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Frequency-domain space-time block coded single-carrier distributed antenna network

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Abstract: In this paper, space-time block coding (STBC) is applied to single-carrier distributed antenna network (SC-DAN). By using the frequency-domain STBC coded joint transmit/receive diversity (FD-STBC-JTRD) for the downlink while using the well-known frequency-domain space-time transmit diversity (FD-STTD) for the uplink, the diversity order is given by the product of the number of distributed antennas and that of mobile terminal (MT) antennas. It is shown by computer simulation that the downlink and uplink can achieve almost the same bit error rate (BER) performance and that by increasing the number of distributed antennas, the BER performance can be significantly improved while keeping the MT complexity low.

Keywords: distributed antenna network, space-time block coding, frequency-domain equalization

Classification: Wireless Communication Technologies

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1 Introduction

In conventional cellular networks, the received signal power drops due to path loss, shadowing loss, and multi-path fading when a mobile terminal (MT) approaches the cell edge. The negative impact of multi-path fading can be mitigated by antenna diversity. However, if diversity antennas are collocated at the same base station (BS), the impacts of path loss and shadowing loss cannot be mitigated. A promising solution to mitigate all the problems arising from path loss, shadowing loss, and multi-path fading is to distribute spatially many antennas in each wireless cell. In this paper, we call this cellular network as the distributed antenna network (DAN). Figure 1 illustrates the conceptual structure of the DAN. The conventional BS is replaced by the signal processing center (SPC) and each distributed antenna is connected to the SPC by an optical link. It was shown in [1] that DAN using transmit diversity can improve the signal-to-interference plus noise power ratio (SINR) compared to the conventional cellular network.

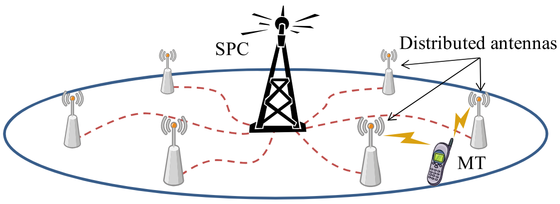

Fig. 1. Conceptual structure of DANs

In this paper, space-time block coding (STBC) [2] is applied to single-carrier DAN (SC-DAN). At the transmitter side, the time-domain symbol block to be transmitted is transformed by fast Fourier transform (FFT) into the frequency-domain signal before performing STBC coding and inverse FFT (IFFT), thereby generating the STBC coded SC waveform (note that the multi-carrier transmission such as orthogonal frequency division multiplexing (OFDM) does not require FFT at the transmitter side). Two types of STBC diversity exist: space-time transmit diversity (STTD) and STBC coded joint transmit/receive diversity (STBC-JTRD). STTD requires no channel state information (CSI) at its encoder and hence, its computational complexity is low. In a frequency-selective fading channel, STTD can be combined with receive antenna diversity using frequency-domain equalization (FDE) [3] (this is called frequency-domain STTD (FD-STTD) in this paper). In FD-STTD, an arbitrary number of receive antennas can be used while keeping the same coding rate (however, the coding rate reduces as the number of transmit antennas increases). In contrast to FD-STTD, frequency-domain STBC-JTRD (FD-STBC-JTRD) [4] allows the use of an arbitrary number of transmit antennas while keeping the same coding rate. FD-STBC-JTRD jointly uses STBC encoding and transmit FDE. Since it requires no CSI but only addition, subtraction, and conjugate operations at the decoder while it requires the CSI for transmit FDE at the transmitter, the computational complexity of the receiver is low.

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Because of the above properties of FD-STBC-JTRD and FD-STTD, the former and latter are suitable for the SC-DAN downlink and uplink transmissions. Although we investigated in [5] the downlink using FD-STBC-JTRD, the performance comparison between the downlink using FD-STBC-JTRD and uplink using FD-STTD has not been made yet. In this paper, it is shown that FD-STBC-JTRD can be constructed based on the same STBC coding matrix used for FD-STTD. By using FD-STBC-JTRD for the downlink while using the well-known FD-STTD for the uplink, the diversity order is given by the product of the number of distributed antennas and that of MT antennas. Therefore, a sufficiently large diversity order can be obtained by increasing the number of distributed antennas while keeping the number of MT antennas low. Furthermore, transmit FDE and receive FDE both of which require the CSI can be done at the network side only. Accordingly, the MT complexity problem can be alleviated. It is shown by computer simulation that the downlink and uplink can achieve almost the same bit error rate (BER) performance and that increasing the number of distributed antennas can improve the down/uplink BER performance while keeping the MT's complexity low.

2 SC-DAN System Model

The number of distributed antennas to be used for a transmission is denoted by N_{dan} and the number of MT antennas is denoted by N_{mt}. Figure 2 illustrates the DAN antenna distribution. A single-user and single-cell DAN model is assumed. Distributed antennas are uniformly distributed with distance R between adjacent antennas. An MT equipped with N_{mt} antennas is assumed to be randomly located in the shaded area indicated in Fig. 2. N_{dan} distributed antennas are selected for the transmission.

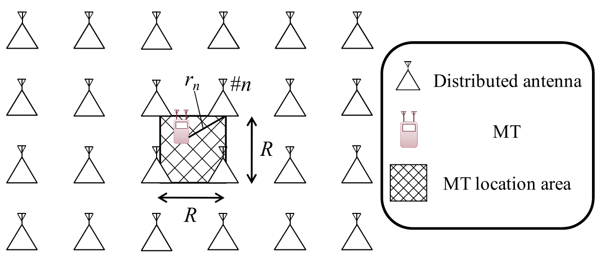

Fig. 2. Antenna distribution

The channel is assumed to be composed of symbol-spaced L discrete paths. The channel impulse response between the n-th distributed antenna ($n = 0{\sim}N_{dan} - 1$) and the m-th MT antenna ($m = 0{\sim}N_{mt} - 1$) can be expressed as

$$h_{m,n}(\tau) = \sum_{l=0}^{L-1} h_{m,n,l}\delta(\tau - \tau_l) = \sqrt{r_n^{-\alpha} \cdot 10^{-\frac{\eta_n}{10}}} \sum_{l=0}^{L-1} \tilde{h}_{m,n,l}\delta(\tau - \tau_l), \qquad (1)$$

where $\tilde{h}_{m,n,l}$ and τ_l are respectively the complex-valued path gain with $E[\sum_{l=0}^{L-1} |\tilde{h}_{m,n,l}|^2] = 1$ and the time delay of the l-th path. r_n is the distance

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between the MT and the n-th distributed antenna, and α and η_n are respectively the path loss exponent and shadowing loss in dB. η_n is a zero-mean Gaussian variable with standard deviation σ. The instantaneous received power of the signal transmitted from the n-th distributed antenna can be expressed as

$$\begin{aligned} P_{r,n} &= p_{t,n} \cdot r_n^{-\alpha} \cdot 10^{-\frac{\eta_n}{10}} \sum_{m=0}^{N_{mt}-1} \sum_{l=0}^{L-1} \left|\tilde{h}_{m,n,l}\right|^2 \\ &= P_{t,n} \cdot R_n^{-\alpha} \cdot 10^{-\frac{\eta_n}{10}} \sum_{m=0}^{N_{mt}-1} \sum_{l=0}^{L-1} \left|\tilde{h}_{m,n,l}\right|^2, \end{aligned} \quad (2)$$

where $p_{t,n}$ represents the transmit power from the n-th distributed antenna. In Eq. (2), $P_{t,n} = p_{t,n} \cdot R^{-\alpha}$ and $R_n = r_n/R$ are the normalized transmit power and distance, respectively.

In this paper, the local average power (LAP) based antenna selection (AS) of N_{dan} distributed antennas is considered. The LAP-based AS selects N_{dan} distributed antennas having the strongest LAP, where LAP is given as

$$\overline{P}_{r,n} = P_{t,n} \cdot R_n^{-\alpha} \cdot 10^{-\frac{\eta_n}{10}}. \quad (3)$$

3 FD-STBC-JTRD and FD-STTD

By applying FD-STBC-JTRD and FD-STTD to the downlink and uplink, respectively, a small value of N_{mt} can be used by increasing the value of N_{dan}. As a consequence, the MT complexity can be kept low while obtaining a sufficiently high diversity order.

3.1 Downlink Using FD-STBC-JTRD

A series of J blocks of N_c symbols each is to be transmitted. N_c-point FFT is applied to transform the j-th symbol block $\{d_j(t);\ t = 0 \sim N_c - 1\}$ into the frequency-domain signal $\{D_j(k);\ k = 0 \sim N_c - 1\}$. The frequency-domain signal vector $\mathbf{D}(k) = [D_0(k), \ldots, D_j(k), \ldots, D_{J-1}(k)]^T$ is STBC coded into N_{mt} parallel streams of Q signal blocks each, represented by STBC coding matrix $\mathbf{E}_{N_{mt}}(k)$ of size $N_{mt} \times Q$. Note that the values of J and Q depend on the number N_{mt} of MT antennas [4]. When $N_{mt} = 2$, $\mathbf{E}_{N_{mt}}(k)$ is given as (see [4] for $N_{mt} = 3 \sim 6$)

$$\mathbf{E}_{N_{mt}=2}(k) = \begin{pmatrix} D_0(k) & -D_1^*(k) \\ D_1(k) & D_0^*(k) \end{pmatrix}, \quad (4)$$

where the m-th row corresponds to the m-th receive antenna of an MT and the q-th column corresponds to the q-th block time, where $m = 0 \sim N_{mt} - 1$ and $q = 0 \sim Q - 1$.

The Hermitian transpose of transmit FDE matrix $\mathbf{W}_t(k)$ of size $N_{mt} \times N_{dan}$ based on minimum mean square error (MMSE) [5] is multiplied to $\mathbf{E}_{N_{mt}}(k)$ to obtain N_{dan} streams of frequency-domain coded signals. $\mathbf{W}_t(k)$ has a form of

$$\mathbf{W}_t(k) = A(k)\mathbf{H}(k). \quad (5)$$

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In Eq. (5), $\mathbf{H}(k)$ represents the channel matrix of size $N_{mt} \times N_{dan}$, whose (m,n)-th element is the k-th frequency channel gain $H_{m,n}(k)$ between the n-th distributed antenna and the m-th MT antenna. $A(k)$ is given as

$$A(k) = \left\{ (1/N_{mt}) \sum_{m=0}^{N_{mt}-1} \sum_{n=0}^{N_{dan}-1} |H_{m,n}(k)|^2 + \Gamma_t^{-1} \right\}^{-1}, \tag{6}$$

where $\Gamma_t = P_t/(N_0/T_s)$ denotes the transmit signal-to-noise power ratio with $P_t = \sum_{n=0}^{N_{dan}-1} p_{t,n}$, N_0, and T_s being respectively the total transmit power of selected antennas, the single-sided AWGN power spectrum density, and the coded symbol duration. The resulting frequency-domain coded signal can be represented using the matrix form as

$$\mathbf{S}_{stbc\text{-}jtrd}(k) = \sqrt{2P_t} C \mathbf{W}_t^H(k) \mathbf{E}_{N_{mt}}(k) = \sqrt{2P_t} C A(k) \mathbf{H}^H(k) \mathbf{E}_{N_{mt}}(k), \tag{7}$$

where C is the power normalization factor to keep P_t constant. The time-domain coded signals to be transmitted from N_{dan} antennas is obtained by applying N_c-point IFFT to $\mathbf{S}_{stbc\text{-}jtrd}(k)$. After inserting a cyclic prefix (CP) of N_g-symbol length into the guard interval (GI), N_{dan} streams of time-domain Q symbol blocks are transmitter from N_{dan} antennas.

At the MT receiver, a superposition of N_{dan} FD-STBC-JTRD coded signals is received by each of N_{mt} antennas. After removing the CP, N_c-point FFT is applied to transform each received signal block into the frequency-domain signal. N_{mt} frequency-domain received signals can be expressed using the matrix form of size $N_{mt} \times Q$ as

$$\mathbf{R}(k) = \mathbf{H}(k)\mathbf{S}_{stbc\text{-}jtrd}(k) + \mathbf{Z}(k) = \sqrt{2P_t} C A(k) \overline{\mathbf{H}}_{stbc\text{-}jtrd}(k) \mathbf{E}_{N_{mt}}(k) + \mathbf{Z}(k), \tag{8}$$

where $\mathbf{Z}(k)$ represents the noise matrix of size $N_{mt} \times Q$, whose elements are i.i.d. complex Gaussian variables having zero mean and variance $2N_0/T_s$. The matrix $\overline{\mathbf{H}}_{stbc\text{-}jtrd}(k) = \mathbf{H}^H(k)\mathbf{H}(k)$ is of size $N_{mt} \times N_{mt}$ and is called the equivalent channel matrix with $(.)^H$ representing the Hermitian transpose operation.

When $N_{mt} = 2$, the decoding operation to obtain $\hat{\mathbf{D}}_{N_{mt}}(k) = [\hat{D}_0(k), \ldots, \hat{D}_j(k), \ldots, \hat{D}_{J-1}(k)]^T$ is described as (see [4] for $N_{mt} = 3 \sim 6$)

$$\hat{\mathbf{D}}_{N_{mt}=2}(k) = \begin{pmatrix} R_{0,0}(k) + R_{1,1}^*(k) \\ R_{1,0}(k) - R_{0,1}^*(k) \end{pmatrix}, \tag{9}$$

where $R_{m,q}(k)$ represents the (m,q)-th element of $\mathbf{R}(k)$. The j-th soft-decision time-domain symbol block $\{\hat{d}_j(t);\ t = 0 \sim N_c - 1\}$ is obtained by N_c-point IFFT.

3.2 Uplink Using FD-STTD

The j-th signal block $\{d_j(t);\ t = 0 \sim N_c - 1\}$ is transformed into the frequency-domain signal block $\{D_j(k);\ k = 0 \sim N_c - 1\}$. The frequency-domain signal vector $\mathbf{D}(k) = [D_0(k), \ldots, D_j(k), \ldots, D_{J-1}(k)]^T$ at the k-th frequency is

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STBC coded into N_{mt} streams of Q coded frequency-domain signals. The frequency-domain coded signal matrix of size $N_{mt} \times Q$ can be represented as

$$\mathbf{S}_{sttd}(k) = \sqrt{2P_t/N_{mt}}\mathbf{E}_{N_{mt}}(k). \tag{10}$$

where $\mathbf{E}_{N_{mt}}(k)$ is given as Eq. (4). After STBC coding, N_c-point IFFT is applied to $\{S_{m,q}(k);\ k = 0{\sim}N_c - 1\}$, $m = 0{\sim}N_{mt} - 1$ and $q = 0{\sim}Q - 1$, to obtain the time-domain transmit signal matrix, where $S_{m,q}(k)$ is the (m, q)-th element of $\mathbf{S}_{sttd}(k)$. After inserting the CP, N_{mt} streams of time-domain Q symbol blocks are transmitted from N_{mt} antennas.

At the receiver, a superposition of N_{mt} FD-STTD coded signals is received by N_{dan} receive antennas. N_{dan} frequency-domain received signals can be expressed using the matrix form of size $N_{dan} \times Q$ as

$$\tilde{\mathbf{R}}_{sttd}(k) = \mathbf{H}^T(k)\mathbf{S}_{sttd}(k) + \mathbf{Z}(k) = \sqrt{2P_t/N_{mt}}\mathbf{H}^T(k)\mathbf{E}_{N_{mt}}(k) + \mathbf{Z}(k), \tag{11}$$

which is multiplied by the receive FDE weight matrix $\mathbf{W}_r(k) = A(k)\mathbf{H}^T(k)$ of size $N_{dan} \times N_{mt}$. The received signal matrix after the equalization is given as

$$\mathbf{R}(k) = \mathbf{W}_r^H(k)\tilde{\mathbf{R}}_{sttd}(k) = \sqrt{2P_t/N_{mt}}A(k)\overline{\mathbf{H}}_{sttd}(k)\mathbf{E}_{N_{mt}}(k) + \mathbf{W}_r^H(k)\mathbf{Z}(k), \tag{12}$$

where the matrix $\overline{\mathbf{H}}_{sttd}(k) = \mathbf{H}^*(k)\mathbf{H}^T(k)$ is of size $N_{mt} \times N_{mt}$. The same decoding operation as in Eq. (8) can be carried out to estimate the transmitted frequency-domain signal vector $\mathbf{D}$.

3.3 STBC Coding Rate

The STBC coding rate $R_s = J/Q$ reduces when $N_{mt} > 2$ (R_s reduces to $3/4{\sim}2/3$ when $N_{mt} = 3{\sim}6$ [4]). However, R_s does not depend on N_{dan}. This allows the use of an arbitrary number N_{dan} of distributed antennas while keeping the same code rate R_s.

4 Simulation Results

The SC block transmission using QPSK data modulation, FFT block size $N_c = 256$ and CP length $N_g = 32$ is assumed. The propagation channel is assumed to be a symbol-spaced $L = 16$-path block Rayleigh fading having uniform power delay profile and the path loss exponent and shadowing standard deviation are set to $\alpha = 3.5$ and $\sigma = 7.0$, respectively.

Figure 3 plots the complementary cumulative distribution function (CCDF) of bit error rate (BER) when the normalized transmit symbol energy-to-noise power spectrum density ratio $E_s/N_0 = 5\,\text{dB}$. It can be seen from Fig. 3 that the FD-STBC-JTRD downlink and the FD-STTD uplink achieve almost identical performance. This is because the same diversity order of $N_{mt} \times N_{dan}$ is obtained [4]. A well-balanced transmission performance can be realized. It can be seen from Fig. 3 that increasing N_{dan} reduces significantly the outage probability for the given BER. This is because the effects of shadowing loss as well as path loss can be mitigated.

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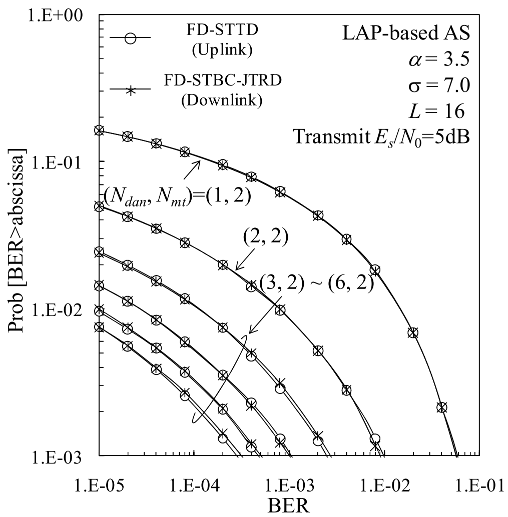

Fig. 3. Down/uplink performance comparison

5 Conclusion

In this paper, STBC was applied to SC-DAN. By using FD-STBC-JTRD for the downlink while using FD-STTD for the uplink, an arbitrary number of distributed antennas can be used while keeping the number of MT antennas low. Furthermore, transmit FDE and receive FDE both of which require the CSI can be done at the network side only. Accordingly, the MT complexity can be kept low. It was shown by computer simulation that the downlink using FD-STBC-JTRD and uplink using FD-STTD can achieve almost the same BER performance and that by increasing the number N_{dan} of distributed antennas, the BER performance can be significantly improved while keeping the MT complexity low.

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