

A NEW PRACTICAL RECEIVER FOR A DECODE-AND-FORWARD COOPERATIVE CDMA SYSTEMS BASED ON A BLIND λ -COMBINER

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Abstract—This paper develops a practical receiver suggested for cooperative systems using decode-and-forward transmission and compares it to the theoretical sub-optimum λ -MRC receiver model. The proposed receiver model adopts a channel blind λ -combiner and employs a practical estimation of the combiner's weight λ that changes adaptively for each received bit. The λ estimation process relies on a dynamic-blind calculation performed on the incoming bit stream using an approximate formula. The accuracy of the estimated values of λ against the numerical (optimum) values is verified by comparing their effects on the performance curves. Next, the performance of the proposed receiver is evaluated against the sub-optimum receiver using the closed-form performance equations then verified using an actual implementation of the decode-and-forward cooperative algorithm. The use of the proposed receiver is shown to have reliable performance under different channel assignments and provides adaptivity to channel variations without complexity or exaggerated signal processing.

1. INTRODUCTION

The early papers introducing the concept of decode-and-forward cooperative diversity for multiple access communication systems [1–8] were in concurrence with one theoretic (sub-optimum) basic receiver model that consists of a matched filter followed by a sub-optimum λ -MRC (Maximum-Ratio Combining). The λ -MRC is a modified two

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branch MRC combiner, and it weights one branch using λ and the other branch with a unity weight. The combiner's weighting factor λ , $\lambda \in [0, 1]$, is defined as a measure of the ultimate receiver's confidence in the cooperative information delivered by the partner. It has the potential to control the amount of cooperation required to minimize the overall P_e (Probability of Error) and provides higher quality of service. The value of λ is a function of the current channel conditions and the inter-user channel probability of error P_{e12} , a quantity which may or may not be available at the ultimate receiver. It is difficult to find an optimum expression for λ ($\lambda_{optimum}$) as a function of P_{e12} due to the non-convex property of the overall probability of error P_e expression. Three solutions remain for any practical receiver model to obtain the value of λ ; finding a sub-optimum expression ($\lambda_{sub-optimum}$), finding an optimized solution using a signal processing tool, and finding an efficient estimation of λ [1–3]. The two former solutions are expected to result in more residual errors, either due to imperfections in the feedback from the users concerning the value of P_{e12} or channel estimation errors, compared to an adaptive estimation of λ [1, 2].

This paper seeks for a practical receiver model for decode-and-forward cooperative based transmissions that provides a performance level comparable to the results using the theoretical (sub-optimum) receiver model. The proposed receiver consists of a matched filter followed by a blind λ -combiner that is capable to estimate the value of λ blindly and adaptively for each received bit. The estimation starts by computing the difference (δ) between the received signal during the odd intervals, sent by the user, and during even intervals, sent by both the user and the partner, for each received bit. This difference describes the deviation between the user's and partner's received signal that happens either due to channel degradation or estimation imperfections of the partner's cooperative bit. Next, a monotonically decreasing expression is proposed and applied to the difference (δ) to obtain the dynamic-blind value of the weight λ providing a minimized P_e for the currently received bit.

In order to evaluate the proposed receiver, the performance of a decode-and-forward cooperative transmission framework using the optimum values of λ , numerically calculated, is compared to the performance using the proposed values of λ . Next, the performance using the theoretical receiver model and the new practical receiver is evaluated. These comparisons use the analytical closed-form probability of error P_e performance introduced in the literature as in [1–5], for different channel assignments. Finally an actual implementation of a decode-and-forward cooperative algorithm is considered, it applies a DS-CDMA (Direct Sequence-Code Division

Multiple Access) transmission and uses the complete complementary (CC) codes set [9]. Its performance using the sub-optimum receiver is used as a reference to evaluate the performance of the proposed practical receiver under several channel models.

The proposed calculation of λ shows a remarkable accuracy and leads to performance levels on the verge of the case using optimum values of λ . On the other hand, the new practical receiver illustrates reliable performance compared to the theoretical receiver model under similar transmission conditions. The paper is organized as follows; Section 2 introduces a full description the λ -MRC applied for the decode-and-forward cooperative systems, Section 3 discusses the proposed practical receiver and the employed dynamic-blind estimation of the combiner's weight λ , Section 4 investigates an actual implementation of a DS-CDMA decode-and-forward cooperative transmission, Section 5 displays the simulation results, and Section 6 is the paper conclusions.

2. THE λ -MRC COMBINER; AN OVERVIEW

In a decode-and-forward cooperative framework [1–3], the transmission is performed over two symbol intervals; odd non-cooperative and even cooperative interval. The odd symbol interval is used to send the user own bit to the ultimate receiver and the partners. Meanwhile, the partners are assigned to detect and estimate the received information. The even symbol interval are cooperative as the user transmits the sum of its own bit (previously sent in the odd duration) and the partner's estimated bit, each spread by the appropriate spreading code. Consequently, the user's data is received over 2 intervals, the first interval's data Y^{odd} and the second interval's data Y^{even} expressed in (1) and (2).

$$Y^{odd} = K_{10}X_1^{odd} + K_{20}X_2^{odd} + Z^{odd} \quad (1)$$

$$Y^{even} = K_{10}X_1^{even} + K_{20}X_2^{even} + Z^{even} \quad (2)$$

where X_k is the k th user transmitted signal, $X_k^{odd} = a_{k,u}b_kC_k$, $X_k^{even} = a_{k,u}b_kC_k + a_{k,u+1}\hat{b}_{k+1}C_{k+1}$, $a_{k,u}$ is the power factor of the k th source during the transmitting interval u , C_k is an index of the spreading code, b is the transmitted bit, \hat{b} is an estimated bit, K_{ij} are the Rayleigh fading coefficients from the source i to the destination j having mean ξ_{ij}^2 , and finally Z the white zero-mean Gaussian noise with spectral height $N_i/2$.

The literature review shows that the optimal detector used for decode-and-forward transmission is complex and doesn't have a closed

form expression [1–3], its expression is illustrated in (3). A sub-optimum receiver model for this type of transmission is proposed and used in almost all references instead of the optimal detector.

$$(1 - P_{e12}) A^{-1} e^{v_1^T y} + P_{e12} A e^{v_2^T y} \stackrel{1}{>} (1 - P_{e12}) A^{-1} e^{-v_1^T y} + P_{e12} A e^{-v_2^T y} \stackrel{-1}{<} \quad (3)$$

where $y = [y_{odd} \ y_{even}]^T \frac{\sqrt{N_C}}{\sigma_0}$, $v_1 = [K_{10}a_{11} \ (K_{10}a_{12}) + (K_{20}a_{22})]^T \frac{\sqrt{N_C}}{\sigma_0}$, $v_2 = [K_{10}a_{11} \ (K_{10}a_{12}) - (K_{20}a_{22})]^T \frac{\sqrt{N_C}}{\sigma_0}$, and $A = \exp(K_{10}K_{20}a_{11}a_{22}N_c/\sigma_0^2)$. The sub-optimum receiver model consists of a matched filter, a sub-optimum combiner, and a decision stage. The sub-optimum combiner λ -MRC, is a modified MRC combiner. It weights the branch with the partner's uncertain bit using the factor λ and a unity weight is used for the branch with the bits coming directly from the desired user. It can be described by (4).

$$\hat{b}_1 = \text{sign}([\gamma_1 \ \lambda(\gamma_2 + \gamma_3)] y) \quad (4)$$

where $\gamma_1 = (K_{10}a_{11}) \frac{\sqrt{N_C}}{\sigma_0}$, $\gamma_2 = (K_{10}a_{12}) \frac{\sqrt{N_C}}{\sigma_0}$, $\gamma_3 = (K_{20}a_{22}) \frac{\sqrt{N_C}}{\sigma_0}$, and $\lambda \in [0, 1]$. The weight λ is a measure of the ultimate receiver's confidence in the bits estimated by the partner. The probability of P_e for the λ -MRC is shown in [1] and is given by (5).

$$P_e = (1 - P_{e12}) Q \left(\frac{v_1^T v_\lambda}{\sqrt{v_\lambda^T v_\lambda}} \right) + P_{e12} Q \left(\frac{v_2^T v_\lambda}{\sqrt{v_\lambda^T v_\lambda}} \right) \quad (5)$$

where $v_1 = [K_{10}a_{11} \ (K_{10}a_{12}) + (K_{20}a_{22})]^T \frac{\sqrt{N_C}}{\sigma_0}$, $v_2 = [K_{10}a_{11} \ (K_{10}a_{12}) - (K_{20}a_{22})]^T \frac{\sqrt{N_C}}{\sigma_0}$, and $v_\lambda = [\gamma_1 \ \lambda(\gamma_2 + \gamma_3)]^T$. From the P_e in (5), it is shown that the λ weight is directly related to the inter-user channel error (P_{e12}) between the user and the partner. For a perfect inter-user channel $P_{e12} = 0$, the optimal detector in (3) collapses to the detector in (5) with $\lambda = 1$. As P_{e12} increases, the inter user channel becomes unreliable, the value of the best λ decreases towards zero. The pre-described receiver model for decode-and-forward transmission is theoretical till present, it assumes perfect channel and inter-user channel knowledge. Moreover, the analytical performance calculations for these cooperative systems utilize values of the combiner's weight λ obtained numerically using (5) for specific transmission conditions. Consequently, any practical receiver model is expected to find actual yet accurate values of λ and to manage efficient channel estimation processes.

3. THE PROPOSED RECEIVER MODEL

This paper reaches a practical receiver model for a decode-and-forward cooperative framework. The proposed model relies on a dynamic-blind method to estimate the value of the combiner's weight λ and adopts a channel blind λ -combiner as a substitute to the λ -MRC combiner model. Due to the importance of λ , it is mandatory to find an expression that calculates this value to reduce the implementation complexity for any practical algorithm using the decode-and-forward cooperative transmission. In fact, finding an optimum expression of λ that minimizes Equation (5) is complex due to the non-convex nature of the P_e expression. Moreover, sub-optimum solutions either a suboptimum expression or using a classifying signal processing tool will result in a significant error due to the channel parameters estimation imperfections or feedback errors from the users concerning the value of P_{e12} [1–3]. These complications support the efficiency of an adaptive estimation of λ over the sub-optimum solutions.

The proposed estimate of λ relies on calculating the bit-by-bit difference (δ) between the ultimate receiver's combined statistics of the odd duration information, y_{odd} , and that of the even duration, y_{even} . Where y_{odd} is expressed by (6), y_{even} by (7) and the difference δ by (8).

$$y_{odd} = K_{10}a_{11}b + n_{odd} \quad (6)$$

$$y_{even} = K_{10}a_{12}b + K_{20}a_{22}\hat{b} + n_{even} \quad (7)$$

$$\delta = y_{odd} - y_{even} = K_{10}a_{11}b - \left(K_{10}a_{12}b + K_{20}a_{22}\hat{b} \right) + n \quad (8)$$

The difference δ is a normally distributed random variable with zero mean and variance equals to $\sigma_{\delta}^2 = \sigma_{y_{odd}}^2 + \sigma_{y_{even}}^2$. It is a measure of the deviation between the user's and partner's information delivered to the ultimate receiver for a specific bit. This deviation results either due to the channel degradation or the partner's bit estimate error that arises from the quality of the inter-user channel error (P_{e12}). Obviously, the value of δ reduces to a definition very close to that of λ . Considering the definition of λ and its range, we suggest an approximate formula that relates the weight λ and the difference δ in a monotonically decreasing expression with parameter α as described in (9) and by the block diagram in Fig. 1(a).

$$\lambda_{blind} = \exp(-\alpha * abs(\delta)). \quad (9)$$

The relation between the difference δ and the weight λ for different values of α is shown in Fig. 1(b). The proper value of alpha is found using an iterative search. Numerous transmission conditions were considered. In each case, the best network performance, found

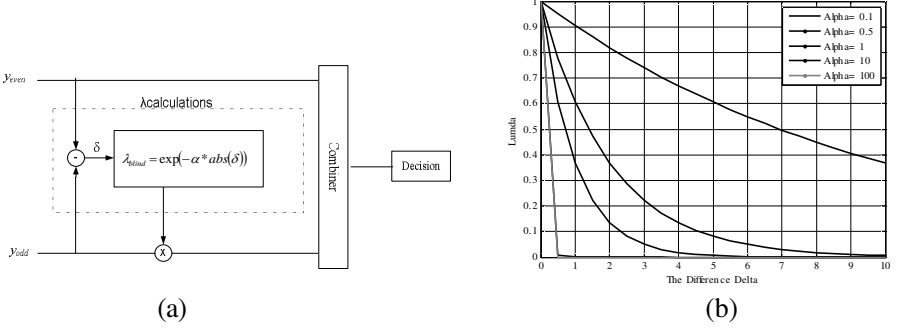


Figure 1. The block diagram representing the proposed calculation of λ in (a) and the monotonically decreasing expression relating the combiner's weight λ and the difference δ for different values of α plotted in (b).

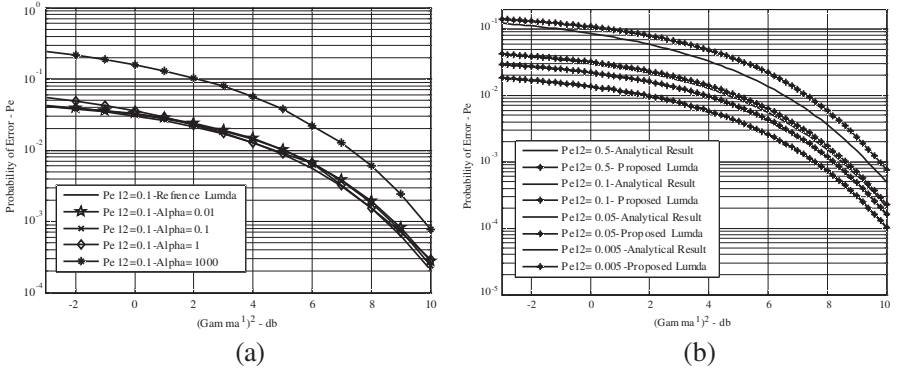


Figure 2. The analytical closed-form of the probability of error P_e performance for different values of α under the effect of $P_{e12} = 0.1$ versus γ_1^2 range from -3 to 10 dB in (a) and the same probability of error P_e performance using the λ -MRC against the use of the dynamic-blind λ estimation for different values of P_{e12} versus γ_1^2 in (b).

using (5), was considered as the criterion to select the best value of alpha. After an intensive search observing a range of α from 10^{-4} to 10^4 in each transmission case, the best value of α was found to be $\alpha = 0.1$. A sample of the pre-described search is shown in Fig. 2(a). Hence, the proposed expression describing the relation between the combiner's weight λ and the difference δ reduces to (10).

$$\lambda_{blind} = \exp(-0.1 * abs(\delta)). \quad (10)$$

We refer to the proposed expression of λ_{blind} as the dynamic-blind as this value is calculated for every received bit and utilized the incoming bit stream without any prior knowledge of the transmission environment. For different values of P_{e12} , the probability of error P_e using optimum values of λ (λ_{opt}) is compared to the performance using λ_{blind} values to evaluate the accuracy of the proposed λ estimation method. It is obvious that the curves in either cases are close and are almost superimposed for small values of P_{e12} as shown in Fig. 2(b). This observation takes place because the accuracy of λ_{blind} is very high as the desired value is close to 1 and loses its accuracy as it approaches zero. The simulations considered a range of γ_1^2 from -3 to 10 dB, $\gamma_2 = 1.2$, and $\gamma_3 = 0.8$.

Next, we suggest the use a channel blind λ -combiner instead of the λ -MRC model. The proposed combiner utilizes the dynamic-blind calculation of the weight λ . The P_e expression for the proposed combiner follows (5) and the weighting vector is expressed by $v_\lambda = [1 \ \lambda_{blind}]^T$. Considering the former difference, the search for the best value of α using the P_e performance is repeated and the best value is found to be $\alpha = 0.1$. A sample of the pre-described search is displayed in Fig. 3(a). Then, the performance of the blind λ -combiner against the λ -MRC is evaluated for different values of inter-user channel error P_{e12} and for the simulation conditions in Fig. 3(b). The proposed

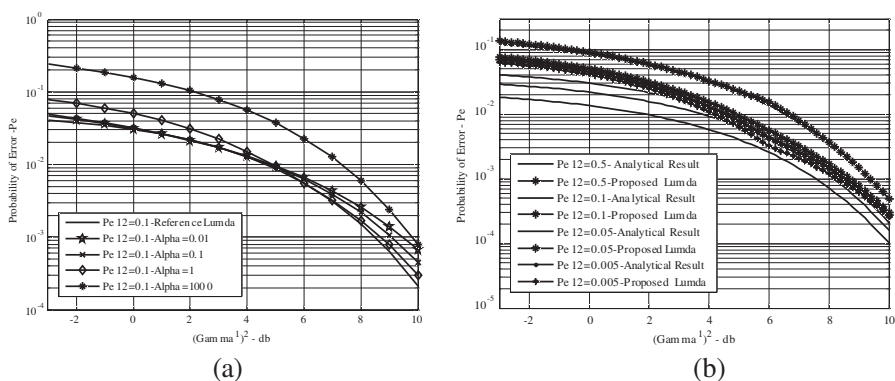


Figure 3. The analytical closed-form of the probability of error P_e performance using the sub-optimum receiver versus the proposed receiver for different values of α under the effect of $P_{e12} = 0.1$ versus γ_1^2 in (a) and the same probability of error P_e performance using the sub-optimum receiver and the proposed receiver different values of P_{e12} versus γ_1^2 in (b).

combiner results in a slight performance difference that increases for low values of P_{e12} . For instance, the proposed receiver causes 0.2 dB P_e performance degradation for a Rayleigh channel variance of 0 dB and $P_{e12} = 10^{-1}$ which is considered very reliable. On the other hand, this value increases for larger values of P_{e12} and larger Rayleigh channel degradation. In fact, this performance deviation is rather acceptable regarding its adaptivity to channel variations without complexity or exaggerated signal processing. The proposed receiver achieves reliable performance compared to the sub-optimum model as shown by analytical system performance, the next sections will go through more evaluations using an actual cooperative algorithm. The channel blind λ -combiner shows accurate estimation of λ and saves all the channel estimation and feedback processes needed for the sub-optimum receiver model.

4. AN ACTUAL IMPLEMENTATION OF A DECODE-AND-FORWARD COOPERATIVE ALGORITHM USING THE COMPLETE COMPLEMENTARY CODE SETS

In this section, an actual implementation of a decode-and-forward cooperative algorithm is considered. It is used to evaluate the performance analysis using the sub-optimum receiver versus the use of the proposed receiver and to observe the efficiency of the λ estimation process. The highlighted cooperative algorithm is presented in [9]; it considers a decode-and-forward multiple-access cooperation transmission framework using the complete complementary (CC) code sets. These codes have particular correlation properties [10–12]. Along each set, the autocorrelation sum is impulsive. Besides, the codes in different sets are orthogonal and particularly the cross correlation sum of these codes along the set size vanishes for all shifts. This special type of codes has been previously used in different applications including CDMA and MIMO transmissions [10, 13–15].

The algorithm supports a number of users equal to the number of sets and performs the transmission over several parallel channels following the number of codes per set. The transmission procedure goes as follows: K users are assigned a CC code set of M codes; each user spreads his information using each of the M codes separately resulting in M different signals sent through M parallel channels following the multi-band DS-CDMA proposed in [15]. Each transmission channel uses a different frequency band that carries the summation of all users' respective CDMA signals, and the block diagram of the highlighted algorithm is shown in Fig. 4.

The cooperative transmission is achieved through two symbol

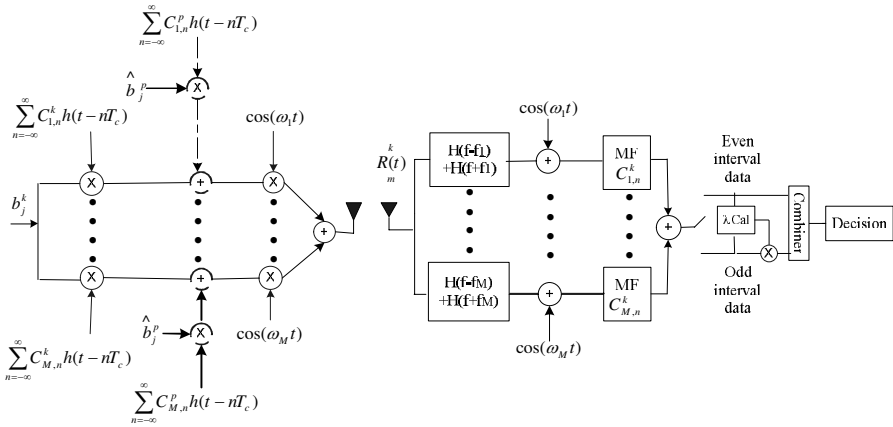


Figure 4. The block diagram of the DS-CDMA decode-and-forward cooperative algorithm using the complete complementary code sets.

duration: the odd and even durations. The odd symbol duration is used to send the user own bit, using M sub-bands, to the base station and partners. Meanwhile, partners are assigned to detect and estimate the received information. During the even symbol duration, the users cooperate and transmit the sum of their own bit (previously sent in the odd duration) and the partner’s estimated bit, each spread by the appropriate spreading code. Based on two users, each user is assigned a set of two codes of length N and two transmitting bands. The user k th signal during the two intervals is observed in (11). While the transmitting signals during the odd and even intervals on band m are observed in (12) and (13) respectively.

$$\begin{aligned} X_1^k &= b_j^k C_{1,N}^k & b_j^k C_{1,N}^k + \hat{b}_j^p C_{1,N}^p \\ X_2^k &= b_j^k C_{2,N}^k & b_j^k C_{2,N}^k + \hat{b}_j^p C_{2,N}^p \end{aligned} \tag{11}$$

$$T_{\text{odd}}^k(t) = \sum_{m,j}^k \sum_{n=-\infty}^{\infty} b_j^k C_{m,n}^k h(t-nT_c - \tau^k) \tag{12}$$

$$T_{\text{even}}^k(t) = \sum_{m,j}^k \sum_{n=-\infty}^{\infty} \left(b_j^k C_{m,n}^k h(t-nT_c - \tau^k) + \hat{b}_j^p C_{m,n}^p h(t-nT_c - \tau^p) \right) \tag{13}$$

where $h(t)$ is the impulse response of the chip wave-shaping filter, T_c the chip duration, j is the data index, p is the partner index, b_j^k is the user k ’s bit, and \hat{b}_j^p is the partner estimated bit, $m = 1, 2, \dots, M$ is the band and code index and $C_{m,n}$ denotes the code sequence m of length

n from the set \mathcal{C} .

The utilized receiver is the sub-optimum model and composed of a matched filter and a λ -MRC combiner. The considered implementation makes only one modification; the matched filter is formed of M parallel branches to match the user's M spreading codes. Equations (14) and (15) describe the output of the correlators of user k signal in the odd and even symbols, respectively. Equation (15) is multiple access interference (MAI) free due to the orthogonality between the different users' sets. Both the user and the partner will be able to extract their information sent through the same interval and band without any overhead interference. Finally, the λ -MRC combines the user information extracted during both odd and even intervals. Note that parameter n' is the same as n after passing through the band pass filter.

$$R_{odd}^k(t) = \sqrt{E_c} \sum_{n=-\infty}^{\infty} b_j^k \left(\sum_{n'=0}^{N-1} \left(\sum_{m=1}^M C_{m,n'}^k \cdot C_{m,n'}^k \right) \right) x(t - nMT_c) \quad (14)$$

$$R_{even}^k(t) = \sqrt{E_c} \sum_{n=-\infty}^{\infty} \left(b_j^k \left(\sum_{n'=0}^{N-1} \left(\sum_{m=1}^M C_{m,n'}^k \cdot C_{m,n'}^k \right) \right) + \hat{b}_j^p \left(\sum_{n'=0}^{N-1} \left(\sum_{m=1}^M C_{m,n'}^k \cdot C_{m,n'}^p \right) \right) \right) x(t - nMT_c) \quad (15)$$

5. THE SIMULATION RESULTS

The P_e performance of the actual decode-and-forward algorithm using the sub-optimum receiver is considered as a reference border against which the efficiency of the proposed practical receiver is evaluated. First, the accuracy of the blind estimation of λ is verified for several transmission conditions. For each transmission case, the best P_e performance using the sub-optimum receiver, found by numerical search, is compared to the performance using the dynamic-blind values of λ . The P_e performance is analyzed for different values of inter-user channel under the effect of a Rayleigh flat fading channel and a unity power AWGN. The Rayleigh channel variance is ranging from -5 to 10 dB during the odd symbol duration while during the even duration two cases are observed.

The first case is 'the bad user-good partner', which assumes that the desired user is experiencing severe attenuation towards the ultimate receiver while the partner enjoys much better channel conditions. The Rayleigh fading coefficient is taken as 0.4 for the user and 1 for the partner. For small values of P_{e12} , the difference δ increases leading

λ_{blind} to approach 1 which results in superimposed curves as shown on Fig. 5(a). As for higher values of P_{e12} , the difference δ decreases causing relative estimation deviation of λ_{blind} , that approaches zero, and a slight performance lag takes place.

The second case is ‘the good user-bad partner’ which assumes the opposite transmission conditions compared to the former case, and the Rayleigh fading coefficient for the user is taken 0.8 and 0.3 for the partner. As P_{e12} increases, the difference δ increases as well as the accuracy of λ_{blind} which results in very close performance curves. On the other hand as P_{e12} decreases, the difference δ decreases as well as the accuracy λ_{blind} , that approaches zero, which causes obvious difference between the curves as observed in Fig. 5(b). A significant difference is noticed between the two cases displayed in Fig. 5; the superimposed curves are in different ranges of P_{e12} . This occurs as the calculations of the difference δ is channel dependent, following Equation (8), which causes the accuracy of λ_{blind} to take place at different ranges of inter-user channel P_{e12} . Generally, the proposed dynamic-blind estimation of λ results in efficient performances under different channel assignments compared to the reference performance curves and illustrates to be simple and reliable. Yet, the estimation process is more accurate as the value of the difference δ is higher and as the desired λ values approaches 1.

Finally, the performance evaluation of the proposed receiver versus

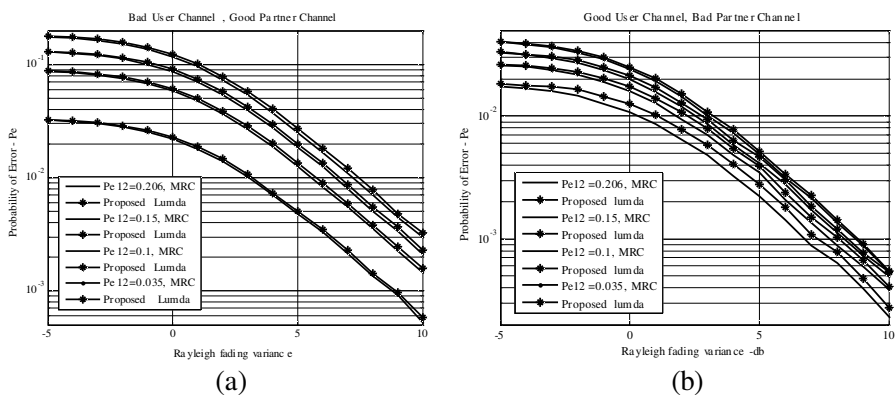


Figure 5. The probability of error performance of the highlighted practical cooperative transmission using the λ -MRC combiner using optimum λ and the proposed λ calculation versus the Rayleigh flat fading channel variance under different values of inter-user channel P_{e12} . For bad user-good partner in (a) and good user-bad partner in (b).

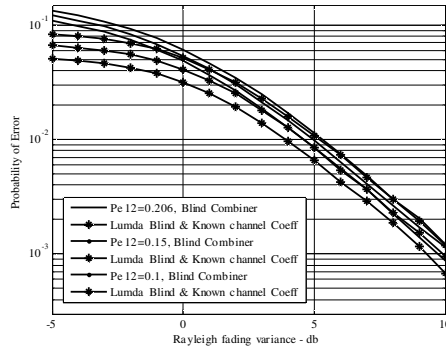


Figure 6. The performance analysis of the complete complementary codes based CDMA cooperative transmission using the λ -MRC combiner against the proposed blind combiner for different values of inter-user channel P_{e12} equals 0.206, 0.15, and 0.1 versus the a Rayleigh flat fading channel variance and a unity power AWGN.

the sub-optimum model under the effect of Rayleigh flat fading channel and a unity power AWGN is provided in Fig. 6. The Rayleigh channel variance ranges from -5 to 10 dB during the odd symbol transmission while during the even symbol duration the Rayleigh fading coefficient is maintained invariant to the value 0.8 for the user and 0.6 for the partner. A significant, yet acceptable, difference between both performances is observed at low values of P_{e12} . By highlighting the Rayleigh channel variance of 0 dB and P_{e12} of 0.1, the performance difference is 0.2 dB. While very close performances are witnessed for high values of P_{e12} . The performance difference occurring with the use of the proposed receiver model is minor regarding the model simplicity, the reduction of both the channel estimation as well as the feedback processes required using the sub-optimum receiver model.

6. CONCLUSION

In this paper, a new practical receiver model for decode-and-forward cooperative multiple-access transmission was proposed. The proposed model adopted a dynamic-blind calculation of the combiner's weighting factor λ that was presented and its approximate expression was provided. Using the sub-optimum receiver, the analytical closed-form P_e performance under several channel conditions was used as a reference level and compared to the performance using the proposed λ_{blind} estimation. It provided an efficient performance and illustrated remarkable accuracy as the value of λ approaches 1. Moreover, it was

shown to be simple, adaptive, and completely blind as it does not required any prior knowledge of the transmission conditions. Then, the proposed channel blind receiver was evaluated as a substitute to the sub-optimum receiver model using the closed-form performance, and it showed a reliable performance as well as simplicity.

Finally, an actual implementation of a decode-and-forward cooperative multiple access transmission using complete complementary codes was discussed. Its performance using the sub-optimum receiver was verified and used to evaluate the use of the proposed λ_{blind} and the channel blind λ -combiner receiver under several channel assignments. The dynamic-blind calculation of λ resulted in almost-identical performances compared to the performance using the desired values of λ . It was remarkable that the accuracy of λ_{blind} increases as it approaches 1 and is directly proportional to the difference δ . While for the proposed receiver, the performance illustrated adjacency with the sub-optimum model at high values of P_{e12} and slightly differs at low values. This performance difference is at no cost regarding the avoided complexity, channel estimation, and feedback processes.

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