Semi-Blind Dual-Hop Relay Selection based on Long-term Channel Statistics on the First Relaying Hop

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Abstract—**In this paper, we propose a novel relay selection scheme based on the *maximum a posteriori* (MAP) decision criterion for a dual-hop semi-blind (DHSB) amplify-and-forward (AF) relaying, where only long-term channel statistics at the first relaying hops are taken into consideration. The observed channel gain vectors across the cluster of the first hops are provided to the selection algorithm, which then selects the relay node which has the "*most likely highest probability of channel power gain distribution*" using a posteriori likelihood ratio over a burst time period. The other selection scheme based on the maximum first-hop signal-to-noise power ratio (SNR) is also compared, taking into account sample mean of channel power gain. Fixed gain relaying is adopted to constrain our DHSB system for both MAP and first-hop SNR based relay selection schemes. The outage performance of max-min sense end-to-end SNR relay selection, as a conventional scheme and benchmark, is compared to our proposed schemes. Simulation results demonstrate that, in terms of outage performance, our proposed MAP-based relay selection scheme is particularly appropriate for a DHSB relaying network.**

Keywords- Relaying network; dual-hop; outage probability; maximum a posteriori probability; Rayleigh fading.

I. INTRODUCTION

Various selective cooperation schemes have been investigated recently with the objective of improving transmission throughput and reducing outage probability [1, 2, 3, 4]. There are two common selection relay schemes for which the amplify-and-forward (AF) and decode-and-forward (DF) modes are adopted. For practical relay networking, it is realized that the AF relaying protocol provides the simplest and most economic relaying approach [1, 2, 5, 6, 7], where the relay node (R) forwards the received signal from the source (S) to destination (D) after scaling it to meet its power constraint. The relay selection schemes presented in the literature [1, 5], using the so-called max-min relay selection scheme, are primarily based on the selection criteria of instantaneous SNR across both relaying hops (S-R $\cap$ R-D), with the proviso that the achieved transmission rate is satisfied. However, this approach likely introduces high computational complexity of the relay link instantaneous channel power gains (via channel estimations) and inadequate real-time capability for executing the selection algorithm [8, 9]. As a consequence, it results in performance degradation of the relay selection operationally. These drawbacks can be mitigated if relay selection solely depends on the long-term channel statistics of the source to relay link (i.e., first-hops), where the dual-hop semi-blind (DHSB) AF relay was introduced [12, 14].

In reality, it is impossible to switch (select) the relay node per symbol base, but which can be determined objectively in terms of sample mean of SNR_i with long-term channel statistics. Therefore, the maximum a posteriori probability (MAP) is based on the maximum-likelihood decision criterion which is simple and needs a minimal amount of statistical information (i.e., probabilistic channel description). Similar to the MAP approach using long-term channel statistics, a first-hop SNR-based relay selection is also considered in the DHSB relay system, in comparison with MAP-based outage performance. This is measured on the first and second statistical moments of the channel parameters (i.e., sample mean of channel power gains) without stochastic channel description. However, the conditional mean is not linear in the time-varying fading channel. Therefore, it is possible to cause a large error variance of the channel power gain that will result in the performance degradation on the relay selection. Accordingly, that gives the instantaneous end-to-end SNR based max-min relay selection a degraded performance. Hence, we turned our attention to the MAP relay selection, and the problem in determining the optimum channel range over the observed relaying links which has the minimum average risk for the relay selection. We assumed that the perfect channel state information (CSI) and statistics orders are estimated at the source node via the down-link pilot sub-channels. These parameters are then fed back to the destination for decision algorithm via dedicated uplink control channel sequentially.

Recently, a performance analysis of DHSB AF relaying over Nakagami-*m* fading channel has been investigated based on the end-to-end SNR [11, 14], however, there are no relay selection methods being discussed. In this paper, we have focused on the outage performance of a DHSB AF relaying scenario with our extended the maximum a posteriori probability (MAP) decision algorithm for the relay selection. Hence, the MAP-based relay selection scheme does not require calculation and comparison of end-to-end signal-to-noise ratio (SNR) across relay hops, since it calculates the a posteriori probability using long-term channel statistics and then selects the relay link with the highest probability over multi-relaying links. The main contributions of our work can be summarized as follows.

A) A novel relay selection scheme based on MAP decision rule is proposed for the DHSB relay system, where M-1 likelihood ratios of the first hop channel gains are exploited. Hence, our proposed selection algorithm makes $\frac{1}{2}M\times(M-1)$ comparisons, instead of

M^M comparisons for the general max-min end-to-end SNR relay selection scheme. This greatly reduces the complexity of implementing the selection

B) Our presented outage probabilities also include the performance constraint on the relay selection where it was not discussed previously in most of the publications [1, 5, 9, 12].

The rest of this paper is structured as follows. Section II describes the system model and AF relaying implementation. Section III discusses implementation issues of the MAP relay selection scheme. Simulation and analytical results are compared in terms of outage probabilities are provided in Section IV. Section V concludes this paper.

II. SYSTEM MODEL

Fig. 1 shows a dual-hop AF relaying network incorporating the MAP decision algorithm. For the m^{th} relay node, m = 1, 2,…, M, the channel gains, $r_{S,Rm}$ and $r_{Rm,D}$, denote the first hop from the S node to the R node and the second hop from the R node to the D node respectively. We assume that independent and identically distributed (i.i.d.) static Rayleigh fading [10] occurs across all relay hops S-R and R-D. The channel statistics (i.e., mean, channel covariance) of both relaying segments corresponding to the channel state information (CSI) are assumed to be perfectly estimated via the pilot sub-channels, and centralizes these parameters available to the MAP decision algorithm at D node. Hence, the AF gain can be formulated to an inverse function of the average channel power gain of the first hop [11, 12]. In our paper, the MAP decision algorithm (i.e., a special case of the Bayes decision rule) [13] is implemented to minimize the average cost per decision of relay selection, where the most likely highest probability of channel power gain distribution is measured over M first-hops on a per burst basis. The problem with minimizing the average cost is solved by selecting optimum channel gain regions.

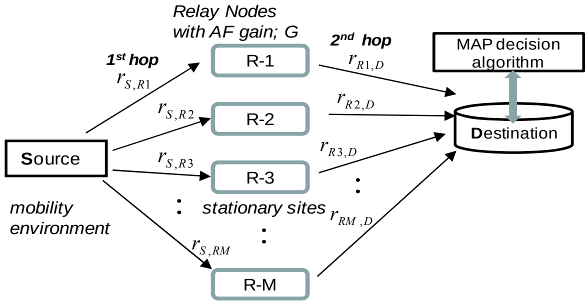

Fig.1. Dual-hop AF multi-relay networking with MAP relay selection algorithm

These optimum regions are then provided to calculate the a posteriori probabilities for each relay node. As a result, the selected relay node with the maximum a posteriori probability is determined from among the set of relay nodes.

As for the transmissions from source to relay, the instantaneous SNR on the S-R link is proportional to its corresponding channel power gain r^2_{S,R_m}, which is usually affected by the path loss (i.e. $d^{-\alpha}_{S,Rm}$), where $d_{S,Rm}$ is defined as the distance between the m^{th} relay and the source node and α represents the path loss factor. Thus, the instantaneous SNR received at relay node with transmitted source power, E_S, and white noise power, N_o, is given as

$$SNR_i = \frac{E_S}{N_o} |h|^2 \, d^{-\alpha}_{S,Rm} \tag{1}$$

where $r^2_{S,Rm} = |h|^2 d^{-\alpha}_{S,Rm}$ is defined as a channel power gain with respect to the channel response, h. We also assumed that all links are reciprocal.

It is assumed that instantaneous channel power gains $r^2_{S,Rm}$ and $r^2_{Rm,D}$, are independent, exponentially distributed (i.i.d.) random variables, corresponding with channel gains, $r_{S,Rm}$ and $r_{Rm,D}$ with means, $\bar{r}_{S,Rm}$ and $\bar{r}_{Rm,D}$, for m = 1, 2,…, M, respectively, according to Rayleigh fading assumptions. As a long-term post processing is applied to our relay selection scheme, the mean channel gains $\bar{r}_{S,Rm}$ and $\bar{r}_{Rm,D}$ are given by averaging over a time-slot period. Thus, the instantaneous SNRs, $\chi_1 = \sigma_1^2 \left| r_{S,Rm} \right|^2$ and $\chi_2 = \sigma_2^2 \left| r_{Rm,D} \right|^2$ are given for the first relay hop and the second relay hops, respectively, which correspond with the average SNRs, σ_1^2 and σ_2^2. It is noted that these channel gains can be obtained by estimating the CSIs via pilot sub-signals, and have Rayleigh distribution. χ_1 and χ_2 have exponential distribution (i.e., chi-squared with two degree of freedom).

Since we consider a dual-hop AF relaying system, the transmission period from the S-node to the D-node is divided into two consecutive phases. In the first phase, the S-node transmits signal s to the m^{th} R-node. Accordingly, the received signal at m^{th} R-node is given as,

$$y_{S,R_m} = r_{S,Rm} \cdot s + n_{S,Rm} \tag{2}$$

where $r_{S,Rm}$ is the channel gain between the m^{th} R-node and the S-node, and $n_{S,Rm}$ is the additive white Gaussian noise (AWGN) at the m^{th} R-node with zero mean and variance σ^2_{Rm} and the signal energy $E\left[ss^*\right] = E_S$. In the second phase, the S-node is on standby and the received signal $y_{S,Rm}$ at the R-node is amplified by a fixed gain, G, and then transmitted to the D-node. The received signal at D-node is therefore given by

$$y_{Rm,D} = G \cdot r_{Rm,D}\left(y_{S,Rm}\right) + n_{Rm,D} \tag{3}$$

where $r_{Rm,D}$ and $n_{Rm,D}$ are the channel gain between the m^{th} R-node and D-node and the AWGN at the D-node with zero mean and variance σ_D^2 respectively. Since our objective for this paper is to exploit a new relay selection scheme and investigate its outage performance, the end-to-end SNR calculated for the outage evaluation will not be further discussed here. The resulting end-to-end SNR (S-R-D) via m^{th} relay node is given by [11, 12, 14]

$$\chi_3 = \frac{\left|G \cdot r_{S,Rm} r_{Rm,D}\right|^2 E_S}{\left|G \cdot r_{Rm,D}\right|^2 \sigma_1^2 + \sigma_D^2} = \frac{\chi_1 \chi_2}{\chi_2 + C} \qquad (4)$$

where C is a constant for AF fixed relay gain

$$C \cong \frac{E_S}{G^2 \cdot \sigma_R^2}.$$

The square of relay gain is given by [12 , 14]

$$G^2 = \frac{E_S}{\sigma_1^2 \left(\overline{\chi}_1 + 1\right)} \qquad (5),$$

where $\overline{\chi}_1$ is the mean power gain of χ_1.

In the following, we consider that the relay system operates in a half-duplex mode (i.e., time division duplexing system) and only one selected relay node is allowed to transmit per time slot.

III. MAP RELAY SELECTION SCHEME

A. Relay Selection Criterion

For a DHSB AF relaying system, the relay selection criterion will proceed to jointly search for the channel statistics which has the maximum a posteriori probability (MAP) over the first hop (stochastic fading channel). The selected relay has $\chi_{S,Rm \cup Rm,D} > 2^{2\nu} - 1$ after scaling it to meet its transmit power constraint for a target spectral efficiency ν (bit/sec/Hz). As such, a relay selection rule can be classified as M-1 likelihood ratios for each relay link (first hop between S-R), and this is subject to : the vector observations of the channel gains, the conditional probability density function, a prior probability and decision cost factor with respect to each radio link. Therefore, the a posteriori probabilities can be determined in terms of these given information individually using Bayes's rule [13]. The MAP selection process can thus be divided into two steps: (1) jointly identify the optimum channel gain ranges on the first hops where the average decision risk is minimized; and (2) achieve maximum a *posterior* probability by integrating its corresponding channel gain range. Let the conditional PDF, $P_{m1}\left(\overline{r}/L_{S,Rm}\right)$ of the channel gain vectors $\overline{r}$ ~$\left[0 < r \le 3\sigma_0\right]$ be known at D node, m =1, 2, .. , M, and these channel gain vectors are random processes with Rayleigh distribution and its variance $E\left[r_{S,Rm}^2\right] = \sigma_0^2$. The channel gain vectors are composed of the channel sequences of the first relay hops. This gives our analysis a boundary over three times the standard deviation of the Rayleigh distribution, $\left[0 \le \Re_{11} \cup \Re_{21} \cup \Re_{31} \cup .. \Re_{M1} \le 3\sigma_0\right]$ for each first relay hop. It also corresponds to the probability of exceeding the Rayleigh envelope by one percent (1%) via setting the standard deviation $\sigma_0 = 3$. These Rayleigh fading channels were generated using Jakes' model [10]. For the m^{th} selected relaying link, $L_{S,Rm}$, the MAP-based relay selection criterion is given by

$$\hat{\Omega} = \arg \max_{r \in R_{m1}} \left\{ \int_{\Re_{m1}} \mathrm{P}_{\mathrm{r}_{m1}}\left(\overline{r} / L_{S,Rm}\right) \mathrm{d}\, r \right\} \qquad (6),$$

m = 1, 2, .., M,

where $\Re_{m1}$ is the optimum region of the channel gain w.r.t. the first hop of the m^{th} relay node, and the conditional probability density function (PDF), $\mathrm{P}_{\mathrm{r}_{m1}}\left(\overline{r} / L_{S,Rm}\right)$, has a Rayleigh distribution. The integrand term inside the bracket of (6) is described as a *posteriori* probability of the channel power gain distribution w.r.t. optimum region R_{m1} the first relay hop $r_{S,Rm}$, and is given by

$$P\left(L_{S,Rm} / R_{m1}\right) = \int_{\Re_{m1}} P_{r_{m1}}\left(\overline{r} / L_{S,Rm}\right) dr \qquad (7)$$

where m =1, 2, .. , M and $\sum_{m=1}^{M} P\left(L_{S,Rm} / R_{m1}\right) = 1$.

Those $\Re_{m1}$ are determined by the MAP decision algorithm (which will be discussed in next sub-section). Hence, the m^{th} relay node selection is determined if

$$P\left(L_{S,Rm} / R_{m1}\right) > P\left(L_{S,Rk} / R_{k1}\right) \qquad (8)$$

for all k ≠ m, and by denoting the maximum decision factor $\beta_m = P\left(L_{S,Rm} / R_{m1}\right)$ for simplicity of notation. It should be noted that our proposed MLD-based relay selection algorithm makes $\frac{1}{2} M \cdot (M-1)$ comparisons, instead of M^M comparisons for the max-min sense based relay selection schemes [7]. In fulfilling the DHSB AF relaying system design, we found that this simplified selection rule is more practical since it resulted in faster selection by eliminating the search through all possible end-to-end SNR comparisons in general relay selection schemes.

B. MAP Decision Algorithm

Consider an extended Likelihood Decision algorithm (Bayes decision rule) for 1-by-M multiple relay links (S-Rs) over the *M*-likelihood of receiving relay nodes, $L_{S,R} = \left[L_{S,R1}, L_{S,R2}, .., L_{S,Rm}, .., L_{S,RM}\right]$ represent the radio link vector corresponding to the first hops w.r.t. M relay nodes. For minimization of the average decision risk per relay selection using Bayes's rule [11]

$$P(L_{S,Rm}/R_{m1}) = \frac{P_{r_{m1}}(\bar{r}/L_{S,Rm})\cdot P(L_{S,Rm})}{P(r)} \qquad (9),$$

and the *average risk* for a selection decision is defined as [11]

$$\hat{C} = \sum_{k=1}^{M}\sum_{m=1}^{M} P(deciding\, L_{S,Rk}/L_{S,Rm})\cdot P(L_{S,Rk})\cdot C_{L_{S,Rk},L_{S,Rm}} \qquad (10)$$

where the a *priori* probability of each relay link, $P(L_{S,R1}), P(L_{S,R2}),\ldots, P(L_{S,RM})$, is equal (i.e. 1/M) and the cost factor, $C_{L_{S,Rk},\,L_{S,Rm}}$ is associated decision of classifying a link from $L_{S,Rk}$ given that it is from a link $L_{S,Rm}$. $P(deciding\, L_{S,Rk}/L_{S,Rm})$ is the conditional probability of deciding radio link $L_{S,Rk}$ given at that $L_{S,Rm}$ belongs, and can be further interpreted as

$$P(deciding\, L_{S,Rk}/L_{S,Rm}) = \iint\cdots\int_{\Re_{k1}} P(\bar{r}/L_{S,Rm})dr \qquad (11),$$

where $k = 1,2,..,M$ and $k \neq m$.

Note that $\Re_{k1}$ represents the optimum channel gain region at the first hop link of the k^{th} relay node. The problem is to select the optimum channel gain regions of $\Re_{11},\Re_{21},\ldots,\Re_{M1}$ such that the average selection risk (9) is minimized. Substituting (11) into (10) and separating out the costs with identical indices, then (10) can be rewritten in terms of M integrals as

$$\begin{aligned}\hat{C} &= \sum_{k=1}^{M}\sum_{m=1}^{M} P(L_{S,Rm})C_{L_{S,Rk},L_{S,Rm}} \iint\cdots\int_{\Re_{k1}} P(\bar{r}/L_{S,Rm})dr \qquad (12)\\ &= \iint\cdots\int_{\Re_{11}} \sum_{m=1}^{M} C_{L_{S,R1},L_{S,Rm}} P(\bar{r}/L_{S,Rm})P(L_{S,Rm})dr + \\ &\quad \iint\cdots\int_{\Re_{21}} \sum_{m=1}^{M} C_{L_{S,R2},L_{S,Rm}} P(\bar{r}/L_{S,Rm})P(L_{S,Rm})dr + \cdots \\ &\quad \iint\cdots\int_{\Re_{M1}} \sum_{m=1}^{M} C_{L_{S,RM},L_{S,Rm}} P(\bar{r}/L_{S,Rm})P(L_{S,Rm})dr\end{aligned}$$

Without loss of the generality, a new function, $y_k(r)$, within the integrands of (12), is given as

$$y_k(r) \cong \sum_{m=1}^{M} C_{L_{S,Rk},L_{S,Rm}} P(\bar{r}/L_{S,Rm})P(L_{S,Rm}) \qquad (13)$$

k =1, 2, .. , M.

From (13), we see that the cost function (12) will be minimized if the optimum region is determined as follows: $r \in \Re_{m1}$ if $y_m(r) < y_k(r)$ *for all* $k = 1, 2, \ldots, M$ and $k \neq m$ (i.e., likelihood ratio). Each of the optimum channel gain regions is found by taking M-1 comparisons of $y_m(r) < y_k(r)$ for the m^{th} first relay hop, where the intersection of M-1 channel ranges, is determined accordingly

$$\Re_{m1} = \bigcap_{\substack{k=1,2,..,M\\ m\neq k}} (y_m(r) < y_k(r)) \qquad (14)$$

These mutually exhaustive and exclusive decision regions, $\Re_{11},\Re_{21},..,\Re_{M1}$, make the average cost, $\hat{C}$, that is minimized. From (5), it is clear that the MAP decision rule for the relay selection is obtained using a zero-one cost assignment [i.e., cost factor $C_{L_{S,Rk},L_{S,Rm}}$ = 0 for k = m, and $C_{L_{S,Rk},L_{S,Rm}}$ = 1 for k ≠ m] and an equal a priori probability of each relay link.

Fig. 2 shows one of the simulation results of optimum regions generated from (14), where the optimum regions are R_{11} = [0.01~0.95], R_{21} = [1.65~3.0], R_{31} = [1.29~1.64] and R_{41} = [0.96~1.28]. During simulations, maximum Doppler frequency, f_d, exists at all radio links of the first hop with normalized $f_d T = 0.05$ and data duration *T*. This simulation is performed using four i.i.d. Rayleigh fading channels [10]. By using these optimum regions, the a posteriori probabilities are obtained as $P(L_{S,R1}/R_{11}) = 0.403$ $P(L_{S,R2}/R_{21}) = 0.3016$, $P(L_{S,R3}/R_{31}) = 0.1681$ and $P(L_{S,R4}/R_{41}) = 0.1141$ respectively. Note that the channel covariance of radio link $L_{S,Rm}$ for each conditional probability is obtained by averaging 100 channel observations, respectively. Accordingly, the 1st relay node has the MAP = 0.403, and is selected as the "best" relay in accordance with our MAP relay selection criterion (6).

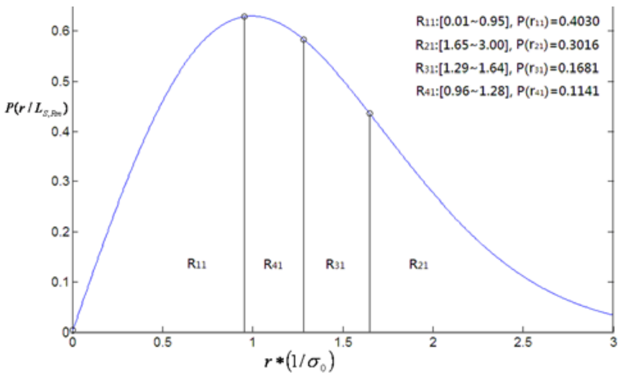

Fig. 2 Channel power gain distribution with the first hop channels are characterized by normalized Doppler frequencies $f_D T_S$ =0.05 and standard deviation $\sigma_0 = 3$ for M = 4.

IV. NUMERICAL ANALYSIS

In this section, we illustrate by simulation the outage performance of our proposed MAP-based relay selection scheme on behalf of a DHSB AF relaying system. Our analyses started with relay selection using the MAP decision algorithm, then the outage performances were analyzed via Monte-Carlo simulations. For a single relay link, the outage is generally given by $P_{out} = \mathrm{P_r}(\chi_3 < 2^{2v} - 1)$, where χ_3 is defined in (4).

The target spectral efficiency is $\upsilon = 1$ bps/Hz and M = 4. To fulfill our optimum decision input parameters and numerical analyses, the variances of the instantaneous channel gain of the first hops were calculated in the basis of block lengths of 100 channel samples at each relay link and the outage probabilities were averaged over a collection of 2000 channel segments for each SNR value. Note that the relay selection is performed form block to block and the average SNR is considered in symmetric relay hops (i.e., $\sigma_1^2 = \sigma_2^2$ single hop SNR). The relay links are generated using Rayleigh fading channel model [10] with normalized Doppler frequency $f_d T = 0.05$, and have equal average end-to-end channel power gain across all relay links.

In Fig. 3, the outage performance of MAP-based relay selection (DHSB AF), is compared with the analytical max-min based selection [Equ (5), 5] as a benchmark, and the first-hop SNR based selection (semi-blind AF) are also presented. Both MAP and first SNR based relay selection schemes are provided for the DHSB AF relay networking. The simulations were conducted for multi-relay M = 2, 3, 4, respectively. We found that with an increase in the number of relay nodes, the outage probabilities decrease as selection diversity gain is available correspondingly in all cases. Comparing with the max-min sense analytical results, our proposed MAP scheme introduces about 3 dB degradation at a10^{-3} outage rate, whilst there is a 4 dB degradation with first hop SNR-based selection. It is generally accepted that end-to-end SNR selection gives higher expected reward, but will consume more computational load.

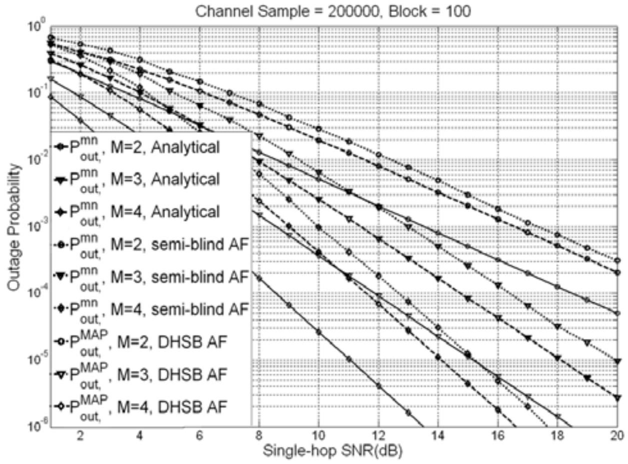

Fig.3. Outage performance comparison with max-min end-to-end SNR based selection (Analytical) and proposed MAP-based selection scheme (DHSB AF) and first-hop SNR based (semi-blind AF) with multi-relay M = 2, 3, and 4 respectively.

Through our simulation results, we confirmed that our proposed MAP-based relay selection scheme consumes approximately 1 dB less energy than the first hop SNR-based selection when considered with a DHSB AF relaying system. Although a full-CSI assisted end-to-end (max-min) selection scheme has better performance than DHSB AF relaying, this incurs a greater computational load in selection algorithm implementation. As a result, our proposed scheme gives a simple and effective approach to practical DHSB AF relay networking design.

V. CONCLUSION AND FUTURE WORK

Through our simulations, we confirmed that the MAP-based probabilistic channel description approach relay selection outperforms the first-hop sample mean SNR based selection for a DHSB AF relaying system using a long-term channel statistics scenario. We also found that it introduces a 3 dB performance degradation at outage level 10^{-3} against max-min sense relay selection scheme, whilst substantially simplifying and reducing the relay selection process in terms of computational load. The numerical and simulation results demonstrate that our proposed MAP-based relay selection is appropriate to DHSB relay network design in terms of the implementation simplicity and outage performance. It is also interesting to derive an analytical expression of the outage probability jointly considering the relay selection performance (i.e., MAP-based selection algorithm), not merely adopting a generic outage definition. This will be helpful to evaluate the overall system performance in practical relaying network design.

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