

# Joint Transmitter-Receiver UWB Rake Design in the Presence of ISI

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**Abstract**—In this paper, the performance of a time-division duplex ultra-wideband system that has a transmitter/receiver pair of rake combining structures is optimized, where the total number of rake fingers to be deployed at the transmitter and the receiver is fixed. It is shown that there exists an optimum distribution of fingers between the two structures for systems with intersymbol interference, which maximizes the signal-to-interference plus noise ratio. Depending on the total number of rake fingers and/or post-rake fingers, i.e., those at the receiver, the optimum placement of post-rake fingers changes as the simulation results demonstrate.

**Index Terms**—pre-rake, rake, ultra-wideband (UWB), intersymbol interference

## I. INTRODUCTION

Ultra-wideband (UWB) systems have a much lower fading margin than narrowband systems, since the wide system bandwidth enables fine resolution in time of the received multipaths [1]. Experimental investigations of the wideband indoor channel lying in the 2-8 GHz band confirm this fact and indicate that rake receivers can achieve significant diversity gains by collecting the total signal energy distributed over a large number of paths [2]. Furthermore, for time-division duplex (TDD) systems it is possible to move the rake structure from the receiver to the transmitter by making use of the channel information estimated in the reverse link. To be specific, the transmitter scales and delays the original transmitted signal in such a way that the operation of multipath combining is already performed when the signal arrives at the receiver, in which case the receiver may use the conventional design that tunes to a single path [3], [4].

Pre-raked transmission has initially been proposed in [3] for code division multiple access systems, where its performance is shown to be equivalent to the conventional rake receiver over single-user links with moderate data rates. Later studies conducted for UWB systems in particular, such as [5], indicate that pre-raking may lead to suppressed intersymbol interference (ISI) with high data rates, since the maximal ratio combining (MRC) stage of rake reception, which boosts interference energy at the receiver, is avoided. This desirable property of pre-raking is accompanied by a larger number of multipaths at the receiver than that exists for the channel impulse response between the transmitter and the receiver. When

properly exploited, those paths allow an improved performance compared to the pre-rake or post-rake, i.e., the rake structure at the receiver, only systems. The pre/post-rake structure in [6], for instance, uses an MRC post-rake to collect all of the multipaths. Moving one step further, the eigenprecoder proposed in [7] has its pre- and post-rake weights determined jointly to maximize the signal-to-noise ratio (SNR) at the receiver. The principal ratio combining (PRC) pre/post-rake with a flexible number of pre-rake fingers [8] is a variation of the eigenprecoder.

The PRC pre/post-rake has to have an unlimited number of post-rake fingers for optimum performance, since the received SNR increases with the number of pre-rake fingers, which in turn requires a larger number of post-rake fingers. An infeasible number of pre- and post-rake fingers may have to be deployed in total at the transmitter and the receiver for UWB channels that tend to be extremely frequency-selective. The problem of how to distribute a fixed total number of rake fingers between the transmitter and the receiver was addressed previously in [9]. Specifically, it is shown that in the absence of ISI, there is an optimum number of pre-rake fingers, and thus post-rake vectors, that maximizes the received SNR when the post-rake structure combines the first arriving paths. In this paper, it is demonstrated that the presence of ISI results in a transmitter/receiver design that does not allow a closed form expression for the pre- and post-rake vectors, but rather an iterative algorithm has to be used to arrive at the rake vectors that are optimum in the sense that they maximize the signal-to-interference plus noise ratio (SINR) of the decision statistic. Moreover, simulations indicate that depending on the total number of rake and/or pre-rake fingers, the optimum placement of the post-rake fingers becomes a difficult problem, which may even require an exhaustive search in some cases (e.g., as in [10] for a minimum mean-square error post-rake-only system), where combining the first arriving paths does not exhibit sufficient performance.

## II. UWB SYSTEM MODEL

Considering a system which uses binary phase shift keying (BPSK) for data modulation, the signal transmitted after pre-

rake processing with  $F_t$  fingers is given by

$$s(t) = \sqrt{E_b} \sum_{i=-\infty}^{\infty} b_i \sum_{k=0}^{F_t-1} v_k w_{tr}(t - iT_b - \beta_k),$$

where  $E_b$  is the bit energy,  $b_i \in \{-1, 1\}$  is the  $i$ th bit,  $w_{tr}(t)$  is the transmitted pulse, and  $v_k$  and  $\beta_k$  are the gain and delay of the  $k$ th pre-rake finger, respectively. The transmitted signal propagates through the UWB channel, whose impulse response is modeled as

$$h(t) = \sum_{\ell=0}^{L-1} \alpha_\ell \delta(t - \tau_\ell),$$

where  $\alpha_\ell$  and  $\tau_\ell$  denote the gain and delay of the  $\ell$ th multipath, respectively, and  $\delta(\cdot)$  is the Dirac delta function. Accordingly, the signal received over a single-user link is

$$r(t) = \sqrt{E_b} \sum_{i=-\infty}^{\infty} b_i \sum_{\ell=0}^{L-1} \alpha_\ell \sum_{k=0}^{F_t-1} v_k w_{rec}(t - iT_b - \beta_k - \tau_\ell) + n(t) \quad (1)$$

at the receiver antenna output, where the received unit energy pulse  $w_{rec}(t)$ , which has duration  $T_p$ , is different from  $w_{tr}(t)$  due to the differentiation effect of the antenna, and  $n(t)$  is an additive white Gaussian noise (AWGN) component with two-sided power spectral density  $N_0/2$ .

Inspection of (1) reveals that since the pre-rake finger delays,  $\beta_k = \tau_{L-1} - \tau_k$ , are obtained from the channel impulse response, for  $\tau_\ell = \ell T_p$  the number of multipath components at the receiver is  $L + F_t - 1$ . Representing the received signal at the output of the correlator that is matched to the  $m$ th multipath by

$$r_{i,m} = \int_{iT_b + mT_p}^{iT_b + (m+1)T_p} r(t) w_{rec}(t - iT_b - mT_p) dt, \quad m = 0, \dots, L + F_t - 2,$$

the received vector for the  $i$ th bit is written as

$$\mathbf{r}_i = [r_{i,0} \ \dots \ r_{i,L+F_t-2}]^T.$$

The final decision for the  $i$ th bit, where the post-rake vector  $\mathbf{w} = [w_0 \ \dots \ w_{L+F_t-2}]^T$  is used to perform rake combining at the receiving side, is made as in

$$\hat{b}_i = \text{sgn} \{ \mathbf{w}^T \mathbf{r}_i \}. \quad (2)$$

### III. TRANSCIVER DESIGN

The aim in this work is to maximize the SINR for systems with ISI, which perform transmitter/receiver rake processing under the constraint that the total number of rake fingers is bounded by some number,  $F$ :

$$F_t + F_r \leq F$$

where  $F_r$  is the number of post-rake fingers. Such a limit may be desirable to control the cost, complexity and size of the TDD transceiver. Although the number of multipaths created in response to pre-raked transmission is  $L + F_t - 1$ , and hence the number of post-rake fingers may be as large as that as

indicated in (2), we investigate the case where  $F_r < L + F_t - 1$ . Note that one should really expect  $F_t > F_r$  from a practical stand-point.

In the following, while the length of the pre-rake vector is the same as the number of pre-rake fingers such that

$$\mathbf{v}_t = [v_{F_t-1} \ \dots \ v_0]^T,$$

the vector  $\mathbf{w}_r$  represents the post-rake vector of length  $L + F_t - 1$  that has  $F_r$  nonzero elements.

High data rate transmission introduces ISI to the decision statistic for the  $i$ th bit as in

$$\xi = \sqrt{E_b} b_i \mathbf{w}_r^T \mathbf{H} \mathbf{v}_t + \sqrt{E_b} \sum_{\substack{m=-I \\ m \neq 0}}^I b_{i+m} \mathbf{w}_r^T \mathbf{H}_m \mathbf{v}_t + \mathbf{w}_r^T \mathbf{n}_i, \quad (3)$$

where  $\xi = \mathbf{w}_r^T \mathbf{r}_i$  is the decision statistic before thresholding,  $I = \lfloor (L + F_t - 1) / \chi \rfloor$  and  $\chi = T_b / T_p$ . The elements of  $\mathbf{n}_i$  are the noise samples

$$n_{i,m} = \int_{iT_b + mT_p}^{iT_b + (m+1)T_p} n(t) w_{rec}(t - iT_b - mT_p) dt,$$

which are zero-mean Gaussian random variables that have a variance of  $N_0/2$ . In (3) the channel matrix for the desired signal component is the  $(L + F_t - 1) \times F_t$  convolution matrix

$$\mathbf{H} = \begin{bmatrix} \alpha_0 & 0 & 0 & \dots & 0 \\ \alpha_1 & \alpha_0 & 0 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \alpha_{L-1} & & & & \\ 0 & & & \ddots & 0 \\ \vdots & \ddots & & \ddots & \alpha_0 \\ 0 & \dots & & 0 & \alpha_{L-1} \end{bmatrix}.$$

The channel matrices in (3) that describe the signals due to interfering bits are derived from  $\mathbf{H}$  as

$$\mathbf{H}_m = \begin{cases} \begin{bmatrix} \mathbf{H}(-\chi m + 1 : L + F_t - 1, :) \\ \mathbf{0}_{-\chi m \times F_t} \end{bmatrix}, & m < 0, \\ \begin{bmatrix} \mathbf{0}_{\chi m \times F_t} \\ \mathbf{H}(1 : L + F_t - 1 - \chi m, :) \end{bmatrix}, & m > 0, \end{cases}$$

where  $\mathbf{H}(r_1 : r_2, c_1 : c_2)$  denotes a submatrix of  $\mathbf{H}$  that contains rows  $r_1$  through  $r_2$  and columns  $c_1$  through  $c_2$ , and  $\mathbf{0}_{d_1 \times d_2}$  is an all-zero matrix of dimension  $d_1 \times d_2$ .

With independent and equiprobable bits, the SINR of  $\xi$ , which is denoted by  $\gamma$ , is expressed as

$$\gamma = \frac{|\mathbf{w}_r^T \mathbf{H} \mathbf{v}_t|^2}{\frac{N_0}{2E_b} \mathbf{w}_r^T \mathbf{w}_r + \sum_{\substack{m=-I \\ m \neq 0}}^I |\mathbf{w}_r^T \mathbf{H}_m \mathbf{v}_t|^2}. \quad (4)$$

Because the post-rake vector has  $F_r$  non-zero elements, it can be written as

$$\mathbf{w}_r = \mathbf{S}_r^T \tilde{\mathbf{w}}_r, \quad (5)$$

where  $\tilde{\mathbf{w}}_r$  is an  $F_r \times 1$  vector and  $\mathbf{S}_r$  is an  $F_r \times (L + F_t - 1)$  selection matrix that determines which paths, i.e., elements of  $\mathbf{r}_i$ , are combined at the receiver. The paths that arrive first, in the middle and at the end are combined by using the matrices given respectively by

$$\mathbf{S}_r = [\mathbf{I}_{F_r} \quad \mathbf{0}_{F_r \times (L+F_t-F_r-1)}], \quad (6)$$

$$\mathbf{S}_r = [\mathbf{0}_{F_r \times F_t-1} \quad \mathbf{I}_{F_r} \quad \mathbf{0}_{F_r \times (L-F_r)}], \quad (7)$$

$$\mathbf{S}_r = [\mathbf{0}_{F_r \times (L+F_t-F_r-1)} \quad \mathbf{I}_{F_r}], \quad (8)$$

where  $\mathbf{I}_M$  represents an  $M \times M$  identity matrix. By substituting (5) in (4) and observing that  $\mathbf{S}_r \mathbf{S}_r^T = \mathbf{I}_{F_r}$ , another expression is obtained for  $\gamma$ :

$$\begin{aligned} \gamma &= \frac{|\tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H} \mathbf{v}_t|^2}{\tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{S}_r^T \tilde{\mathbf{w}}_r \frac{N_0}{2E_b} + \sum_{m \neq 0}^I |\tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H}_m \mathbf{v}_t|^2} \\ &= \frac{|\tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H} \mathbf{v}_t|^2}{\tilde{\mathbf{w}}_r^T \tilde{\mathbf{w}}_r \frac{N_0}{2E_b} + \sum_{m \neq 0}^I |\tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H}_m \mathbf{v}_t|^2}. \end{aligned}$$

When ISI is present, the joint transmitter-receiver rake design that has a limited total number of rake fingers is the solution to the problem

$$\max_{\tilde{\mathbf{w}}_r, \mathbf{v}_t} \frac{\tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H} \mathbf{v}_t \mathbf{v}_t^T \mathbf{H}^T \mathbf{S}_r^T \tilde{\mathbf{w}}_r}{\tilde{\mathbf{w}}_r^T \left( \frac{N_0}{2E_b} \mathbf{I}_{F_r} + \sum_{m \neq 0}^I \mathbf{S}_r \mathbf{H}_m \mathbf{v}_t \mathbf{v}_t^T \mathbf{H}_m^T \mathbf{S}_r^T \right) \tilde{\mathbf{w}}_r}. \quad (9)$$

The pre- and post-rake vectors that satisfy (9) are optimal in the sense that they maximize the SINR of the decision statistic.

Defining  $\gamma_0 \triangleq 2E_b/N_0$  and the matrices

$$\begin{aligned} \mathbf{C}_v &\triangleq \mathbf{S}_r \mathbf{H} \mathbf{v}_t \mathbf{v}_t^T \mathbf{H}^T \mathbf{S}_r^T, \\ \mathbf{D}_v &\triangleq \frac{1}{\gamma_0} \mathbf{I}_{F_r} + \sum_{\substack{m=-I \\ I \neq 0}}^I \mathbf{S}_r \mathbf{H}_m \mathbf{v}_t \mathbf{v}_t^T \mathbf{H}_m^T \mathbf{S}_r^T, \end{aligned}$$

it is recognized that the expression in (9) is in the form of the generalized Rayleigh quotient,

$$\gamma = \frac{\tilde{\mathbf{w}}_r^T \mathbf{C}_v \tilde{\mathbf{w}}_r}{\tilde{\mathbf{w}}_r^T \mathbf{D}_v \tilde{\mathbf{w}}_r}.$$

The post-rake vector that maximizes  $\gamma$  for a given value of  $\mathbf{v}_t$  (also  $\mathbf{C}_v$  and  $\mathbf{D}_v$ ) is the principal eigenvector (corresponding to the largest eigenvalue) of the generalized eigenvalue problem  $(\mathbf{C}_v, \mathbf{D}_v)$ , which requires solving for  $\tilde{\mathbf{w}}_r$  that satisfy

$$\mathbf{C}_v \tilde{\mathbf{w}}_r = \gamma \mathbf{D}_v \tilde{\mathbf{w}}_r.$$

This result follows from a generalization of the Rayleigh-Ritz theorem, and if the inverse of  $\mathbf{D}_v$  exists,  $\tilde{\mathbf{w}}_r$  is the principal eigenvector of  $\mathbf{D}_v^{-1} \mathbf{C}_v$  [11]. In this case, since  $\mathbf{C}_v$  is of rank one, the principal eigenvector is  $\mathbf{D}_v^{-1} \mathbf{S}_r \mathbf{H} \mathbf{v}_t$  corresponding to the eigenvalue  $\mathbf{v}_t^T \mathbf{H}^T \mathbf{S}_r^T \mathbf{D}_v^{-1} \mathbf{S}_r \mathbf{H} \mathbf{v}_t$ . As a result, the optimal post-rake vector for a given  $\mathbf{v}_t$  is

$$\tilde{\mathbf{w}}_r^{\text{opt}} = \mathbf{D}_v^{-1} \mathbf{S}_r \mathbf{H} \mathbf{v}_t, \quad (10)$$

and the related SINR is given by

$$\gamma = \mathbf{v}_t^T \mathbf{H}^T \mathbf{S}_r^T \mathbf{D}_v^{-1} \mathbf{S}_r \mathbf{H} \mathbf{v}_t. \quad (11)$$

Let  $\mathbf{v}_t^{\text{opt}}$  be the solution to the optimization problem

$$\mathbf{v}_t^{\text{opt}} = \arg \max_{\mathbf{v}_t} \mathbf{v}_t^T \mathbf{H}^T \mathbf{S}_r^T \mathbf{D}_v^{-1} \mathbf{S}_r \mathbf{H} \mathbf{v}_t \quad (12)$$

This is a very structured problem when there is ISI, since  $\mathbf{D}_v$  contains terms involving  $\mathbf{v}_t$ . It cannot be posed as an eigenvalue problem, which would lead to a closed form expression for  $\mathbf{v}_t^{\text{opt}}$ , and the Rayleigh-Ritz theorem is not applicable. However, under the constraints  $\tilde{\mathbf{w}}_r^T \tilde{\mathbf{w}}_r / P_w = \mathbf{v}_t^T \mathbf{v}_t = 1$ , the optimum pre-rake vector  $\mathbf{v}_t$  for a given  $\tilde{\mathbf{w}}_r$  is obtained by rewriting  $\gamma$  as

$$\begin{aligned} \gamma &= \frac{|\tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H} \mathbf{v}_t|^2}{\frac{P_w}{\gamma_0} \mathbf{v}_t^T \mathbf{v}_t + \sum_{\substack{m=-I \\ m \neq 0}}^I |\tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H}_m \mathbf{v}_t|^2} \\ &= \frac{\tilde{\mathbf{w}}_r^T \mathbf{H}^T \mathbf{S}_r^T \tilde{\mathbf{w}}_r \tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H} \mathbf{v}_t}{\mathbf{v}_t^T \left( \frac{P_w}{\gamma_0} \mathbf{I}_{F_t} + \sum_{\substack{m=-I \\ m \neq 0}}^I \mathbf{H}_m^T \mathbf{S}_r^T \tilde{\mathbf{w}}_r \tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H}_m \right) \mathbf{v}_t}. \end{aligned}$$

Defining

$$\begin{aligned} \mathbf{C}_w &\triangleq \mathbf{H}^T \mathbf{S}_r^T \tilde{\mathbf{w}}_r \tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H}, \\ \mathbf{D}_w &\triangleq \frac{P_w}{\gamma_0} \mathbf{I}_{F_t} + \sum_{\substack{m=-I \\ m \neq 0}}^I \mathbf{H}_m^T \mathbf{S}_r^T \tilde{\mathbf{w}}_r \tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H}_m, \end{aligned}$$

the pre-rake vector that maximizes  $\gamma$  for a given  $\tilde{\mathbf{w}}_r$  is found as the principal eigenvector of the matrix  $\mathbf{D}_w^{-1} \mathbf{C}_w$ , which is

$$\mathbf{v}_t^{\text{opt}} = \mathbf{D}_w^{-1} \mathbf{H}^T \mathbf{S}_r^T \tilde{\mathbf{w}}_r. \quad (13)$$

This also results in the optimization problem

$$\tilde{\mathbf{w}}_r^{\text{opt}} = \arg \max_{\tilde{\mathbf{w}}_r} \tilde{\mathbf{w}}_r^T \mathbf{S}_r \mathbf{H} \mathbf{D}_w^{-1} \mathbf{H}^T \mathbf{S}_r^T \tilde{\mathbf{w}}_r. \quad (14)$$

The solutions in (10) and (13) are coupled, and independent closed form expressions for  $\mathbf{v}_t^{\text{opt}}$  and  $\tilde{\mathbf{w}}_r^{\text{opt}}$  targeting the ISI-limited scenarios do not exist. However, it is possible to solve for  $(\mathbf{v}_t^{\text{opt}}, \tilde{\mathbf{w}}_r^{\text{opt}})$  jointly using an iterative procedure similar to the approach in [12], which is initialized with the pre- and post-rake vectors for the ISI-free case. In the absence of ISI,  $\mathbf{v}_t^{\text{opt}}$  and  $\tilde{\mathbf{w}}_r^{\text{opt}}$  correspond to the principal eigenvectors of the matrices  $\mathbf{H}^T \mathbf{S}_r^T \mathbf{S}_r \mathbf{H}$  and  $\mathbf{S}_r \mathbf{H} \mathbf{H}^T \mathbf{S}_r^T$ , which follow from (12) and (14) for  $\mathbf{D}_v = (1/\gamma_0) \mathbf{I}_{F_r}$  and  $\mathbf{D}_w = (P_w/\gamma_0) \mathbf{I}_{F_t}$ , respectively. The solution algorithm can be described as follows.

- 1) Set the initial value of  $\tilde{\mathbf{w}}_r$  to, e.g., the optimal ISI-free solution, which is the principal eigenvector of  $\mathbf{S}_r \mathbf{H} \mathbf{H}^T \mathbf{S}_r^T$ .
- 2) Using  $\tilde{\mathbf{w}}_r$  obtained previously, compute  $\mathbf{D}_w^{-1} \mathbf{H}^T \mathbf{S}_r^T \tilde{\mathbf{w}}_r$ , which becomes the new  $\mathbf{v}_t$ .
- 3) Update  $\tilde{\mathbf{w}}_r$  to  $\mathbf{D}_v^{-1} \mathbf{S}_r \mathbf{H} \mathbf{v}_t$  based on the latest value of  $\mathbf{v}_t$  from step 2.
- 4) Evaluate  $\gamma$  according to the expression in (11).
- 5) If the change in  $\gamma$  compared to the outcome of the previous iteration exceeds a preset threshold, compute one more iteration by repeating the procedure in steps 2-5. Otherwise stop the algorithm.

The iterations are guaranteed to converge so that  $\gamma$  reaches a maximum because steps 2 and 3 above both increase the SINR.

#### IV. NUMERICAL RESULTS

The results for distributing a total fixed number of rake fingers optimally between the transmitter and the receiver so as to maximize the SINR of the decision statistic,  $\xi$ , are presented in this section. Simulations have been performed for the line-of-sight (LOS) CM1 UWB channel model in [2], where the 1000 channel realizations created are normalized to unity in their average energy as  $E \left\{ \sum_{\ell=0}^{L-1} \alpha_{\ell}^2 \right\} = 1$ .

The optimal selection of the finger positions of the post-rake, which maximizes the SINR of  $\xi$  for  $F = L + 1$  and  $T_b > (2L - 1)T_p$  is the problem addressed in Fig. 1. The total number of fingers,  $F$ , in Fig. 1 is  $L + 1$  so that  $F_r = L$  when  $F_t = 1$ , and similarly  $F_r = 1$  when  $F_t = L$ . Also, the condition  $T_b > (2L - 1)T_p$  ensures that there is no ISI in the figure, where, in other words,  $\gamma$  is the SNR of  $\xi$ . Then  $\gamma$  is the maximum eigenvalue of the matrix  $\mathbf{S}_r \mathbf{H} \mathbf{H}^T \mathbf{S}_r^T$  or equivalently  $\mathbf{H}^T \mathbf{S}_r^T \mathbf{S}_r \mathbf{H}$  scaled by  $\gamma_0$ , which is obtained by evaluating (12) or (14) for  $\mathbf{D}_v = (1/\gamma_0) \mathbf{I}_{F_r}$  or  $\mathbf{D}_w = (P_w/\gamma_0) \mathbf{I}_{F_t}$ , respectively.

In addition to the post-rake vectors that select paths arriving first, in the middle and at the end as defined in (6)-(8), the all-post-rake which has  $\mathbf{S}_r = \mathbf{I}_{L+F_t-1}$ , i.e.,  $F_r = L + F_t - 1$ , is included in Fig. 1. While the all-post-rake structure is equivalent to the eigenprecoder in [7] for  $F_t = L$ , the PRC pre/post-rake design in [8], which considers arbitrary  $F_t$  corresponds to the curve ‘‘all’’ in Fig. 1. Thus, it is possible to compare the performance of the proposed design with those in previous works using Fig. 1. It is observed from the figure that for all  $F_t$  the highest  $\gamma$  is obtained by the PRC/post-rake scheme using all post-rake fingers, where  $\gamma$  increases with  $F_t$ , which makes the eigenprecoder the optimum structure in terms of maximizing  $\gamma$ . However, in order to operate at a high  $\gamma$  when  $F$  is constrained to the length of the channel impulse response, it is best to distribute the total number of rake fingers almost equally between the transmitter and the receiver if the first arriving paths are combined at the receiver. For a large number of rake fingers at the transmitter, the figure suggests that selecting the paths that arrive in the middle as in (7) improves  $\gamma$ . As the two curves for the ‘‘first’’ and ‘‘middle’’ arriving paths fail to be continuous at large values of  $F_t$ , it is likely that there is a better way to select the finger positions for the post-rake than these two. Note that the form of (7) is a generalization of the pre-rake only structure that has a peak at the  $F_t$ th path of the composite channel impulse response with  $L + F_t - 1$  paths if the pre-rake vector of length  $F_t$  consists of the channel coefficients,  $\alpha_{\ell}$  [13].

The  $\gamma/\gamma_0$  values in Fig. 2 support the previous claim that a more systematic way of selecting the paths at the receiver to form the post-rake fingers is necessary for the proposed transmitter/receiver structure, and that intuition may not be enough. For especially  $F = 9$  the idea of combining the first arriving paths loses its optimality, where the paths that arrive in the middle as in (7) should be combined to obtain a larger  $\gamma$  value.

Displayed in Fig. 3 are the maximum SINR values achiev-

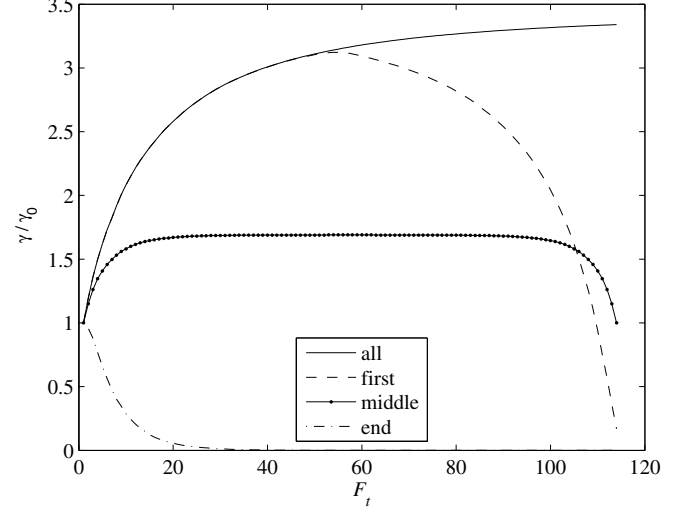


Fig. 1. The normalized SINR values,  $\gamma/\gamma_0$ , against  $F_t$  for  $F = L + 1$ ,  $T_b > (2L - 1)T_p$ , i.e., no ISI, and different positions of the post-rake fingers.

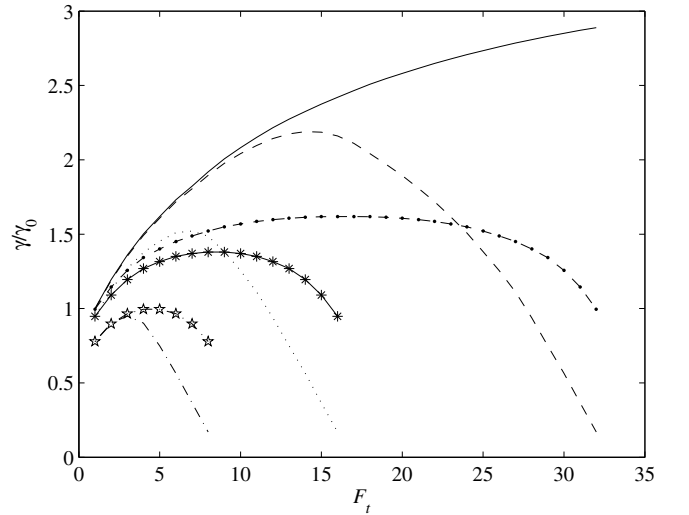


Fig. 2. The normalized SINR values,  $\gamma/\gamma_0$ , against  $F_t$  for  $F = 9, 17, 33$  and  $T_b > (L + F_t - 1)T_p$ , i.e., no ISI. Without markers: First arriving paths (6). With markers: Middle arriving paths (7). Solid curve: All-post rake.

able in dB for  $F = 33$  and various values of  $E_b/N_0$ , where  $T_b = 10$  ns and  $T_p = 1$  ns. The first arriving paths are combined at the receiver using the matrix in (6). It is observed that the effects of ISI are less of a problem when  $E_b/N_0$  is low, where in particular the ISI makes the accurate selection of the optimal  $(F_t, F_r)$  pair less critical as shown more clearly in Fig. 4 for  $E_b/N_0 = 20$  dB. Yet another observation is that in general the optimal  $(F_t, F_r)$  pair does not change with ISI, which has been validated by unreported simulations covering other cases. Finally, these two figures obtained using the iterative algorithm described both point to the fact that moving the rake structure from the receiver to the transmitter helps mitigate ISI as advocated previously in [5]. In Fig. 3 and

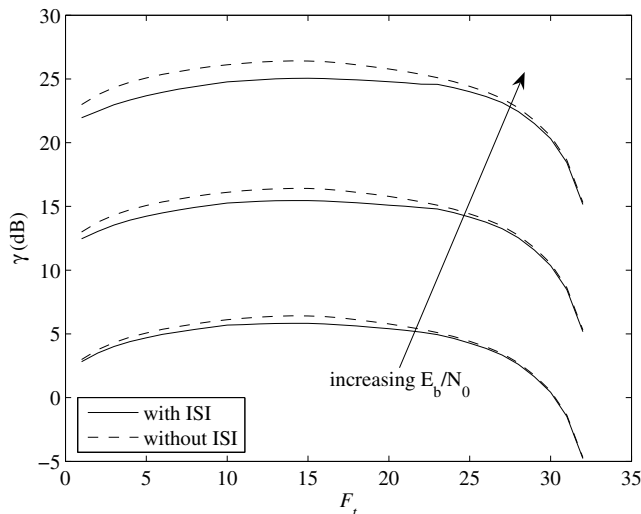


Fig. 3. The SINR values for the transmitter-receiver design that combines the first arriving paths, i.e., uses (6), against  $F_t$  for  $F = 33$ , where  $E_b/N_0 = 0, 10, 20$  dB,  $T_b = 10$  ns and  $T_p = 1$  ns.

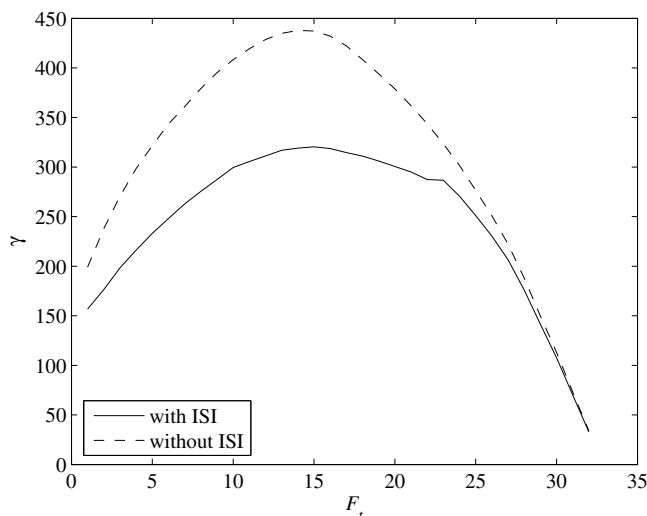


Fig. 4. The SINR values for the transmitter-receiver design that combines the first arriving paths, i.e., uses (6), against  $F_t$  for  $F = 33$ , where  $E_b/N_0 = 20$  dB,  $T_b = 10$  ns and  $T_p = 1$  ns.

4, with  $F_t = 1$  we observe a lowering of the  $\gamma$  value when ISI is present. However, for  $F_t = 32$  the effect of ISI on  $\gamma$  is insignificant, where  $F_t = 32$  and  $F_t = 1$  correspond to the pre-rake only and post-rake only systems, respectively.

## V. CONCLUSION

The maximum SINR values achievable by a transmitter/receiver pair that employs rake combining both at the transmitter and the receiver with a limited total number of rake fingers,  $F$ , is investigated in a search for the optimum transceiver design. Although the design with the post-rake structure that combines the first arriving paths has a sufficient

performance at larger values of  $F$ , simulations suggest that there might be better choices for the paths to be combined when  $F$  is lower. The complexity of the calculation of the pre- and post-rake vectors for systems that have ISI requires an iterative algorithm as opposed to the ISI-free case which admits closed form expressions. However, it is shown that the optimum distribution of the rake fingers between the transmitter and the receiver does not change significantly when ISI is present. Thus the optimization of the finger selection process for the post-rake structure of systems without ISI should provide valuable insight for how systems with ISI should be designed.

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