Finger Replacement Schemes for RAKE Receivers in the Soft Handover Region With Multiple Base Stations

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Abstract—We propose and analyze new finger replacement techniques for RAKE reception in the soft handover (SHO) region with multiple base stations. The proposed schemes are basically based on the block comparison among groups of resolvable paths from different base stations and lead to the reduction of complexity while offering commensurate performance in comparison with previously proposed schemes. Relying on the newly derived analytical expressions, we investigate not only the complexity in terms of the average number of required path estimations/comparisons and the SHO overhead but the error performance of the proposed scheme over independent identically distributed (i.i.d.) fading channels as well. We also examine, via computer simulations, the effect of path unbalance/correlation as well as outdated/imperfect channel estimation and show the robustness of our proposed scheme to these practical limitations.

Index Terms—Diversity techniques, fading channels, performance analysis, RAKE receiver, soft handover (SHO).

I. INTRODUCTION

MULTIPATH fading is an unavoidable physical phenomenon that affects considerably the performance of wideband wireless communication systems. While usually viewed as a deteriorating factor, multipath fading can also be exploited to improve the performance by using RAKE-type receivers [1, Sec. 9.5.1]. These receivers use several baseband correlators, called fingers, to individually process multipath signal components from different base stations (BSs) and, as such, facilitate soft handover (SHO). The outputs from the different correlators are coherently combined to achieve improved reliability and performance. The effects of bandwidth on spread spectrum systems have been investigated in [2] and [3] by quantifying the RAKE receiver output signal-to-noise ratio (SNR) and the error performance in terms of the number of fingers, spreading bandwidth, and multipath spread of the channel.

In the SHO region, however, due to the limited number of fingers in the mobile unit, we are faced with a problem of how to judiciously select a subset of paths for the RAKE reception to achieve the required performance while doing the following: 1) maintaining a low complexity and low processing power consumption and 2) using a minimal amount of additional network resources. Recently, by considering macroscopic diversity schemes with two BSs, the authors have proposed and analyzed new finger assignment schemes that maintain a low complexity and reduce the usage of the network resources in the SHO region [4], [5]. The main idea behind [4] and [5] is that in the SHO region, the receiver uses the additional network resources only if needed. More specifically, with the scheme in [4], whenever the received signal from the currently used BS (serving BS) is unsatisfactory, the receiver scans the additional resolvable paths from the neighboring BS (target BS) and selects the strongest paths among the total available paths from both the serving and the target BSs. It has been shown that this scheme can reduce the unnecessary path SNR estimations and the SHO overhead compared to the conventional generalized selection combining (GSC) scheme [6]–[10] in the SHO region. In [11], the results in [4] are generalized to the multi-BS situation by developing two different path scanning schemes, which are denoted as the full scanning scheme and the sequential scanning scheme. With the full scanning scheme, whenever the received signal becomes unsatisfactory, the RAKE receiver scans all the available paths from all potential target BSs, whereas with the sequential scanning scheme, the RAKE receiver sequentially scans the target BSs until the combined SNR is satisfactory or all potential target BSs are scanned.

In [5], an alternative finger selection scheme for the SHO region was proposed to further reduce the SHO overhead at the expense of a certain degradation in performance. With this scheme, when the output SNR falls below the target SNR, the receiver scans the additional resolvable paths from the target BS. However, unlike the scheme in [4], the receiver compares the sum of the SNRs of the strongest paths among the paths from the target BS with the sum of the weakest SNRs among the currently used paths from the serving BS and selects the better group. This scheme compares two blocks of equal size and, as such, avoids reordering all the paths,

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which is required for the scheme in [4]. Therefore, a reduction in path estimations, SNR comparisons, and SHO overhead can be obtained. The schemes proposed in [4] and [5] were further investigated in more practical fading environments in [12]. In this paper, we generalize the results in [5] to the multi-BS situation. Similar to [11], we propose two scanning schemes, which are denoted the full scanning scheme and the sequential scanning scheme. Both scanning schemes employ block comparison instead of the full GSC used in [11]. For the sake of clarity, we call the proposed scheme in this paper the replacement scheme and the scheme in [11] the reassignment scheme.

The main contribution of this paper is to present a general comprehensive framework for the performance and the complexity assessment of the replacement scheme by providing not only analytical results for independent identically distributed (i.i.d.) fading environments but computer simulation results for non-i.i.d. fading channels and under outdated/imperfect channel estimates as well. More specifically, in our derivations, we accurately quantify the complexity measures of interest and statistics of the receiver output SNR, which are used to analyze the performance of the proposed scheme over i.i.d. fading channels. Through computer simulations, we show that the replacement scheme is also applicable to practical fading conditions with correlated and/or nonidentical resolvable paths. More importantly, the simulation results show that the replacement scheme shows, in comparison to the reassignment scheme, a considerable robustness to channel estimation errors.

The rest of this paper is organized as follows: In Section II, we present the channel and system model under consideration as well as the mode of operation of the proposed scheme. Based on this mode of operation, we illustrate in Section III the complexity of the proposed schemes by quantifying the average number of path estimations, the average number of SNR comparisons, and the SHO overhead. We then derive the expressions for the statistics of the combined SNR in Section IV. These results are next applied to the performance analysis of the proposed systems in Section V. We consider the effect of path unbalance/correlation in Section VI and evaluate the performance in the presence of an outdated or imperfect channel estimate in Section VII. Finally, Section VIII provides some concluding remarks.

II. SYSTEM MODEL

A. Channel and System Model

We assume that in the SHO region, \( N \) BSs are active, and there are a total of \( L_{(N)} \) resolvable paths, where \( L_{(N)} = \sum_{n=1}^{N} L_n \), and \( L_n \) is the number of resolvable paths from the \( n \)th BS. We also assume that the mobile unit in the SHO region is at roughly the same distance from the serving and the target BSs, and therefore, the average signal strength on each path from the BSs is assumed to be the same. As such, we first assume that the received signals on all the resolvable paths from the serving and the target BSs experience i.i.d. Rayleigh fading in which the instantaneous received SNRs \( \gamma \) of all the available resolvable paths follow the same exponential distribution with a common probability density function (PDF) and cumulative distribution function (CDF) given by [1, eq. (6.5)]

\[
f_\gamma(x) = \frac{1}{\bar{\gamma}} \exp \left(-\frac{x}{\bar{\gamma}}\right), \quad x \geq 0
\]

\[
F_\gamma(x) = 1 - \exp \left(-\frac{x}{\bar{\gamma}}\right), \quad x \geq 0
\]

respectively, where \( \bar{\gamma} \) is the common average faded SNR. Later on, more practical fading environments will be considered.

Next, we consider that the mobile unit is equipped with an \( L_c \) finger RAKE receiver and is capable of despearing signals from different BSs using different fingers to facilitate the SHO process. The receiver operates over a “perfect” uniform propagation delay profile provided by a multipath searcher in a way that the multipath components are correctly assigned to the RAKE fingers. In the SHO region, according to the mode of operation described in Section II-B, only \( L_{(n)} \) out of \( L_{(n)} \) paths are used for RAKE reception.

B. Mode of Operation

Without loss of generality, let \( L_1 \) be the number of resolvable paths from the serving BS and \( L_2, L_3, \ldots, L_N \) be those from the target BSs. In the SHO region, the receiver is assumed at first to rely only on \( L_1 \) resolvable paths and, as such, starts with \( L_c/L_1 \)-GSC. The proposed schemes are based on the comparison of blocks consisting of \( L_s(< L_c < L_1) \) paths from each BS.

For simplicity, if we let

\[
Y = \sum_{i=1}^{L_c-L_s} \gamma_i;L_1
\]

\[
W_n = \begin{cases} \sum_{i=L_c-L_s+1}^{L_c} \gamma_i;L_n, & n = 1 \\ \sum_{i=1}^{L_c} \gamma_i;L_n, & n = 2, \ldots, N \end{cases}
\]

where \( \gamma_i;L_n \) is the \( i \)th order statistics out of \( L_n \) SNRs of paths from the \( n \)th BS (see [8] for terminology), then, the received output SNR after GSC is given by \( Y + W_1 \). At the beginning of every time slot, the receiver compares the GSC output SNR \( Y + W_1 \) with a certain target SNR, which is denoted by \( \gamma_T \). If \( Y + W_1 \) is greater than or equal to \( \gamma_T \), a one-way SHO is used, and no finger replacement is needed. On the other hand, whenever \( Y + W_1 \) falls below \( \gamma_T \), the receiver attempts a two-way SHO by starting to scan additional paths from the serving and the target BSs experience i.i.d. Rayleigh fading in which the instantaneous received SNRs \( \gamma \) of all the available

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one. Hence, the final combined SNR, which is denoted by $\gamma_{\text{Full}}$, is mathematically given by

$$
\gamma_{\text{Full}} = \begin{cases} 
Y + W_1, & Y + W_1 \geq \gamma_T \\
Y + \max\{W_1, \ldots, W_n\}, & Y + W_1 < \gamma_T.
\end{cases}
$$

(5)

Note that even in the case of $Y + W_1 < \gamma_T$, no replacement occurs if $W_1 = \max\{W_1, \ldots, W_N\}$.

**Case II—Sequential Scanning:** In this case, when $Y + W_1 < \gamma_T$, the RAKE receiver estimates $L_2$ paths from the first target BS and replaces $W_1$ with $W_2$. The receiver then checks whether the combined SNR $Y + W_2$ is above $\gamma_T$ or not. By sequentially scanning the remaining target BSs, this process is repeated until either the combined SNR $Y + W_i$, $2 \leq i \leq N$ is above $\gamma_T$ or all the $N$ BSs are examined. In the latter case, since the SNRs of all the paths are known, the receiver selects the largest $W_n$. Based on this mode of operation, we can see that the final combined SNR, which is denoted by $\gamma_{\text{Seq}}$, is mathematically given by

$$
\gamma_{\text{Seq}} = \begin{cases} 
Y + W_1, & Y + W_1 \geq \gamma_T \\
Y + W_i, & Y + W_j < \gamma_T \\
Y + W_i \geq \gamma_T & \text{for } j = 1, \ldots, i - 1 \\
Y + \max\{W_1, \ldots, W_n\}, & Y + W_n < \gamma_T \\
& \text{for } n = 1, \ldots, N.
\end{cases}
$$

(6)

### III. COMPLEXITY COMPARISONS

In this section, we look into the complexity of the proposed schemes by accurately quantifying the average number of path estimations, the average number of SNR comparisons, and the SHO overhead, which are required during the SHO process of these schemes.

**A. Average Number of Path Estimations**

**Case I—Full Scanning:** With this scheme, the RAKE receiver estimates SNRs of $L_1$ paths in the case of $Y + W_1 \geq \gamma_T$ or $L_{(N)}$ in the case of $Y + W_1 < \gamma_T$. Hence, we can easily quantify the average number of path estimations, which is denoted by $E_{\text{Full}}$, as

$$
E_{\text{Full}} = L_1 \Pr[Y + W_1 \geq \gamma_T] + L_{(N)} \Pr[Y + W_1 < \gamma_T]
$$

(7)

which reduces to

$$
E_{\text{Full}} = L_1 + (L_{(N)} - L_1) F_{Y+W_1}(\gamma_T)
$$

(8)

where $F_{Y+W_1}(\cdot)$ is the well-known CDF of the $L_c/L_1$-GSC output SNR [13, eq. (9.433)].

**Case II—Sequential Scanning:** In this scheme, we can write the average number of path estimations, which is denoted by $E_{\text{Seq}}$, in the following summation form:

$$
E_{\text{Seq}} = \sum_{n=1}^{N} L_{(n)} \cdot \pi_n
$$

(9)

where $\pi_n$ is the probability that $L_{(n)}$ paths are estimated. Based on the mode of operation in Section II-B2, we have

$$
\pi_n = \begin{cases} 
\Pr[Y + W_1 \geq \gamma_T], & n = 1 \\
\Pr[Y + W_1 < \gamma_T, \ldots, Y + W_{n-1} < \gamma_T, Y + W_n \geq \gamma_T], & 1 < n < N \\
\Pr[Y + W_1 < \gamma_T, \ldots, Y + W_{N-1} < \gamma_T], & n = N.
\end{cases}
$$

(10)

Note that $W_n$ are independent, whereas $Y + W_n$ are correlated. Hence, by conditioning on $Y$, the joint probabilities in (10) can be calculated as

$$
\Pr[Y + W_1 < \gamma_T, \ldots, Y + W_{n-1} < \gamma_T, Y + W_n \geq \gamma_T] = \int_{0}^\gamma T f_Y(y) F_{W_1}(y=\gamma_T-y) \\
\times \prod_{m=2}^{n-1} F_{W_m}(\gamma_T-y) \left(1 - F_{W_n}(\gamma_T-y)\right) dy
$$

(11)

$$
\Pr[Y + W_1 < \gamma_T, \ldots, Y + W_{N-1} < \gamma_T] = \int_{0}^\gamma T f_Y(y) F_{W_1}(y=\gamma_T-y) \prod_{m=2}^{N-1} F_{W_m}(\gamma_T-y) dy
$$

(12)

respectively, where $f_Y(\cdot)$ is the PDF of $(L_c - L_a)/L_1$-GSC output SNR [13, eq. (9.433)], $F_{W_m}(\cdot)$ and $F_{W_n}(\cdot)$ are the CDFs of $L_a/L_m$-GSC and $L_a/L_n$-GSC output SNR [13, eq. (9.440)], respectively, and

$$
F_{W_1}(y=\gamma_T-x) = \begin{cases} 
\int_{0}^{\gamma_T-x} f_{Y,W_1}(y,u) du, & 0 \leq x < \frac{L_1}{L_c-L_a} \\
1, & \frac{L_1}{L_c-L_a} \leq x.
\end{cases}
$$

(13)

In (13), $f_{Y,W_1}(\cdot,\cdot)$ is the joint PDF of two adjacent partial sums $Y$ and $W_1$ of order statistics and can be found in [5, eq. (27)]. After successive substitutions from (13) to (9), we can analytically obtain the average number of path estimations.

**B. Average Number of SNR Comparisons**

As another complexity measure, in this section, we evaluate the average number of required SNR comparisons. Noting that the average number of SNR comparisons for $i/j$-GSC, which is denoted by $C_{\text{GSC}(i,j)}$, can be obtained as

$$
C_{\text{GSC}(i,j)} = \sum_{k=1}^{\min[i,j-1]} (j - k)
$$

(14)

we can express the average number of SNR comparisons for the full scanning scheme and the sequential scanning scheme as

$$
C_{\text{Full}} = C_{\text{GSC}(L_c,L_1)} \Pr[Y + W_1 \geq \gamma_T] \\
+ \left( C_{\text{GSC}(L_c,L_1)} + C_{\text{GSC}(L_c,L_a)} \right) \\
+ \sum_{n=2}^{N} \left( C_{\text{GSC}(L_c,L_n)} + C_{\text{GSC}(1,N)} \right) \times \Pr[Y + W_1 < \gamma_T]
$$

(15)
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\[ C_{\text{Seq}} = C_{\text{GSC}(L_c, L_s)} \Pr [Y + W_1 \geq \gamma T] \]
\[ + \sum_{n=2}^{N} \left( C_{\text{GSC}(L_c, L_s)} + C_{\text{GSC}(L_s, L_c)} \right) \cdot \pi_n \]
\[ + \left( C_{\text{GSC}(L_c, L_s)} + C_{\text{GSC}(L_s, L_c)} \right) \cdot \phi_N \]
\[ + C_{\text{GSC}(1, N)} \cdot \pi_N \]

where \( \pi_n \) is defined in (10), and
\[ \phi_N = \Pr [Y + W_1 < \gamma T, \ldots, Y + W_{N-1} < \gamma T, Y + W_N \geq \gamma T]. \]

\[ (16) \]

C. SHO Overhead

The SHO overhead, denoted by \( \beta \), is commonly used to quantify the SHO activity in a network and is defined as \[ \beta = \sum_{n=1}^{2} nP_n - 1 \]

where \( P_n \) is the average probability that the mobile unit uses \( n \)-way SHO. Note that in the proposed schemes, at most, two-way SHO is used, and both schemes have the same SHO overhead since in both schemes, one-way SHO will be used if \( Y + W_1 \geq \gamma T \) or \( Y + W_1 < \gamma T, W_1 \geq W_i \) for \( i = 2, 3, \ldots, N \); otherwise, two-way SHO is used. Therefore, we have

\[ \beta = P_2 = 1 - P_1 \]

\[ P_1 = \Pr [Y + W_1 \geq \gamma T] \]
\[ + \Pr [Y + W_1 < \gamma T, W_1 = \max \{ W_1, \ldots, W_N \}]. \]

\[ (19) \]

Using the same conditioning method, we can express the joint probability in (20) as

\[ \Pr [Y + W_1 < \gamma T, W_1 = \max \{ W_1, \ldots, W_N \}] \]
\[ = \Pr [Y + W_1 < \gamma T, W_1 > W_2, \ldots, W_1 > W_N] \]
\[ = \int_{0}^{\gamma T} f_{W_1}(w_1) F_{Y|W_1=w_1}(\gamma_T - w_1) \]
\[ \cdot \prod_{i=2}^{N} F_{W_i}(w_i) dw_i. \]

\[ (21) \]

Successive substitutions from (21) to (19) lead to the analytical expression for the SHO overhead as

\[ \beta = F_{Y + W_1}(\gamma_T) - \int_{0}^{\gamma_T} f_{W_1}(w_1) F_{Y|W_1=w_1}(\gamma_T - w_1) \]
\[ \times \prod_{i=2}^{N} F_{W_i}(w_i) dw_i \]

\[ (22) \]

where \( f_{W_1}(\cdot) \) is the marginal density of \( W_1 \), which can be obtained from the joint PDF \( f_{Y,W_1}(\cdot,\cdot) \) as

\[ f_{W_1}(w_1) = \int_{\frac{L_c - L_s}{w_1}}^{\infty} f_{Y,W_1}(y,w_1) dy \]

\[ (23) \]

\[ F_{Y|W_1=w_1}(x) = \begin{cases} 0, & 0 \leq x < \frac{L_c - L_s}{w_1} \\int_{\frac{L_c - L_s}{w_1}}^{\infty} f_{Y,W_1}(y,w_1) dy \end{cases}, \]

\[ x \geq \frac{L_c - L_s}{L_s} w_1. \]

\[ (24) \]

D. Numerical Examples

In Fig. 1, we plot the following: 1) the average number of path estimations; 2) the average number of SNR comparisons; and 3) the SHO overhead versus the output threshold \( \gamma_T \) of the proposed replacement scheme for various values of \( L_s \) over i.i.d. Rayleigh fading channels when \( N = 4, L_1 = L_2 = L_3 = L_4 = 5, L_c = 3, \) and \( \gamma = 0 \) dB. For comparison purposes, we also plot those for the reassignment scheme\( ^1 \) [11] and conventional \( L_c/L(N) \)-GSC. Recall from [11] that the reassignment scheme is acting as \( L_s/L(N) \)-GSC when the output threshold becomes large. Hence, we can observe from all the subfigures that the reassignment scheme converges to GSC as \( \gamma_T \) increases.

Although both the replacement and reassignment schemes have almost the same path estimation load [see Fig. 1(a)], it can be seen in Fig. 1(b) that the replacement scheme leads to a greater reduction of the SNR comparison load compared to the reassignment scheme, and the amount of the reduction increases as \( \gamma_T \) increases or the block size \( L_s \) decreases.

For the SHO overhead, it is clear from Fig. 1(c) that both schemes have a better chance of relying on the target BSs as \( \gamma_T \) increases. Note that unlike the reassignment scheme, the proposed replacement scheme selects the acceptable paths from at most two BSs in any case. Hence, the maximum value of the SHO overhead for the replacement scheme is one, which essentially leads to a reduction of the SHO overhead compared to the reassignment scheme. Also, we can see that in our proposed scheme, the smaller block size provides a slightly higher SHO overhead for large \( \gamma_T \). This is because as \( L_s \) decreases, the sum of the \( L_s \) smallest paths among the \( L_c \) currently used paths from the serving BS has a higher probability of being less than the sums of the \( L_s \) strongest paths from the target BSs, and as such, we have a higher chance to replace groups.

\( ^1 \)As a double check, all numerical evaluations obtained from the analytical results derived in this paper have been compared and verified by Monte Carlo simulations.

\( ^2 \)Note that the analytical results in [11] are based on the approximation methods used in [4]. Although these approximation methods have proved to be precise, for a more accurate comparison in this paper, we use the simulation results for the reassignment scheme.
IV. Statistics of Combined SNR

Based on the mode of operation in Section II-B, we derive in this section the statistics of the combined SNR of the proposed scheme.

Case I—Full Scanning: From (5), the CDF of the combined SNR $\gamma_{\text{Full}}$ can be written as

$$F_{\gamma_{\text{Full}}}(x) = \Pr[\gamma_{\text{Full}} < x] = \Pr[\gamma_T \leq Y + W_1 < x] + \Pr[Y + W_1 < \gamma_T \leq Y + \max\{W_1, \ldots, W_N\} < x].$$  \hspace{1cm} (25)

Following the same conditioning approach, we have

$$\Pr[Y + W_1 < \gamma_T, Y + \max\{W_1, \ldots, W_N\} < x] = \int_0^x f_Y(y)F_{W_1|Y=y}(\min\{x, \gamma_T\} - y) \times \prod_{i=2}^N F_{W_i}(x-y)dy.$$ \hspace{1cm} (26)

Substituting (26) into (25), we can obtain the analytical expression for the CDF of $\gamma_{\text{Full}}$ in (27), shown at the bottom of the page.

By using Leibnitz’s rule [15, eq. (6.40)] and differentiating (27) with respect to $x$, we can obtain the generic expression for the PDF of the combined SNR $\gamma_{\text{Full}}$. Specifically, if we assume that the number of resolvable paths from each BS is the same (i.e., $L_1 = \cdots = L_N$), then the PDF of $\gamma_{\text{Full}}$ can be given in (28), shown at the bottom of the page, where

$$f_{W_1|Y=y}(x) = \begin{cases} \frac{f_Y(y)W_1(y,x)}{f_Y(y)}, & 0 \leq x < \frac{L_2}{L_2-L_y}y \\ 0, & x \geq \frac{L_2}{L_2-L_y}y. \end{cases}$$ \hspace{1cm} (29)

$$F_{\gamma_{\text{Full}}}(x) = \begin{cases} \int_0^x f_Y(y)F_{W_1|Y=y}(x-y)\prod_{i=2}^N F_{W_i}(x-y)dy, & 0 \leq x < \gamma_T \\ F_{Y+W_1}(x) - F_{Y+W_1}(\gamma_T) + \int_0^{\gamma_T} f_Y(y)F_{W_1|Y=y}(\gamma_T - y)\prod_{i=2}^N F_{W_i}(x-y)dy, & x \geq \gamma_T \end{cases}$$ \hspace{1cm} (27)

$$f_{\gamma_{\text{Full}}}(x) = \begin{cases} \int_0^x f_Y(y)\left(f_{W_1|Y=y}(x-y) (F_{W_2}(x-y))^{N-1} \right. \\ \left. + f_{W_1|Y=y}(x-y) (N-1) (F_{W_2}(x-y))^{N-2} f_{W_2}(x-y) \right)dy, & 0 \leq x < \gamma_T \\ f_{Y+W_1}(x) + \int_0^{\gamma_T} f_Y(y)F_{W_1|Y=y}(\gamma_T - y) \times (N-1) (F_{W_2}(x-y))^{N-2} f_{W_2}(x-y)dy, & x \geq \gamma_T \end{cases}$$ \hspace{1cm} (28)
Case II—Sequential Scanning: From (6), the CDF of the combined SNR $\gamma_{\text{Seq}}$ can be expressed as

$$F_{\gamma_{\text{Seq}}}(x) = \Pr[\gamma_{\text{Seq}} < x] = \Pr[\gamma_T \leq Y + W_1 < x] + \sum_{i=2}^{N} \Pr[Y + W_i < \gamma_T, \ldots, Y + W_N < \gamma_T, Y + \max\{W_1, \ldots, W_N\} < x].$$

(30)

All the joint probabilities in (30) can be expressed using the same conditioning approach, leading to (31), shown at the bottom of the page. For $L_1 = \cdots = L_N$, we can obtain the PDF of $\gamma_{\text{Seq}}$ as in (32), shown at the bottom of the page.

V. AVERAGE BER COMPARISONS

In this section, we apply the results from Section IV to the performance analysis of our proposed combining schemes over i.i.d. Rayleigh fading channels. More specifically, by presenting some selected numerical examples, we examine its average BER. The average BER can be calculated by finding the expected value of the conditional probability of error. For example, the average BER for binary phase-shift keying (BPSK) can be expressed as

$$P_b(E) = \int_0^\infty Q(\sqrt{2x}) f(x) dx$$

(33)

where $Q(\cdot)$ is the Gaussian $Q$-function, which is defined as $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-t^2/2} dt$, and $f(x)$ is the PDF of the combined SNR, which is obtained in (28) for the full scanning scheme and in (32) for the sequential scanning scheme.

\[
F_{\gamma_{\text{Seq}}}(x) = \left\{ \begin{array}{ll}
\int_0^x f_Y(y) F_{W_1|Y=y}(x-y) \prod_{i=2}^{N} F_{W_i}(x-y) dy, & 0 \leq x < \gamma_T \\
F_{Y+W_1}(x) - F_{Y+W_1}(\gamma_T) & x \geq \gamma_T \\
\end{array} \right.
\]

(31)

\[
f_{\gamma_{\text{Seq}}}(x) = \left\{ \begin{array}{ll}
\int_0^x f_Y(y) \left( f_{W_1|Y=y}(x-y) (F_{W_2}(x-y))^{N-1} \\
+F_{W_1|Y=y}(x-y)(N-1) (F_{W_2}(x-y))^{N-2} f_{W_2}(x-y) \right) dy, & 0 \leq x < \gamma_T \\
f_{Y+W_1}(x) + \int_0^\gamma f_Y(y) F_{W_1|Y=y}(\gamma_T-y) f_{W_2}(x-y) \left( \frac{1-(F_{W_2}(\gamma_T-y))^{N-1}}{1-F_{W_2}(\gamma_T-y)} \right) dy, & x \geq \gamma_T \\
\end{array} \right.
\]

(32)
benefit from the additional paths if \( L_s = 1 \) compared to the case of \( L_s = 2 \), whereas for the low threshold, the variation of the block size does not affect the performance since, in this case, no replacement is needed. For the midrange of the output threshold (i.e., \( \gamma_T = 5 \) dB), the full scanning scheme has slightly better performance than the sequential scanning scheme over the medium SNR range. However, as shown in Fig. 1, with this slight (negligible) performance loss, the sequential scanning scheme can reduce the unnecessary path estimations and SNR comparisons, compared to the full scanning scheme.

In Fig. 3, we compare the error performance of the replacement scheme to that of the reassignment scheme when \( L_s = 2 \) and other parameters are the same as in Fig. 2. For the full scanning scheme [Fig. 3(a)], since the paths with the largest SNR values are selected whenever needed, the reassignment scheme always provides better performance than the replacement scheme. However, with the sequential scanning scheme [Fig. 3(b)], we can observe that although the performance of the reassignment scheme is better than that of the replacement scheme for most cases, the replacement scheme performs better for the high-average-SNR region (\( \tau > 0 \) dB) and medium values of the threshold (\( \gamma_T = 5 \) dB). This can be interpreted as follows: In this case, to exceed the output threshold, the replacement scheme has to scan more and more BSs, and as such, there is a higher chance to acquire a block with better quality, whereas the reassignment scheme needs fewer BSs to meet that threshold requirement.

VI. EFFECT OF PATH UNBALANCE/CORRELATION

In practice, the i.i.d. fading scenario on the diversity paths is not always realistic due to, for example, the different adjacent multipath routes with the same path loss and the resulting unbalance and correlation among paths. In this section, we assess through some computer simulations the effect of nonidentically distributed paths with correlation on the performance of both the reassignment and the replacement schemes. More specifically, instead of the uniform power delay profile (PDP) considered so far, we now consider an exponentially decaying PDP, for which \( \tau_j = \gamma_T e^{-\delta(j-1)} \), where \( \tau_j (1 \leq j \leq L_n, 1 \leq n \leq N) \) is the average SNR of the \( j \)th path out of the total available resolvable paths from each BS, and \( \delta \) is the average fading power decaying factor. For the correlated paths, we consider the exponential correlation models where an exponential power correlation coefficient \( \rho^{j-j'} \), for \( \rho \in [0,1] \), between any pair of paths \( \gamma_j \) and \( \gamma_{j'} \) from a certain BS is assumed. Note that \( \delta = 0 \) means identically distributed paths, and \( \delta = 0 \) means independent fading paths. When we set \( \delta = 0 \) and \( \rho = 0 \), we revert to the i.i.d. fading channels.

In Fig. 4, we plot the average BER of BPSK versus \( \gamma_T \) of the replacement and the reassignment schemes over an exponentially decaying PDP with an exponential correlation across the multipaths. These results show that the PDP and the correlation among paths induce a non-negligible degradation in the performance and, therefore, must be taken into account for the accurate prediction of the performance of proposed schemes. In all cases, we can see the same relationship between the replacement and the reassignment schemes as observed in Fig. 3.

VII. EFFECT OF OUTDATED OR IMPERFECT CHANNEL ESTIMATION

In general, diversity-combining techniques rely, to a large extent, on accurate channel estimation. As a typical first step in performance analysis, perfect estimation was assumed so far. However, in practice, these estimates must be obtained in the presence of noise and time delay. Hence, the effects of channel estimation error or channel decorrelation on the performance of diversity systems are of interest. In this section, we study the effect of outdated or imperfect channel estimates on the performance. To isolate the effects from other factors, all the diversity paths are assumed to be i.i.d. Let \( \gamma^* \) be the estimated received signal power. Due to imperfect or outdated channel estimates, \( \gamma^* \) may or may not be the same as \( \gamma \). Hence, we can assume that \( \gamma^* \) is the correlated sample from \( \gamma \) with a power correlation factor \( \rho^* \in [0,1] \) between \( \gamma \) and \( \gamma^* \). Here, \( \rho^* \) can be viewed as a measure of the channel fluctuation rate and a measure of the channel estimation quality as well. As an example, from the well-known Clark’s model, we know that \( \rho^* = J_0^* (2 \pi f_D \tau) \) [1, Sec. 2.1.1], where \( J_0(\cdot) \) is the zero-order Bessel function of the first kind, \( \tau \) is the time delay, and \( f_D \) is the maximum Doppler frequency shift. Note that \( \rho^* = 0 \) means
completely outdated channel estimates, whereas $\rho^\tau = 1$ means up-to-date and perfect channel estimates.

Fig. 5 compares the effect of the correlation factor $\rho^\tau$ on the average BER of BPSK of the replacement and the reassignment schemes with full scanning for several values of the output threshold $\gamma_T$ over i.i.d. Rayleigh fading channels. We can see from these curves that in all cases, the diversity gain offered by the proposed schemes decreases as $\rho^\tau$ decreases, as expected. It is very notable that contrary to the analysis over perfect channel estimation, the replacement scheme shows a lower error probability than the reassignment scheme when $\rho^\tau = 0$ and 0.5 for $\gamma_T = 5$ and 15 dB. Recall that the replacement scheme compares two sums of paths from the serving and target BSs, whereas the reassignment scheme relies on the SNR of each path. Therefore, the replacement scheme is more robust to the channel estimation errors, particularly when the comparisons of the two sums are needed. In other words, the more often the combined SNR is below the threshold, the less sensitive to the channel estimation error the replacement scheme is, and the more sensitive the reassignment scheme is.

VIII. CONCLUSION

In this paper, we proposed new finger replacement schemes that are applicable for RAKE receivers in the SHO region. We considered two path scanning schemes: a full scanning scheme and a sequential scanning scheme. For both schemes, we provided a general comprehensive framework for the assessment of these proposed schemes by offering not only analytical results for i.i.d. fading environments but also computer simulation results for non-i.i.d. fading channels and an outdated channel estimation. We showed through numerical examples that the proposed schemes can save a certain amount of complexity with negligible performance loss compared to the previously proposed schemes. Computer simulation results showed that our proposed scheme is also applicable to non-i.i.d. fading channels and offers, moreover, a great advantage in the presence of channel estimation errors.

REFERENCES


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