Single-carrier Incremental Relaying with Joint Tx/Rx FDE

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Abstract—**We propose an incremental relaying scheme using joint Tx/Rx frequency-domain equalization (FDE) for single-carrier (SC) transmission. If a packet sent by a source node (S) has been correctly decoded at a relay node (R), but not at the destination node (D), retransmission is cooperatively done by S and R. Assuming that the channel state information (CSI) is shared by S, R, and D, joint Tx/Rx FDE is performed. We derive a set of optimal/suboptimal Tx/Rx FDE weights among S, R, and D, based on the minimum mean square error (MMSE) criterion under total transmit power constraint of S and R. Computer simulation verifies the effectiveness of the proposed scheme.**

Keywords-component; Single-carrier, cooperative relay, hybrid ARQ, frequency-domain equalization

I. INTRODUCTION

Broadband wireless channel is characterized by distance-dependent path-loss, log-normally distributed shadowing-loss, and frequency-selective fading [1]. In order to overcome the severe frequency-selective fading, various types of equalization strategies have been proposed for broadband single-carrier (SC) transmission [2-4]. Among them, simple one-tap frequency-domain equalization (FDE) has been gaining much attention because of its simplicity, affinity for multi-carrier (MC) transmission, e.g., orthogonal frequency-division multiplexing (OFDM), and extendibility to more advanced equalization techniques, i.e., turbo FDE [5,6]. Recently, we proposed a joint transmit/receive (Tx/Rx) FDE for SC transmission [7], in which one-tap FDE is carried out at both transmitter (Tx) and receiver (Rx) by sharing the same channel state information (CSI), where they are jointly designed based on the minimum mean square error (MMSE) criterion under the transmit power constraint. In [8,9], we extended the proposed scheme for hybrid automatic repeat request (HARQ) with Chase combining (CC); the Tx and Rx FDE weights are multiplied to the packet upon each request of packet retransmission, where they jointly minimize mean square error (MSE) after packet combining. It was shown that the proposed scheme provides higher packet combining gain and improves the throughput performance.

In cellular networks, throughput is seriously degraded even with HARQ since the received signal power fluctuates due to path-loss and shadowing-loss, as well as the frequency-selective fading. Recently, cooperative relaying has been extensively studied [10,11], in which a relay node (R) is deployed and used to mitigate the above power fluctuation problem. Among many relay protocols, incremental relay [10] is effective to achieve higher throughput. In the incremental relay, R is used only in the case that the packet has been correctly decoded at R, but not at a destination node (D) (i.e., receiver). On one hand, the use of R provides spatial diversity gain for retransmission. On the other hand, if the initial transmission from a source node (S) to D is successful, R is not used and thus, the same transmission rate is kept as that without relaying.

In this paper, we propose an SC incremental relaying using joint Tx/Rx FDE. Chase combining [12] is considered. If a packet sent by S has not been correctly decoded at D, but done at R, retransmission is cooperatively carried out by S and R. When the cooperative retransmission is implemented, Tx FDE is carried out. At D, the same packet is combined in frequency-domain using Rx FDE. We derive a set of optimal/suboptimal FDE weights among S, R, and D, based on the MMSE criterion with the total transmit power constraint. We show how the proposed scheme improves the throughput by computer simulation.

The rest of the paper is organized as follows. The principle of SC incremental relaying using joint Tx/Rx FDE is explained in Sec. II. In Sec. III, several sets of FDE weights are derived. We show computer simulation results in Sec. IV. Section V concludes this paper.

Notations: $(.)^T$, $(.)^H$ denotes transpose and Hermitian transpose operation, respectively. $E[.]$ denotes the ensemble average operation.

II. SC INCREMENTAL RELAYING WITH JOINT TX/RX FDE

A. *Basic concept*

Figure 1 shows a flowchart of the proposed scheme. In the initial transmission, a packet transmitted from S is received at both R and D. Each receiving station performs FDE, channel decoding, and error detection. If D correctly decodes the packet, it sends an ACK signal to S to request a new packet transmission. If D detects any error in the received packet after decoding, it sends a NACK signal to both S and R to request retransmission. There are two retransmission modes: if the packet is correctly decoded at R, the retransmission is cooperatively performed by S&R; if not, it is done by S only.

In the proposed scheme, Tx FDE is not performed for the initial transmission and retransmission from S only. This is because S is broadcasting toward both R and D. The Tx FDE is carried out only when the retransmission is cooperatively done by S&R. In the following, without loss of generality, we assume the qth retransmission and the initially transmitted and $(q-1)$ retransmitted packets have been buffered at D (i.e., q received packets are buffered). They are combined at D in frequency-domain similar to [13].

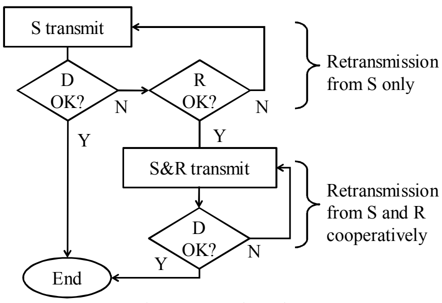


Figure 1. Flowchart.

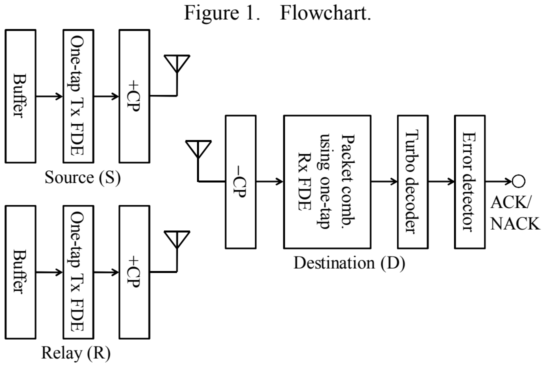


Figure 2. Transceiver design.

B. Transmit signal from S and R

The channel impulse response is assumed to last only within cyclic prefix (CP) length. Symbol-spaced discrete-time signal representation is used.

A data-modulated symbol sequence in a packet is divided into a number of symbol blocks having N_c-symbols each, where N_c is the number of fast Fourier transform (FFT) and inverse FFT (IFFT) points for FDE. Without loss of generality, we show a signal representation for one N_c-symbol block. The block is expressed using a vector form as $\mathbf{d}=[d(0), \ldots, d(n), \ldots, d(N_c-1)]^T$. $\mathbf{d}$ is transformed into frequency-domain signal by N_c-point FFT as

$$\mathbf{D}=[D(0), \ \ldots, \ D(k), \ \ldots, \ D(N_c-1)]^T=\mathbf{Fd}, \quad (1)$$

where $\mathbf{F}$ is an $N_c \times N_c$ FFT matrix, with its (x,y)th element $(1/\sqrt{N_c})\exp(-j2\pi xy/N_c)$, $x,y=0, 1, \ldots, N_c-1$.

At each transmitting node, each frequency component of the signal is multiplied by a Tx FDE weight. The weighted frequency-domain signal can be represented as

$$\mathbf{S}_x^q=\mathbf{W}_x^q\mathbf{D}, \quad x=1 \text{ at S}, \quad x=2 \text{ at R}, \quad (2)$$

where $\mathbf{W}_1^q$ and $\mathbf{W}_2^q$ are $N_c \times N_c$ matrix representation of the Tx FDE weights for the qth retransmitting packet:

$$\mathbf{W}_x^q=diag\{W_x^q(0), \ \ldots, \ W_x^q(k), \ \ldots, \ W_x^q(N_c-1)\}, \quad x=1 \text{ at S}, \quad x=2 \text{ at R}. \quad (3)$$

As it will be shown later, the Tx FDE weights are computed under the transmit power constraint.

N_c-point IFFT is carried out to transform the signal back to the time-domain signal. The time-domain signal block is represented as

$$\mathbf{s}_x^q=\mathbf{F}^H\mathbf{S}_x^q, \quad x=1 \text{ at S}, \quad x=2 \text{ at R}. \quad (4)$$

After inserting CP into the guard interval, the signals are transmitted from S and R simultaneously.

C. Received signal

The received signal in the qth retransmission after removing the CP is written as

$$\begin{aligned}\mathbf{r}^q&=[r^q(0), \ \ldots, \ r^q(n), \ \ldots, \ r^q(N_c-1)]^T\\&=\mathbf{h}_1^q\mathbf{s}_1^q+\mathbf{h}_2^q\mathbf{s}_2^q+\boldsymbol{\pi}^q,\end{aligned} \quad (5)$$

where $\mathbf{h}_1{}^q$ and $\mathbf{h}_2{}^q$ are $N_c \times N_c$ circulant matrices representing the impulse responses of the propagation channels between S and D and between R and D in the qth retransmission, respectively, and they are given by

$$\mathbf{h}_x^q=\begin{bmatrix} h_{x,0}^q & & & h_{x,L-1}^q & \cdots & h_{x,1}^i \\ h_{x,1}^q & \ddots & & & \ddots & \vdots \\ \vdots & & h_{x,0}^q & \mathbf{0} & & h_{x,L-1}^q \\ h_{x,L-1}^q & & h_{x,1}^q & \ddots & & \\ & \ddots & \vdots & & \ddots & \\ \mathbf{0} & & h_{x,L-1}^q & \cdots & \cdots & h_{x,0}^q \end{bmatrix}, \quad x=1 \text{ for S}, \quad x=2 \text{ for R}, \quad (6)$$

and $\boldsymbol{\pi}^q=[\pi^q(0), \ldots, \pi^q(n), \ldots, \pi^q(N_c-1)]^T$ is the noise vector in the qth retransmission with each element $\pi^q(n)$ being a zero-mean additive white Gaussian noise (AWGN) having variance $2\sigma^2$.

$\mathbf{r}^q$ is transformed into frequency-domain signal $\mathbf{R}^q$ by N_c-point FFT, where $\mathbf{R}^q$ can be given as

$$\begin{aligned}\mathbf{R}^q&=[R^q(0), \ \ldots, \ R^q(k), \ \ldots, \ R^q(N_c-1)]^T\\&=\mathbf{Fr}^q=\mathbf{H}_1^q\mathbf{S}_1^q+\mathbf{H}_2^q\mathbf{S}_2^q+\boldsymbol{\Pi}^q\end{aligned} \quad (7)$$

with $\mathbf{H}_1{}^q=\mathbf{Fh}_1{}^q\mathbf{F}$, $\mathbf{H}_2{}^q=\mathbf{Fh}_2{}^q\mathbf{F}$, and $\boldsymbol{\Pi}^q=\mathbf{F}\boldsymbol{\pi}^q$. Due to the circulant properties of $\mathbf{h}_1{}^q$ and $\mathbf{h}_2{}^q$, the channel gain matrices, $\mathbf{H}_1{}^q$ and $\mathbf{H}_2{}^q$, of size $N_c \times N_c$ are diagonal and are expressed as

$$\mathbf{H}_x^q=diag\{H_x^q(0), \ \ldots, \ H_x^q(k), \ \ldots, \ H_x^q(N_c-1)\}, \quad x=1 \text{ for S}, \quad x=2 \text{ for R}. \quad (8)$$

After receiving the qth retransmitted packet, D has $(q+1)$ received packets in the buffer to decode the same packet; i.e., initially transmitted and q retransmitted packets. They are combined in frequency-domain using Rx FDE as

$$\hat{\mathbf{D}}=\sum\nolimits_{q'=0}^{q}\mathbf{V}^{q'}\mathbf{R}^{q'}, \quad (9)$$

where $q'=0$ denotes the initial transmission. $\mathbf{R}^0$ is expressed as

$$\mathbf{R}^0=\mathbf{H}^0\cdot\sqrt{2P}\cdot\mathbf{D}+\boldsymbol{\Pi}^0, \quad (10)$$

where P is the transmit power at S, $\mathbf{H}^0=diag\{H^0(0), \ldots, H^0(k), \ldots, H^0(N_c-1)\}$ is the channel gain matrix between S-D, and $\boldsymbol{\Pi}^0=[\Pi^0(0), \ldots, \Pi^0(k), \ldots, \Pi^0(N_c-1)]^T$ is the noise vector in the initial transmission. Similar to Eq. (7), $\mathbf{R}^{q'}$, $q'=1\sim q-1$, can be expressed as

$$\begin{aligned}\mathbf{R}^{q'}&=[R^{q'}(0), \ \ldots, \ R^{q'}(k), \ \ldots, \ R^{q'}(N_c-1)]^T\\&=\mathbf{Fr}^{q'}=\mathbf{H}_1^{q'}\mathbf{S}_1^{q'}+\mathbf{H}_2^{q'}\mathbf{S}_2^{q'}+\boldsymbol{\Pi}^{q'},\end{aligned} \quad (11)$$

where $\mathbf{S}_1^{q'}=\sqrt{2P}\cdot\mathbf{D}$ and $\mathbf{S}_2^{q'}=\mathbf{0}$ if the q'th retransmission was done by S only, (if it was done by S and R cooperatively, $\mathbf{S}_1^{q'}=\mathbf{W}_1^{q'}\mathbf{D}$ and $\mathbf{S}_2^{q'}=\mathbf{W}_2^{q'}\mathbf{D}$). $\mathbf{V}^{q'}=diag\{V^{q'}(0), \ldots, V^{q'}(k), \ldots, V^{q'}(N_c-1)\}$, $q'=0\sim q$, in Eq. (9) are Rx FDE weights for packet combining at D.

After combining all the packets in frequency-domain, the signal is transformed back to the time-domain signal by N_c-point IFFT as

$$\hat{\mathbf{d}} = [\hat{d}(0), \ \ldots, \ \hat{d}(n), \ \ldots, \ \hat{d}(N_c-1)]^T = \mathbf{F}^H \hat{\mathbf{D}}. \quad (12)$$

III. JOINT TX/RX MMSE-FDE WEIGHTS

A. Mean square error (MSE) and optimization problem

We define the error vector between the transmitted and the equalized data blocks as $\mathbf{e} = \mathbf{d} - \hat{\mathbf{d}}$. The MSE is given as

$$e = tr[E\{(\mathbf{d}-\hat{\mathbf{d}})(\mathbf{d}-\hat{\mathbf{d}})^H\}] = E[\sum_{k=0}^{N_c-1}\left|D(k)-\hat{D}(k)\right|^2]. \quad (13)$$

From Eqs. (2), (7), and (9)-(12), the above can be rewritten as

$$e = 2\sigma^2 \sum_{k=0}^{N_c-1}\sum_{q'=0}^{q}\left|V^{q'}(k)\right|^2 + \sum_{k=0}^{N_c-1}\left|1-\sqrt{2P}\cdot V^0(k)H^0(k) - \sum_{q'=1}^{q} V^{q'}(k)\{H_1^{q'}(k)W_1^{q'}(k)+H_2^{q'}(k)W_2^{q'}(k)\}\right|^2. \quad (14)$$

The transmit signal power of each retransmission should be kept the same as the initial transmission, i.e., P. Therefore, an optimization problem for deriving the FDE weights in the qth retransmission is formulated as

$$\underset{\mathbf{W}_1^q,\mathbf{W}_2^q,\{\mathbf{V}^{q'};q'=0\sim q\}}{\text{minimize}} \quad e$$
$$\text{s.t.} \quad \sum_{k=0}^{N_c-1}\left|W_1^q(k)\right|^2 + \sum_{k=0}^{N_c-1}\left|W_2^q(k)\right|^2 \le 2P. \quad (15)$$

Below, we will firstly derive Rx FDE weights at D for packet combining, $\{\mathbf{V}^{q'}; q'=0\sim q\}$, for arbitrarily given S and R Tx FDE weights for the qth retransmission, $\mathbf{W}_1^q$ and $\mathbf{W}_2^q$. Then, for the given derived $\{\mathbf{V}^{q'}; q'=0\sim q\}$, the optimal $\mathbf{W}_1^q$ and $\mathbf{W}_2^q$ will be derived.

B. Rx FDE weights for packet combining at D

The set of Rx FDE weights for packet combining at D should satisfy

$$\partial e/\partial V^{q'}(k) = 0 \quad \text{for} \quad q'=0\sim q. \quad (16)$$

These weights can be easily derived using Eq. (14) as

$$V^{q'}(k) = \frac{\{H_1^{q'}(k)W_1^{q'}(k)+H_2^{q'}(k)W_2^{q'}(k)\}^*}{2P\left|H^0(k)\right|^2 + \sum_{q''=1}^{q}\left|H_1^{q''}(k)W_1^{q''}(k)+H_2^{q''}(k)W_2^{q''}(k)\right|^2 + 2\sigma^2}. \quad (17)$$

D computes the Rx FDE weights for packet combining using Eq. (17) every time it receives the retransmitted packet.

Substituting Eq. (17) into Eq. (14), we rewrite the MSE as a function of S and R Tx FDE weights only. The optimization problem in (15) becomes

$$\underset{\{W_1^q(k),W_2^q(k)\}}{\text{minimize}} \ e = \sum_{k=0}^{N_c-1}\frac{2\sigma^2}{2\Omega(k)+\left|H_1^q(k)W_1^q(k)+H_2^q(k)W_2^q(k)\right|^2} \quad (18)$$
$$\text{s.t.} \quad \sum_{k=0}^{N_c-1}\left|W_1^q(k)\right|^2 + \sum_{k=0}^{N_c-1}\left|W_2^q(k)\right|^2 - 2P \le 0,$$

where

$$\Omega(k) = P\left|H^0(k)\right|^2 + \frac{1}{2}\sum_{q'=1}^{q-1}\left|H_1^{q'}(k)W_1^{q'}(k)+H_2^{q'}(k)W_2^{q'}(k)\right|^2 + \sigma^2 \quad (19)$$

is a given, invariable, and positive quantity when doing the qth retransmission since it only depends on the previous transmissions.

C. Optimal S and R Tx FDE weights for the retransmission

Next, we derive the optimal S and R Tx FDE weights for the qth retransmission. The MSE, e in Eq. (18), can be lower bounded by Cauchy-Schwarz inequality [1] as

$$e \ge \sum_{k=0}^{N_c-1}\frac{2\sigma^2}{2\Omega(k)+\left\{\left|H_1^q(k)\right|^2+\left|H_2^q(k)\right|^2\right\}\cdot\left\{\left|W_1^q(k)\right|^2+\left|W_2^q(k)\right|^2\right\}}, \quad (20)$$

where equality in the above holds if and only if

$$\{W_1^q(k)\}^*/H_1^q(k) = \{W_2^q(k)\}^*/H_2^q(k) = \Theta \in \Re. \quad (21)$$

Note that $\Re$ represents a set of real numbers.

Assuming (21) holds, the optimization problem can be rewritten as

$$\underset{\{P_1^q(k),P_2^q(k)\}}{\text{minimize}} \ e = \sum_{k=0}^{N_c-1}\frac{\sigma^2}{\Omega(k)+\left\{\left|H_1^q(k)\right|^2+\left|H_2^q(k)\right|^2\right\}\left\{P_1^q(k)+P_2^q(k)\right\}} \quad (22)$$
$$\text{s.t.} \quad \left\{\sum_{k=0}^{N_c-1}\{P_1^q(k)+P_2^q(k)\}-P\le 0, \quad -P_1^q(k)\le 0, \quad -P_2^q(k)\le 0,\right.$$

where $P_1^q(k)=|W_1^q(k)|^2/2$ and $P_2^q(k)=|W_2^q(k)|^2/2$.

To solve Eq. (22), we define a Lagrange function as

$$J = e + \mu\left\{\sum_{k=0}^{N_c-1}\{P_1^q(k)+P_2^q(k)\}-P\right\} - \sum_{k=0}^{N_c-1}\{\eta_1^q(k)P_1^q(k)+\eta_2^q(k)P_2^q(k)\}, \quad (23)$$

where μ and $\{\eta_1^q(k), \eta_2^q(k); k=0\sim N_c-1\}$ are non-negative Lagrange multipliers. Since Eq. (22) is a convex optimization problem [14], the solution satisfies the following KKT condition [15, 16]:

$$\begin{cases}\partial J/\partial P_1^q(k)=0, \ \partial J/\partial P_2^q(k)=0, \ P_1^q(k)\ge 0, \ P_2^q(k)\ge 0, \\ \sum_{k=0}^{N_c-1}\{P_1^q(k)+P_2^q(k)\}-P\le 0, \quad \mu\ge 0, \\ \eta_1^q(k)\ge 0, \ \eta_2^q(k)\ge 0, \ \eta_1^q(k)P_1^q(k)=0, \ \eta_2^q(k)P_2^q(k)=0, \\ \mu\sum_{k=0}^{N_c-1}\{P_1^q(k)+P_2^q(k)\}=0.\end{cases} \quad (24)$$

Solving the above, we have

$$P_{1,opt}^q(k)+P_{2,opt}^q(k) = \max\left[\frac{1}{\sqrt{\mu}}\sqrt{\frac{\sigma^2}{\left|H_1^q(k)\right|^2+\left|H_2^q(k)\right|^2}} - \frac{\Omega(k)}{\left|H_1^q(k)\right|^2+\left|H_2^q(k)\right|^2}, \quad 0\right], \quad (25)$$

where μ is determined so as to satisfy

$$\sum_{k=0}^{N_c-1}\{P_{1,opt}^q(k)+P_{2,opt}^q(k)\}=P. \quad (26)$$

Taking into account Eqs. (21) and (25), we obtain the optimal Tx FDE weights for S and R as

$$W_x^q(k)=\frac{\{H_x^q(k)\}^*}{\sqrt{\left|H_1^q(k)\right|^2+\left|H_2^q(k)\right|^2}}\cdot\sqrt{P_{1,opt}^q(k)+P_{2,opt}^q(k)}, \quad x=1 \text{ at S}, \quad x=2 \text{ at R}. \quad (27)$$

We see from Eqs. (21), (25), and (27) that the optimal S and R Tx FDE weights can be interpreted as two-dimensional weights; one dimension is frequency, and the other is transmitting node, i.e., space. The frequency-domain power allocation is done based on MMSE as Eq. (25) with $\sqrt{|H_1^q(k)|^2+|H_2^q(k)|^2}$ being regarded as an equivalent channel gain. The allocated power at each frequency is then distributed to S and R based on Eq. (27), where the phases of the weights are decided based on Eq. (21). At each frequency, the transmit FDE weights are maximal ratio (MR) transmission weights between S and R [17].

D. *Suboptimal S and R Tx FDE weights for the retransmission*

The set of optimal S and R Tx FDE weights can be obtained only when a complete set of CSI is available at S, R, and D. In order to relax this condition, we consider some suboptimal Tx FDE weights for S and R in the retransmission. The first idea to replace the MR-based retransmission by selection-based one, similar to antenna selection diversity. We consider two types of selection-based Tx FDE weights: transmitting node-selection (SNS) method and subcarrier-selection (SCS) method. In SNS method, one of S and R that has larger channel gain averaged over frequency is selected for each retransmission. SCS method selects S or R that has larger channel gain at each frequency. The Tx FDE weights of SNS and SCS are respectively given by (derivation is omitted due to the space limitation)

$$|W_x^q(k)|^2=\max\left[\frac{1}{\sqrt{\mu}}\sqrt{\frac{\sigma^2}{\left|H_x^q(k)\right|^2}}-\frac{\Omega(k)}{\left|H_x^q(k)\right|^2},\quad 0\right],$$

$$\begin{cases} x=1 \text{ and } |W_2^q(k)|^2=0 \quad \text{for } \forall k \\ \quad \text{if } \sum_{k'=0}^{N_c-1}|H_1^q(k')|^2\geq\sum_{k'=0}^{N_c-1}|H_2^q(k')|^2 \\ x=2 \text{ and } |W_1^q(k)|^2=0 \quad \text{for } \forall k \quad \text{otherwise} \end{cases} \quad \text{in SNS,(28)}$$

$$\begin{cases} x=1 \text{ and } |W_2^q(k)|^2=0 \quad \text{if } |H_1^q(k)|^2\geq|H_2^q(k)|^2 \\ x=2 \text{ and } |W_1^q(k)|^2=0 \quad \text{otherwise} \end{cases} \quad \text{in SCS.(29)}$$

Since $|W_1^q(k)|^2$ (or $|W_2^q(k)|^2$) in Eqs. (28) and (29) is not a function of $|H_2^q(k)|^2$ (or $|H_1^q(k)|^2$), each transmitting node does not need to know full CSI of the other link. Furthermore, the transmitting node does not need the phase information of its own channel.

In addition to selection-based retransmission, equal gain (EG)-based suboptimal Tx FDE weights can also be used. In this scheme, the S and R Tx FDE weights are chosen so as to satisfy

$$W_x^q(k)=\sqrt{P}\cdot\{H_x^q(k)\}^*/|H_x^q(k)|,\ \ x=1 \text{ at S},\ \ x=2 \text{ at R}. (30)$$

In the case of EG-based suboptimal Tx FDE weights, the amplitude information of each channel is not required at S and R. Hence the system complexity can be reduced.

IV. Performance Evaluation

A. *Simulation Parameters*

Simulation parameters are summarized in table 1. Each packet is turbo-coded. Quadrature phase shift keying (QPSK) data-modulation is used. Figure 3 illustrates the deployment of S, R, and D. We consider linear network model. The distance between R and D is fixed to 1.0. The transmit power, *P*, is normalized so as to make the received signal-to-noise power ratio (SNR) at the distance 1.0 to be 0dB~9dB (this is referred to as normalized SNR in this paper).

Table 1. Simulation parameters.

Channel parameters	
Pass-loss exponent	α=3.5
Shadowing standard deviation	σ=7dB
No. of resolvable paths	L=16
Power delay profile	Uniform
Signaling parameters	
Coding / Decoding	Turbo coding with (13, 15) two RSC encoders / Log-MAP decoders with 8 iterations
Coding rate	R=2/3
Data modulation	QPSK
No. of FFT/IFFT points	N_c=256
No. of GI samples	N_g=32
Type of hybrid ARQ	Chase combining
Ch. gains among retrans.	Independent
Feedback delay	None
Ch. est. and error detect.	Ideal
Normalized SNR	3.0dB~9.0dB at the distance 1.0

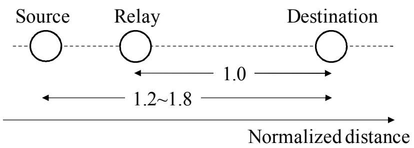
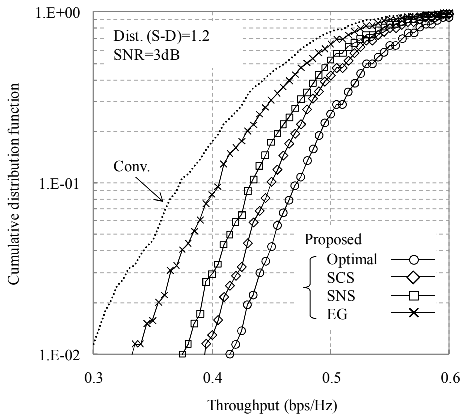


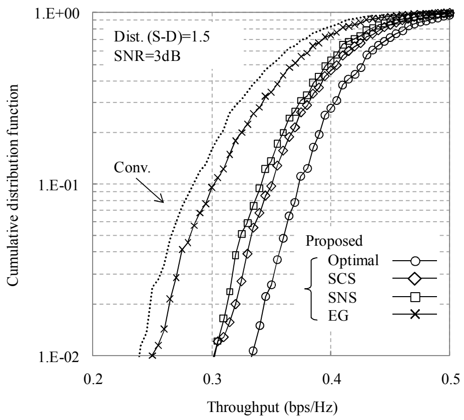
Figure 3. Deployment of source, relay, and destination nodes for simulation.

B. *Throughput distribution*

Figure 4 shows cumulative distribution functions (CDFs) of throughput of the proposed scheme with different Tx FDE weights. Normalized SNR=3dB and the distance between S and D of 1.2 or 1.5 is assumed. The throughput performance of the conventional scheme is also plotted for comparison. Here, the conventional scheme indicates the SNS without Tx FDE (i.e., one of S and R is just selected for each retransmission). It can be seen from Fig. 4 that the proposed schemes improve the throughput distributions, i.e., CDF curves shift to right. For example, the proposed scheme with the optimal weight achieves throughput of 0.42 (0.33) bps/Hz when the distance between S and D is 1.2 (1.5), with the probability of 99% (defined 1%-outage throughput in this paper). This means the proposed scheme with the optimal weights can increase 1%-outage throughput by 44% (37%) compared to the conventional scheme. SNS and SCS weights provide better performance



(a) Distance (S-D) = 1.2



(b) Distance (S-D) = 1.5

Figure 4. Throughput distribution.

than the conventional as well.

C. 1%-outage throughput versus normalized distance

In Fig. 5, we compare the achievable 1%-outage throughput as a function of the normalized distance between S and D for the given normalized SNR of 3dB. It can be seen that the allowable distance between S and D for achieving 1%-outage throughput of 0.3bps/Hz can be extended by about 0.4 using the optimal weights from the conventional scheme. In the case of SNS and SCS weights, the improvement is smaller than the optimal weight, but still much better than the conventional scheme. Therefore, we can conclude that the proposed scheme with optimal, SNS, and SCS weights are useful for achieving higher throughput.

V. CONCLUSION

In this paper, we proposed a single-carrier incremental relay system using joint Tx/Rx FDE. The packet retransmission is cooperatively carried out by S and R, and the packet combining is done by D using FDE. We derived the optimal and suboptimal FDE weights based on the MMSE criterion. The throughput performance was evaluated by computer simulation and it was found out that the proposed scheme provides much higher throughput than the conventional scheme.

The channel state information was assumed to be ideally shared by at all the terminals in this paper. How to share the channel information and the impact of sharing on the system throughput (or capacity) of different retransmission schemes are left as future research topics.

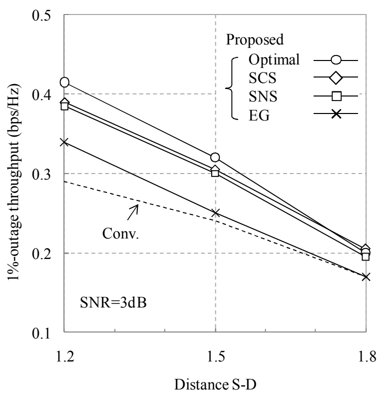


Figure 5. Throughput versus normalized distance.

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