.

As an illustration of the evaluation of $P_{b,T}(E)$ using (2) and (5), we consider the case of Nakagami-$m$ branch fading with $m = 1$ (which is equivalent to Rayleigh fading). For this example, $P_{b,M}(E|M = l)$ is obtained from [16, equation (40)] after substituting $l = L_c$ as

$$P_{b,M}(E|M = l) = \left( \frac{L}{l} \right) \sum_{k=0}^{l-1} \frac{(-1)^k}{1 + k/l} \cdot I_{l-1} \left( \frac{\pi}{2}, \frac{g\gamma}{1 + k/l} \right),$$

where $g = 1$ for binary PSK signals, and $I_x(\theta; c_1, c_2)$ is defined as $\frac{1}{\pi} \int_{0}^{\theta} (\sin^2 \phi / (\sin^2 \phi + c_1))^{(n/2)} (\sin^2 \phi / (\sin^2 \phi + c_2)) d\phi$. A closed-form result for this integral has been obtained in [15].

Setting $m = 1$ in (5) and expanding the result in binomial series leads to

$$Pr(M = l) = \frac{(-1)^{l-1}}{L-1} \sum_{k=0}^{L-1} \binom{L-1}{k} (-1)^{l-1-k} \exp \left\{ (-\beta_{\text{max}}[L-1-k(1-T)]) \right\} \cdot \frac{L-1}{q} \cdot (-1)^{l-1-q} \exp \left\{ (-T\beta_{\text{max}}[L-l-q]) \right\}.$$

Note from (7) that $T = 0$, corresponding to MRC, yields $Pr(M = l) = 0$, $l = 1, 2, \ldots, L - 1$, $Pr(M = L) = 1$. Similarly, for $T = 1$, corresponding to CSC, $Pr(M = l) = 0$, $l = 2, 3, \ldots, L$, $Pr(M = 1) = 1$, thus verifying the upper and lower bounds on the BER for the T-GSC scheme.

Substituting (6) and (7) into (2) yields the following expression for the average BER of T-GSC:

$$P_{b,T}(E) = \sum_{l=1}^{L} \frac{(-1)^{l-1}}{L-1} \sum_{k=0}^{L-1} \binom{L-1}{k} (-1)^{l-1-k} \exp \left\{ (-\beta_{\text{max}}[L-1-k(1-T)]) \right\} \sum_{n=0}^{L-1} \binom{L-1}{n} (-1)^{l-1-n} \exp \left\{ (-\beta_{\text{max}}[L-1-n]) \right\}$$

$$\cdot \left( \frac{L}{l} \right) \sum_{q=0}^{L-1} \binom{L-1}{q} (-1)^{l-1-q} \exp \left\{ (-T\beta_{\text{max}}[L-l-q]) \right\}$$

$$\cdot \left( \frac{L}{l} \right) \sum_{p=0}^{L-1} \binom{L-1}{p} \frac{(\gamma/\gamma)^p}{1 + p/l} I_{l-1} \left( \frac{\pi}{2}, \frac{\gamma}{1 + p/l} \right),$$

(8)

where $I_{l-1}(\theta; c_1, c_2) = I_l(\theta; c)$ for $c_1 = c_2 = c$ is given by [15]

$$I_l(\theta; c) = \frac{\theta}{\pi} - \frac{1 + \text{sgn}(\theta - \pi) + A_2}{2}$$

$$\cdot \sqrt{\frac{c}{1 + c}} \sum_{i=0}^{l-1} \frac{2i}{4(1 + c)} - \frac{2}{\pi} \sqrt{\frac{c}{1 + c}} \sum_{j=0}^{l-2} \frac{\sin \left( (2i - 2j)A_1 \right)}{2i - 2j}, \quad 0 \leq \theta \leq 2\pi,$$

(9)

$$\text{sgn}(\theta - \pi) = \begin{cases} 1, & \text{if } \theta < \pi, \\ 0, & \text{if } \theta = \pi, \\ -1, & \text{if } \theta > \pi \end{cases}$$

$$A_1 = \frac{1}{2} \arctan \left( \frac{\gamma}{\pi} \right) + \pi \left[ 1 - \text{sgn} \left( \frac{\gamma}{\pi} \right) \right]$$

$$\frac{1}{\pi} = \sqrt{\frac{c}{1 + c}} \sum_{i=0}^{l-1} \frac{2i}{4(1 + c)}$$

$$\cdot \left( \frac{2i}{(2i - 2j)} \right) \frac{\sin \left( (2i - 2j)A_1 \right)}{2i - 2j}, \quad 0 \leq \theta \leq 2\pi,$$

(10)

$$\text{sgn}(\theta - \pi) = \begin{cases} 1, & \text{if } \theta < \pi, \\ 0, & \text{if } \theta = \pi, \\ -1, & \text{if } \theta > \pi \end{cases}$$

$$A_1 = \frac{1}{2} \arctan \left( \frac{\gamma}{\pi} \right) + \pi \left[ 1 - \text{sgn} \left( \frac{\gamma}{\pi} \right) \right]$$

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$$\cdot \left( \frac{2i}{(2i - 2j)} \right) \frac{\sin \left( (2i - 2j)A_1 \right)}{2i - 2j}, \quad 0 \leq \theta \leq 2\pi,$$

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$$A_1 = \frac{1}{2} \arctan \left( \frac{\gamma}{\pi} \right) + \pi \left[ 1 - \text{sgn} \left( \frac{\gamma}{\pi} \right) \right]$$

$$\frac{1}{\pi} = \sqrt{\frac{c}{1 + c}} \sum_{i=0}^{l-1} \frac{2i}{4(1 + c)}$$

$$\cdot \left( \frac{2i}{(2i - 2j)} \right) \frac{\sin \left( (2i - 2j)A_1 \right)}{2i - 2j}, \quad 0 \leq \theta \leq 2\pi,$$

(12)

4. RESULTS AND DISCUSSION

The T-GSC system was evaluated over Nakagami-$m$ channels for the Nakagami parameters $m = 1$ (Rayleigh), $m = 2$, and $m = 4$. BER curves obtained for Nakagami $m = 1, 2, 4$ are shown in Figures 2, 3, and 4, respectively. In those figures,
the curves for $T = 0$ and $T = 1$ correspond to MRC and SC, respectively. The following observations are evident.

(1) For any particular fading channel, the performance of the T-GSC improves as the threshold level is varied from $T = 1$ to $T = 0$. The figures also indicate that at the threshold value $T = 0.25$, most useful diversity branches that can appreciably contribute to the combined SNR would have been selected and combined. This value of $T$ is valid for all the types of channels studied—ranging from the (severe) Rayleigh fading to the less severe Ricean fading channels.

(2) For any particular threshold level considered, the BER performance improves as the fading becomes less severe.

(3) It is interesting to note that as the channel fading becomes less severe, the performance of the system at low threshold values becomes indistinguishable from that of MRC. Note the closeness of the curves at $T = 0.25$ and $T = 0$ in both Figures 3 and 4. This can be explained as follows. As all diversity channels are not that bad for these values of $m$, they will be most of the time above threshold, and will be combined as in MRC. This is a significant merit of T-GSC over M-GSC that will be illustrated further in the next section.

5. COMPARISON BETWEEN T-GSC AND M-GSC

We have already stated that T-GSC results in power conservation as it does not combine the weak branches, thereby extending battery life for mobile units. In this section, we state other significant differences between the T-GSC and M-GSC schemes.

Figure 5 shows the BER curves of T-GSC for three values of $T$: 0.25, 0.5, and 0.75 and two values of $M$: 2 and 3. Again, we are assuming that $L = 5$. Also shown, as benchmarks, are the BER curves of SC (corresponding to $T = 1$ or $M = 1$) and MRC (corresponding to $T = 0$ or $M = 5$). From the figure, we observe the following.

(1) T-GSC provides a gradual exchange of performance quality and processing intensity. If SC performance is not found to be satisfactory for a certain application, then the next step in M-GSC is to combine two channels all the time, which results in improving the
BER by one order of magnitude at $E_b/N_0 = 15$ dB, for example. However, T-GSC permits any gradual change in BER (and hence processing) by selecting the appropriate threshold $T$. For example, $T = 0.75$ would provide less improvement in BER over SC as compared to $M$-GSC with $M = 2$, but will keep the processing intensity lower as it will be combining two channels occasionally. This will obviously have its impact on power consumption.

(2) We have seen in the previous section that for a particular value of $T$, most useful diversity branches would be combined for various degrees of fading. This is however not the case with the $M$-GSC, in which a value of $M$ that suits one fading channel can be grossly inadequate for another. Clearly, the T-GSC scheme uses a sound criterion for defining the significant and the insignificant branches that will lead to no loss of appreciable information at any time instant, while operating in any mobile communication channel.

(3) It is possible to choose a value of $T$ that yields a BER value identical to some $M$. For example, in Figure 5 T-GSC with $T = 0.5$ has a performance close to $M$-GSC with $M = 2$. The same observation is true for $T = 0.25$ and $M = 3$. Yet, under these identical performance conditions, the $M$-GSC has slightly higher complexity since it requires the ranking of all diversity branch strengths, whereas T-GSC requires only the knowledge of the branch with the maximum SNR and does not rank the remaining $L - 1$ branches after the branch with the maximum SNR is known (i.e., T-GSC does not require full ranking). For $L = 5$, $M$-GSC requires a precombining processing of 10 comparisons and 30 data swaps, while T-GSC requires 8 comparisons and 4 data swaps. The difference in complexities becomes more significant and influential at large $L$, as shown in Table 1.

### Table 1: Precombining processing of M-GSC and T-GSC.

| Diversity order | 2   | 5   | 10  | $N$ |
|-----------------|-----|-----|-----|-----|
| Number of comparisons | M-GSC | 1   | 10  | 5    | $0.5N(N-1)$ |
|                  | T-GSC | 2   | 8   | 18   | $2(N-1)$  |
| Number of swaps  | M-GSC | 3   | 30  | 135  | $1.5N(N-1)$ |
|                  | T-GSC | 1   | 4   | 9    | $N-1$     |

6. CONCLUSION

This paper analyzes a threshold-based generalized selection combining (T-GSC) scheme, which combines all, and only, the significant diversity branches at any given time instant. The scheme compares the strength of each branch to a predefined threshold, and combines only those branches that pass the threshold test. Compared to the general selective diversity scheme based on combining the best $M$ out of $L$ channels ($M$-GSC), T-GSC saves power resources that would have been dissipated into combining very weak branches, thereby extending battery life for mobile receivers. Also, T-GSC has less precombining operations, and provides a gradual mechanism for exchanging quality with processing intensity.

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