Self-Interference Canceller for Full-Duplex Radio Relay Station Using Virtual Coupling Wave Paths

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***Abstract*—The paper considers a coupling wave canceller for full–duplex radio relay station using adaptive antenna array. Taking advantage of the fact that coupling waves to be cancelled at the relay station consist of its own past transmitted signals, we propose a beamforming method using not only received signals at actual antenna elements but also virtual received signals, which are generated in the relay station with artificial channel impulse responses, that is to say, virtual coupling wave paths. With the approach, the proposed method can eliminate coupling waves without increasing the number of actual antenna elements even when the number of coupling wave paths is large due to high–speed communications. Computer simulation results show that the proposed method achieves coupling wave cancellation with smaller number of antenna elements than that of coupling wave paths.**

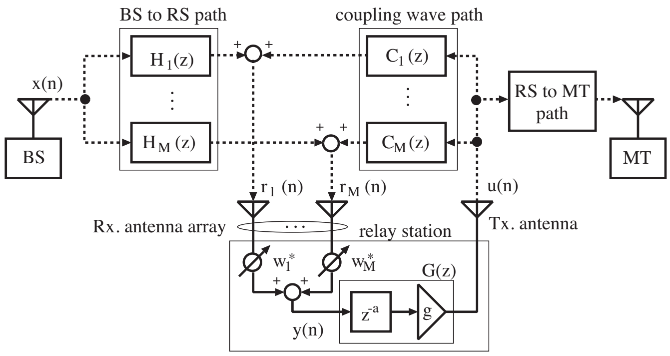

Fig. 1. Full duplex radio relay station using adaptive antenna array.

I. Introduction

There has been an increasing interest in the utilization of radio relay stations for enhancing wireless communications systems. In particular, the concept of full–duplex radio relay station using the same radio resources for the transmission and the reception has drawn much attention due to the potential impact on the spectral efficiency. In such a relay system, a coupling wave from the transmitter to the receiver of the same relay station causes serious problems, such as distortion of the signal or oscillation. So far, coupling wave cancellation schemes using adaptive filter have been proposed [1]-[4], however, the approach requires the gain of the amplifier at the relay station to be small enough to guarantee the stability of the adaptive filter. On the other hand, an adaptive antenna array can be used for the cancellation of the coupling waves as well [5][6], but a large number of antenna elements are needed in order to obtain the necessary degree of freedom of the antenna array to cancel the coupling wave in high–speed communications systems.

In this paper, we consider the coupling wave cancellation scheme for full–duplex radio relay stations using adaptive antenna array. Taking advantage of the fact that the coupling waves to be cancelled at the relay station consist of its own past transmitted signals, we propose a beamforming method using not only received signals at actual antenna elements but also virtual received signals, which are generated in the relay station with artificial FIR (Finite Impulse Response) filters, that is to say, virtual coupling wave paths. The proposed method can obtain sufficient degree of freedom to cancel the coupling waves by just increasing the number of FIR filters in the relay station without increasing the number of actual antennas. Moreover, the proposed canceller can operate in a blind manner for a special configuration. Computer simulation results show that the proposed approach using sufficient number of virtual coupling wave paths can achieve the cancellation regardless of the number of actual antennas.

II. System Model

Consider the downlink communication using full–duplex radio relay station as shown in Fig. 1, where transmit (Tx.) antennas of the base station (BS) and the relay station (RS) have single element, while the receiving (Rx.) antenna of the RS is an antenna array with M elements. The transmitted signal from the BS $x(n)$ is assumed to be white, zero mean and variance of σ_x^2. The received signal at the m-th antenna element of the RS is given by

$$r_m(n) = \sum_{l=0}^{L-1} h_l^m x(n-l) + \sum_{k=0}^{K-1} c_k^m u(n-k) + n_m(n), \quad (1)$$

where $\{h_m^0, \cdots, h_m^{L-1}\}$ and $\{c_m^0, \cdots, c_m^{K-1}\}$ are impulse responses of the channel from the BS to the m-th antenna element and from the Tx. antenna of the RS to the m-th antenna (namely, the m-th coupling wave path), respectively. Moreover, $n_m(n)$ is the additive white noise with zero mean and variance σ_n^2, and $u(n)$ is the transmitted signal from the RS. In the figure,

$$H_m(z) = \sum_{l=0}^{L-1} h_m^l z^{-l}, \tag{2}$$

and

$$C_m(z) = \sum_{k=0}^{K-1} c_m^k z^{-k}, \tag{3}$$

are the transfer functions of the corresponding channels. Defining the received signal vector $\mathbf{r}(n)$ as

$$\begin{aligned}\mathbf{r}(n) &= [r_1(n) \ \cdots \ r_M(n)]^{\mathrm{T}} \\ &= \sum_{l=0}^{L-1} \mathbf{h}_l x(n-l) + \sum_{k=0}^{K-1} \mathbf{c}_k u(n-k) + \mathbf{n}(n),\end{aligned} \tag{4}$$

where

$$\begin{aligned}\mathbf{h}_l &= [h_1^l \ \cdots h_M^l]^{\mathrm{T}}, \\ \mathbf{c}_k &= [c_1^k \ \cdots \ c_M^k]^{\mathrm{T}}, \\ \mathbf{n}(n) &= [n_1(n) \ \cdots \ n_M(n)]^{\mathrm{T}},\end{aligned}$$

the output of the adaptive antenna array is obtained by the inner product between $\mathbf{r}(n)$ and beamforming vector $\mathbf{w} = [w_1 \ \cdots \ w_M]^{\mathrm{T}}$ as

$$\begin{aligned}y(n) &= \mathbf{w}^{\mathrm{H}}\mathbf{r}(n) \\ &= \sum_{l=0}^{L-1} \mathbf{w}^{\mathrm{H}}\mathbf{h}_l x(n-l) + \sum_{k=0}^{K-1} \mathbf{w}^{\mathrm{H}}\mathbf{c}_k u(n-k) + \mathbf{w}^{\mathrm{H}}\mathbf{n}(n).\end{aligned} \tag{5}$$

The fundamental role of the RS is to forward the signal from the BS to the mobile terminal (MT) with the amplification. After giving the gain g by the amplifier, the transmitted signal from the RS is written as

$$u(n) = g z^{-a} y(n), \tag{6}$$

where z^{-a} is a delay of $a \,(\geq L)$ samples artificially introduced so as to make $u(n)$ uncorrelated with $x(n)$ [3].

From (5), in order to eliminate the coupling wave, the beamforming vector has to satisfy the condition

$$\mathbf{w}^{\mathrm{H}}\mathbf{c}_k = 0, \quad (k = 0, \cdots, K-1), \tag{7}$$

where the number of equations is K and that of variables $\{w_1, \cdots, w_M\}$ is M. This means that the number of antenna elements M has to be greater than the number of paths K for the perfect cancellation of the coupling wave for any realization of the coupling wave path. Therefore, with the conventional approach, we need a large number of antenna elements for high–speed transmissions, because of the higher time resolution due to high sampling rate [7].

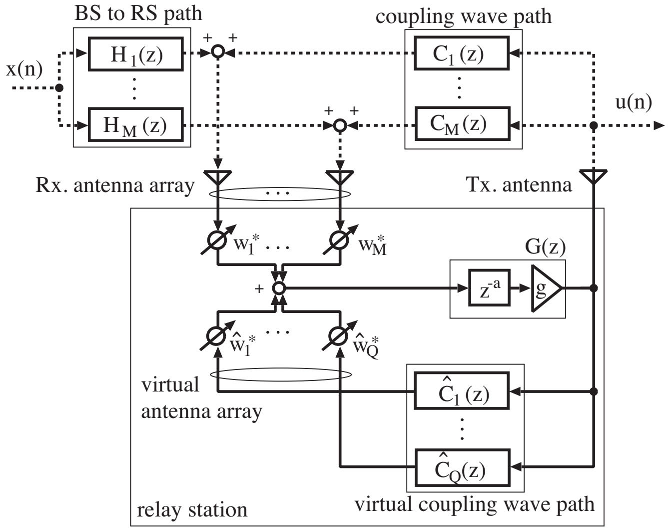

Fig. 2. Proposed radio relay station with virtual coupling wave paths.

III. Proposed Coupling Wave Canceller

A. Virtual Coupling Wave Paths

The coupling waves comprise the relay station's own past transmitted signal $u(n-k)$, $(k = 1, \cdots, K-1)$, which is available if it has a memory device. This means that the relay station can generate artificial received signals of coupling wave paths using $u(n-k)$ and some appropriate FIR filters. We call the FIR filters as *virtual coupling wave paths* and the output signals are processed together with the received signals at actual antenna elements. With the approach, we can increase the degree of freedom of the antenna array for coupling wave cancellation without adding actual antenna elements. Note that the artificial coupling waves are composed only by $u(n-k)$s and do not include signals from the BS or the additive noise.

To be more specific, Q virtual coupling wave paths of FIR filters are employed in the relay station as shown in Fig. 2. The impulse response of the q-th FIR filter is defined as $\{\hat{c}_q^0 \ \cdots \ \hat{c}_q^{K-1}\}$ and the transfer function is given by

$$\hat{C}_q(z) = \sum_{k=0}^{K-1} \hat{c}_q^k z^{-k}. \tag{8}$$

Denoting the received signal of the q-th virtual coupling wave path as $\hat{r}_q(n)$, and defining the virtual received signal vector as

$$\hat{\mathbf{r}}(n) = [\hat{r}_1(n) \ \cdots \ \hat{r}_Q(n)]^{\mathrm{T}}, \tag{9}$$

the concatenated received signal vector of $\mathbf{r}(n)$ and $\hat{\mathbf{r}}(n)$ is given by

$$\begin{aligned}\tilde{\mathbf{r}}(n) &= [\mathbf{r}^{\mathrm{T}}(n) \ \hat{\mathbf{r}}^{\mathrm{T}}(n)]^{\mathrm{T}} \\ &= \sum_{l=0}^{L-1} \tilde{\mathbf{h}}_l x(n-l) + \sum_{k=0}^{K-1} \tilde{\mathbf{c}}_k u(n-k) + \tilde{\mathbf{n}}(n),\end{aligned} \tag{10}$$

where

$$\tilde{\mathbf{h}}_l = [\mathbf{h}_l^{\mathrm{T}}\ \mathbf{0}_{1\times Q}]^{\mathrm{T}},$$
$$\tilde{\mathbf{c}}_k = [\mathbf{c}_k^{\mathrm{T}}\ \hat{\mathbf{c}}_k^{\mathrm{T}}]^{\mathrm{T}},$$
$$\hat{\mathbf{c}}_k = [\hat{c}_1^k\ \cdots\ \hat{c}_Q^k]^{\mathrm{T}},$$
$$\tilde{\mathbf{n}}(n) = [\mathbf{n}^{\mathrm{T}}(n)\ \mathbf{0}_{1\times Q}]^{\mathrm{T}}.$$

Defining virtual beamforming vector as

$$\hat{\mathbf{w}} = [\hat{w}_1\ \cdots\ \hat{w}_Q]^{\mathrm{T}}, \tag{11}$$

and the concatenated beamforming vector as

$$\tilde{\mathbf{w}} = [\mathbf{w}^{\mathrm{T}}\ \hat{\mathbf{w}}^{\mathrm{T}}]^{\mathrm{T}}, \tag{12}$$

the output of the adaptive antenna array is written as

$$y(n) = \sum_{l=0}^{L-1} \tilde{\mathbf{w}}^{\mathrm{H}}\tilde{\mathbf{h}}_l x(n-l) + \sum_{k=0}^{K-1} \tilde{\mathbf{w}}^{\mathrm{H}}\tilde{\mathbf{c}}_k u(n-k) + \tilde{\mathbf{w}}^{\mathrm{H}}\tilde{\mathbf{n}}(n). \tag{13}$$

Therefore, if

$$\tilde{\mathbf{w}}^{\mathrm{H}}\tilde{\mathbf{c}}_k = 0, \quad (k = 0, \cdots, K-1) \tag{14}$$

holds, the coupling waves are completely eliminated. Compared with (7), we recognize that the number of the variables $\{w_1, \cdots, w_M, \hat{w}_1, \cdots \hat{w}_Q\}$ of (14) is increased by the number of the virtual coupling wave paths Q. This enables us to increase the degree of freedom of the adaptive antenna array for the cancellation of the coupling waves.

B. Impulse Responses of Virtual Coupling Wave Paths

We propose two practical methods to determine the impulse responses of virtual coupling wave paths. If we can employ the same number of FIR filters as the length of the impulse response of the coupling wave paths K, the coupling waves can be eliminated by setting

$$\hat{c}_q^k = \begin{cases} \beta, & q = k \\ 0, & \text{otherwise} \end{cases}, \tag{15}$$

where β is an arbitrary constant. Henceforth, we call the approach *VCC (virtual coupling channel) 1.*

On the other hand, an alternative method (*VCC2*) is applicable for the case of $Q < K$. VCC2 uses realizations of random variables of independent and identical distribution as

$$\hat{\mathbf{c}}_0 = \begin{bmatrix} \xi_1^0 \\ \xi_2^0 \\ \vdots \\ \xi_Q^0 \end{bmatrix}, \cdots, \hat{\mathbf{c}}_{K-1} = \begin{bmatrix} \xi_1^{K-1} \\ \xi_2^{K-1} \\ \vdots \\ \xi_Q^{K-1} \end{bmatrix}, \tag{16}$$

where each ξ_s^t $(s = 1, \cdots, Q,\ t = 0, \cdots, K-1)$ is a realization of a random variable Ξ_s^t from a certain distribution.

C. Beamforming Vector of Proposed Adaptive Array

We consider the beamforming vector based on the MMSE criterion. Assuming that d is the delay time of the path with the maximum power as

$$d = \underset{l}{\operatorname{argmax}} \|\mathbf{h}_l\|_2, \tag{17}$$

the cost function can be written as

$$J(\tilde{\mathbf{w}}) = \mathrm{E}\left[\left|x(n-d) - \tilde{\mathbf{w}}^{\mathrm{H}}\tilde{\mathbf{r}}(n)\right|^2\right]. \tag{18}$$

Note that the assumption is just for the simplicity and we can also set the weighted sum of $x(n-l)$, $l = 0, \cdots, L-1$ to be the desired signal in order to improve the SNR (Signal to Noise Ratio) at the MT. The optimal MMSE beamforming vector is obtained as

$$\tilde{\mathbf{w}}_{\mathrm{MMSE}} = \sigma_x^2 \mathbf{R}_{\tilde{r}}^{\dagger}\tilde{\mathbf{h}}_d, \tag{19}$$

where

$$\begin{aligned} \mathbf{R}_{\tilde{r}} &= \mathrm{E}\left[\tilde{\mathbf{r}}(n)\tilde{\mathbf{r}}^{\mathrm{H}}(n)\right] \\ &= \sigma_x^2 \sum_l \tilde{\mathbf{h}}_l\tilde{\mathbf{h}}_l^{\mathrm{H}} + \sigma_u^2 \sum_k \tilde{\mathbf{c}}_k\tilde{\mathbf{c}}_k^{\mathrm{H}} + \sigma_n^2 \mathbf{R}_{\tilde{n}}, \end{aligned} \tag{20}$$

$$\mathbf{R}_{\tilde{n}} = \begin{bmatrix} \mathbf{I}_M & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, \tag{21}$$

and $(\cdot)^{\dagger}$ denotes Moore-Penrose pseudo inverse. Here, we use pseudo inverse because $\mathbf{R}_{\tilde{r}}$ may be singular.

D. Blind Coupling Wave Cancellation

When $M = 1$, the proposed method can operate in a blind manner. Here, the term "blind" means that the beamforming vector can be updated without any prior information such as pilot signals or $\tilde{\mathbf{h}}_d$. Note that, with the configuration, only the coupling waves can be cancelled using the signals from the virtual paths, while the antenna cannot steer the beam pattern to any other signals. As a results, all the signals from the BS are captured in this case.

By setting the weight of the actual antenna to be 1, we obtain the optimum beamforming vector as

$$\tilde{\mathbf{w}} = \left(\mathbf{v}^{\mathrm{H}}\mathbf{R}_{\tilde{r}}^{-1}\mathbf{v}\right)^{-1}\mathbf{R}_{\tilde{r}}^{-1}\mathbf{v}, \tag{22}$$

where $\mathbf{v} = \begin{bmatrix}1 & 0 & \cdots & 0\end{bmatrix}^{\mathrm{T}}$.

As for the correlation matrix, we can replace $\boldsymbol{R}_{\tilde{r}}$ by a sample correlation matrix obtained by using the update rule

$$\hat{\boldsymbol{R}}_{\tilde{r}}(n) = \frac{n-1}{n}\hat{\boldsymbol{R}}_{\tilde{r}}(n-1) + \frac{1}{n}\tilde{\boldsymbol{r}}(n)\tilde{\boldsymbol{r}}^{\mathrm{H}}(n). \tag{23}$$

IV. Numerical Results

Table I shows the numerical experiment conditions. The channels between the BS and the RS, and coupling wave paths are assumed to be Rayleigh fading channel with 2 and 13 paths, respectively. OFDM (Orthogonal Frequency Division Multiplexing) signaling with FFT (Fast Fourier Transform) size of 64 and the guard interval of 16 is used as the modulation scheme. We set the gain of the amplifier at the

TABLE I
SYSTEM PARAMETER OF NUMERICAL EXPERIMENT

BS-RS channel	Rayleigh fading (2 paths)
Coupling wave paths	Rayleigh fading (13 paths)
Transmission scheme	OFDM
Mod./Demod. scheme	QPSK coherent detection
FFT size	64
Guard length	16
Gain at the RS	$g = 10^5$
The number of trials	$100,000$

RS to be $g = 10^5$ and VCC1 is used for the virtual coupling wave paths.

For the evaluation of the coupling wave cancellation performance, we adopt BER (Bit Error Rate) at the output of the adaptive array of the RS, although the RS does not have to decode the received signal in the actual operation. Figure 3 illustrates the BER versus the received SNR of the RS, where the sum of the number of actual and virtual antennas is kept to 16. From the figure, we can see that the proposed method can achieve the best performance when $M = 3$ and $Q = 13$. This is because the proposed method with $Q \geq 13$ can completely eliminate the coupling waves, while greater M is desired from a view point of the diversity effect on the signals from the BS. This also means that the capability of the virtual antennas to cancel the coupling waves is better than that of the actual antennas.

The gain given by the RS to the desired signal depends not only on the gain of the amplifier g but also the beamforming vector, therefore, we have evaluated the overall gain defined as

$$\frac{\sum_l \left| g\tilde{\mathbf{w}}^{\mathrm{H}}\tilde{\mathbf{h}}_l \right|^2}{\sum_i \sum_j \left| h_i^j \right|^2}. \tag{24}$$

Figure 4 shows the overall gain performance of the proposed method. We can see that $M = 3$ and $Q = 13$ can achieve the best gain performance again. This is because, with $Q = 13$, all the degree of freedom of the actual antenna can be used only for the reception of the desired signals from the BS.

Finally, we have evaluated the performance of the proposed method with $M = 1$ and blind operation. The correlation matrix is obtained by (23) and the normalized SCE (squared cancelling error) defined as

$$10 \log_{10} \left| \frac{y(n) - \sum_{l=0}^{L-1} \mathbf{w}^{\mathrm{H}}\mathbf{h}_l x(n-l)}{\sum_{l=0}^{L-1} \mathbf{w}^{\mathrm{H}}\mathbf{h}_l x(n-l)} \right|^2 \tag{25}$$

is used for the performance metric. Figure 5 illustrates the SCE performance using the beamforming vector after the adaptation of $5,000$ steps. From the figure, we can see that the coupling wave is almost perfectly cancelled and only the observation noise is remaining in the output of the array.

V. Conclusions

In this paper, we have proposed a coupling wave canceller with an adaptive array for the realization of a radio relay station, which can simultaneously transmit and receive signals using the same carrier frequency. The key issue about the proposed method is the introduction of the virtual coupling wave paths using the relay station's past transmitted signals. Moreover, we have proposed a blind coupling wave cancellation scheme with an omni–directional antenna and virtual antennas. From the numerical results, it can be concluded that the proposed approach with sufficient number of virtual coupling wave paths can efficiently eliminate the coupling waves even when their number is greater than that of actual antenna elements.

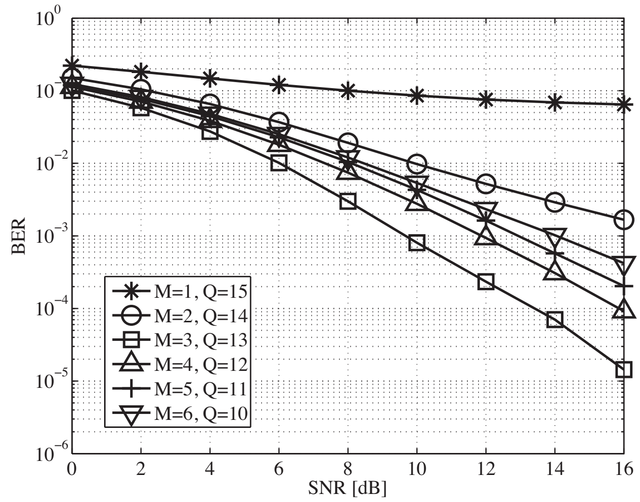

Fig. 3. BER performance

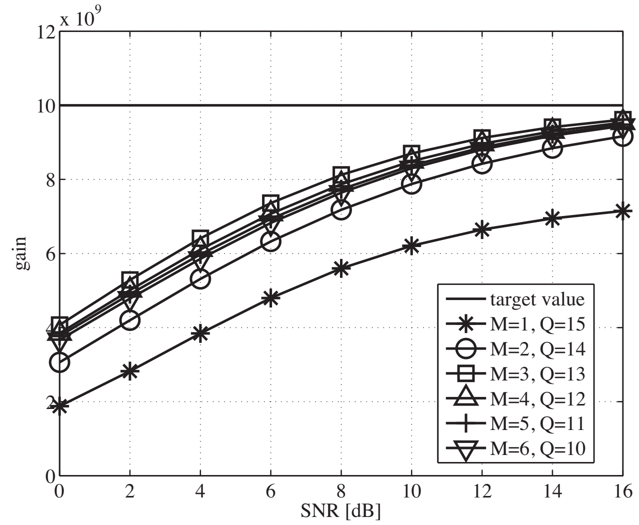

Fig. 4. Gain performance

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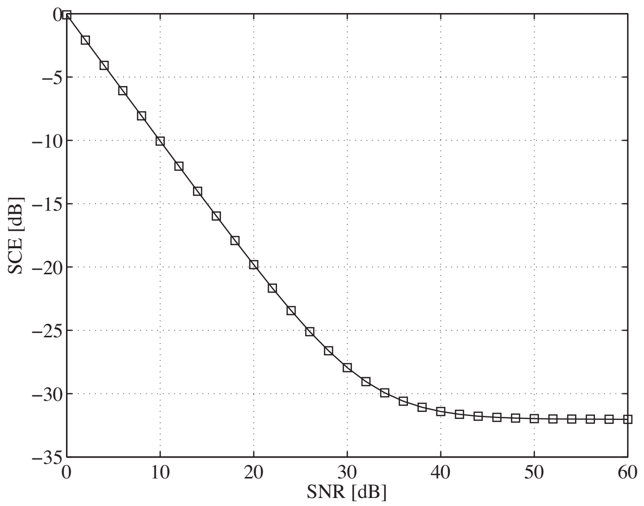

Fig. 5. SCE performance $(M = 1)$

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