Cooperative Distributed Antenna Transmissions

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***Abstract*— Distributed antenna small-cell network is a promising 5G network. In this paper, a comprehensive report of recent advance in the cooperative distributed antenna transmission (CDAT) is provided. Single-user space-time block coded transmit diversity (STBC-TD) and multi-user minimum mean square error filtering combined with singular value decomposition (MMSE-SVD) are presented. Also presented is blind selected mapping (blind SLM) which can suppress the peak-to-average signal power ratio (PAPR) and requires no side information transmission. The effectiveness of CDAT in the presence of co-channel interference (CCI) from adjacent macro-cells is confirmed by computer simulation.**

Keywords—5G mobile communications, distributed antenna, small-cell network, space-time block coding, multi-user spatial multiplexing, selected mapping

I. INTRODUCTION

Mobile communications network has now evolved into the 4th generation (4G) [1]. Recently, the development of 5G network achieving higher spectrum efficiency (SE) and energy efficiency (EE) than 4G network is on-going worldwide [2]. 5G network is expected to provide much broader mobile data services (>1Gbps/user). In Japan, the research and development project for 5G network started in Sept. 2015 [3]. One promising 5G network is a distributed antenna small-cell network [4] that deploys a large number of distributed antennas over a traditional macro-cell area to exploit the spatial-domain more effectively. The authors have been studying the cooperative distributed antenna transmission (CDAT) which includes single-user spatial diversity and multi-user spatial multiplexing. The spatial diversity aims at improving the macro-cell edge users' link capacity while the multi-user spatial multiplexing aims at improving the link capacity of users in a good propagation condition.

The authors proposed, as the single-user spatial diversity, a space-time block coded transmit diversity (STBC-TD) jointly used with maximal ratio transmit frequency-domain equalization (MRT-FDE) for the orthogonal frequency division multiplexing (OFDM) downlink transmission [5] and that with receive minimum mean square error based FDE (MMSE-FDE) for the single-carrier (SC) uplink transmission [6]. As the multi-user spatial multiplexing, the authors proposed MMSE filtering combined with singular value decomposition (MMSE-SVD) for both OFDM downlink and SC uplink transmissions [7, 8]. Since the application of CDAT increases the peak-to-average signal power ratio (PAPR) of SC transmit signal, PAPR reduction technique will be necessary in order to reduce the power consumption of transmit power amplifiers. This is particularly important for battery-operated mobile terminals. The authors proposed blind selected mapping (blind SLM) which does not require the transmission of side information (such as phase rotation sequence information) [9].

This paper provides a comprehensive report of recent advance in CDAT. The performances of CDAT techniques are evaluated and compared under the same simulation condition. The rest of paper is organized as follows. Sect. 2 introduces the distributed antenna small-cell network. Then, the recent advances in CDAT techniques are described in Sect. 3. Sect. 4 presents computer simulation results to confirm the effectiveness of CDAT in multi-macro-cell environment. Sect. 5 offers some conclusions.

II. DISTRIBUTED ANTENNA SMALL-CELL NETWORK

The mobile communications network is designed based on the cellular concept [10]. In order to efficiently utilize the limited available bandwidth, spatially separated base stations (BSs) reuse the same frequency as long as the CCI is kept below a predetermined allowable level. Significantly improving the area SE (ASE) in bps/Hz/km^2 is one important challenge for 5G. Another challenge is to improve the EE in bits/Joule, since increasing the data rates leads to increasing the transmit signal power (this becomes a serious problem for battery-operated mobile terminals).

One promising approach for simultaneously improving the ASE and the EE is to adopt a small-cell structured network. Reducing the BS coverage area (i.e., small-cell) enables the same frequency to be reused more densely in the same service area and accordingly, the ASE can be improved. The short distance communications lowers the transmit signal power significantly, thereby the EE can be improved. However, frequent handover may happen while a user is traveling or even walking and may increase the control signal traffic.

There are two approaches to avoid frequent handover. One is to introduce the distributed antenna small-cell network [4] (or a distributed massive multi-input multi-output (MIMO) network). Another approach is to introduce the so-called massive MIMO [11] (or a centralized massive MIMO). The handover can be replaced with the selection of appropriate distributed antennas for the former network and with the selection of beams for the latter network within the same BS.

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A possible advantage of using distributed antennas over centralized massive MIMO is its capability of alleviating problems arising from the shadowing loss and path loss. The structure of distributed antenna small-cell network is illustrated in Fig. 1 (only single macro-cell area covered by single MBS is shown). Each distributed antenna and macro-cell BS (MBS) are connected by optical fiber link. MBS performs most of the radio signal processing required for signal transmission and reception. A predetermined number of distributed antennas near a user equipment (UE) are selected to form a user-centric small-cell and to perform CDAT.

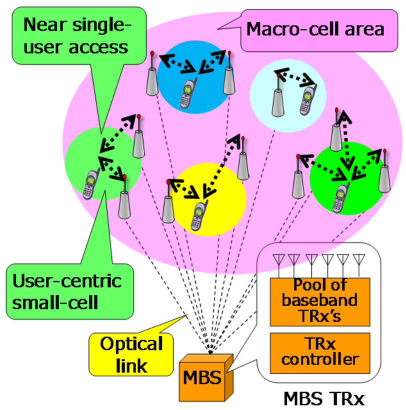


Fig. 1. Conceptual structure of distributed antenna small-cell network.

III. Cooperative Distributed Antenna Transmission (CDAT)

In 5G network, the signal bandwidth wider than 100MHz may be used. Since such a broadband channel is severely frequency-selective, a powerful equalization technique like FDE needs to be used in CDAT. FDE requires accurate channel state information (CSI). When using time division duplex (TDD), the CSI estimate of the uplink reception can be reused for the downlink transmit equalization. Therefore, FDE for both uplink reception and downlink transmission can be done at MBS. In this paper, OFDM and SC block signal transmissions are assumed for downlink and uplink, respectively, similar to LTE/LTE-A. A simplified transmitter/receiver structure of downlink CDAT is illustrated in Fig. 2. N_{mbs} distributed antennas near a UE are selected from N_{macro} distributed antennas to perform CDAT.

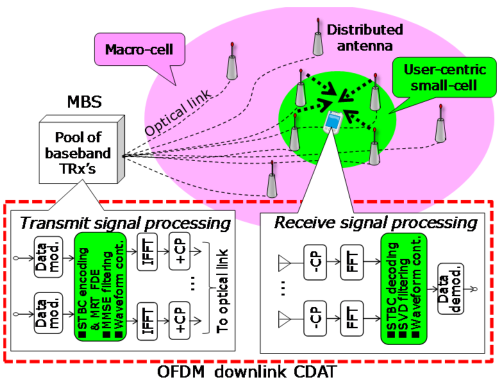


Fig. 2. A simplified transmitter/receiver structure of downlink CDAT.

A. Single-User STBC-TD

The well-known Alamouti STBC-TD encoding of size 2×2 [12] is considered. STBC-TD is jointly used with MRT-FDE for OFDM downlink transmission and with the receive MMSE-FDE for SC uplink transmission. An arbitrary number N_{mbs} of distributed antennas can be used although the number N_{ue} of UE antennas is only 2. Therefore, a large spatial diversity order of $2 \times N_{mbs}$ can be obtained for both downlink and uplink transmissions.

The downlink and uplink transmitter/receiver structures are illustrated in Fig. 3. The frequency division multi-access (FDMA) is considered for both OFDM downlink and SC uplink. If U UEs access the same MBS simultaneously, the number of subcarriers assigned to each UE becomes N_c/U, where N_c denotes the total number of subcarriers in the system bandwidth.

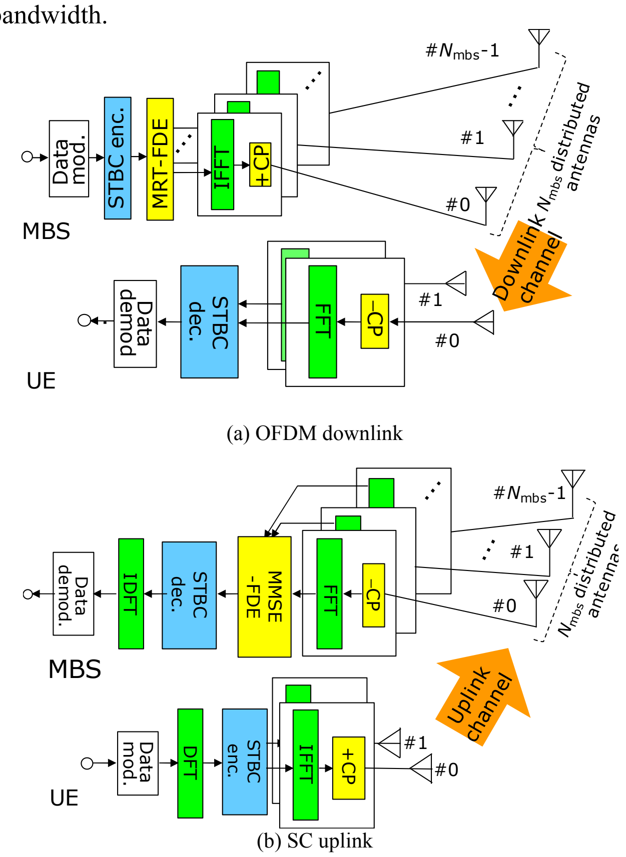
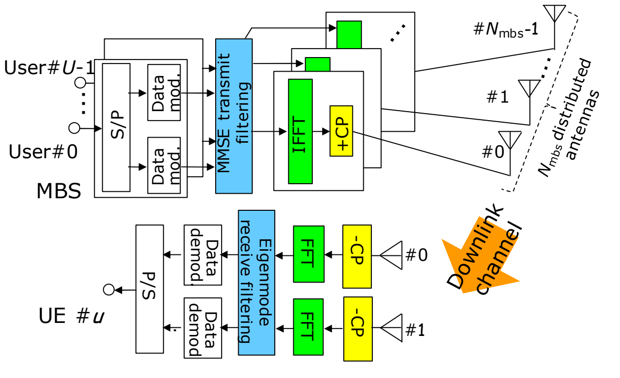


Fig.3. Single-user STBC-TD (N_{mbs}= arbitrary, N_{ue}=2).

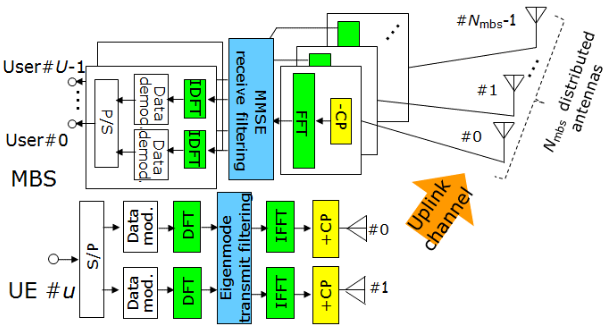
B. Multi-User MMSE-SVD

Each UE is equipped with N_{ue}=2 antennas for simultaneous transmission of 2 data streams. For multi-user spatial multiplexing, suppression of inter-user interference (IUI) and inter-antenna interference (IAI) is necessary. In the SC uplink transmission, suppression of inter-symbol interference (ISI) is necessary in addition to suppression of IAI and IUI. For this purpose, SC frequency-domain maximum likelihood detection which can simultaneously suppress the IUI, IAI, and ISI was proposed in [13]. The SVD based eigenmode transmission removing the IAI was proposed in [14]. Recently, a block diagonalization (BD) combined with SVD (BD-SVD) for downlink transmission was proposed [15]. BD-SVD applies BD to transform the multi-user MIMO channel into multiple single-user MIMO channels and then, applies SVD to perform eigenmode reception/transmission of multiple data streams over each single-user MIMO channel for the downlink/uplink transmission. However, the spatial diversity gain will reduce since the spatial degree of freedom is used for BD [16]. MMSE-SVD can avoid this problem by permitting IUI and IAI to remain to some extent.

The downlink and uplink transmitter/receiver structures are illustrated in Fig. 4. $N_{\rm mbs}$ $(\geq 2\ {\rm streams/UE} \times U)$ distributed antennas are selected from $N_{\rm macro}$ distributed antennas to simultaneously transmit 2 data streams per UE using N_c subcarriers. Assuming the eigenmode reception (transmission) at each UE, the multi-user transmission using transmit (receive) MMSE filtering is carried out to suppress the IUI and IAI.



(a) OFDM downlink



(b) SC uplink

Fig. 4. Multi-user MMSE-SVD ($N_{\rm mbs}$= arbitrary, $N_{\rm ue}$=2).

C. Blind SLM

When using CDAT, PAPR of SC uplink signal increases and therefore, PAPR reduction technique is still necessary. SLM is an effective technique to reduce the PAPR. A selected phase rotation sequence is multiplied to the transmit SC signal in either time-domain or frequency-domain [17].

Blind frequency-domain SLM (FD-SLM) for SC uplink using STBC-TD is illustrated in Fig. 5. If blind time-domain SLM (TD-SLM) is used, phase rotation sequence selection is done in the time-domain before discrete Fourier transform (DFT) at the transmitter. The phase rotation sequence selection can be based on either minimizing the maximum PAPR of multiple transmit blocks (called the minimax criterion) or minimizing the PAPR of each transmit block individually (called the block-by-block minimization criterion). At the receiver, de-mapping is done to remove the phase rotation applied to the transmit signal. In blind SLM, no side information is transmitted and therefore, it is necessary to estimate which phase rotation sequence is used at the transmitter. Blind SLM exploits a fact that the received signal constellation observed after de-mapping is significantly distorted if an incorrect phase rotation sequence is used at the receiver. The phase rotation sequence selection can be based on the minimum squared error between the received signal after de-mapping and the original signal constellation known to the receiver.

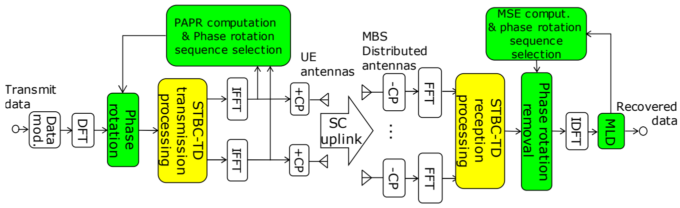


Fig. 5. Blind FD-SLM for SC uplink using STBC-TD.

IV. Computer Simulation

A simple hexagonal cellular model with $N_{\rm macro}$=7 distributed antennas deployed uniformly in each macro-cell is assumed, as shown in Fig. 6. For a comparison purpose, a macro-cell network with 7 co-located antennas at each MBS is also shown in the figure. Simulation parameters are summarized in TABLE I. The macro-cell of interest is surrounded by 6 adjacent macro-cells. In each macro-cell, U=2 UEs, each equipped with $N_{\rm ue}$=2 antennas for transmission of 2 data streams, are randomly located.

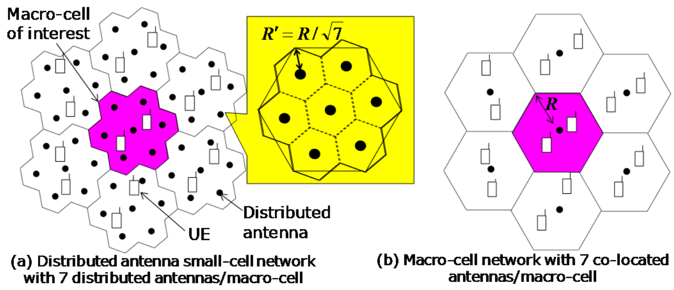


Fig. 6. Cellular model.

TABLE I Simulation Parameters

Tx/Rx	SC uplink	Single-user STBC-TD w/Rx MMSE FDE
		Multi-user MMSE-SVD
	OFDM downlink	Single-user STBC-TD w/Tx MRT-FDE
		Multi-user MMSE-SVD
	Total no. of subcarriers	N_c=128
	GI length	N_g=32
	No. of distributed antennas deployed in a macro-cell	$N_{\rm macro}$=7
	No. of UE antennas	$N_{\rm ue}$=2
	No. of distributed antennas to be selected	$N_{\rm mbs}$=4
	Channel state information	Ideal
Propag. channel	Path loss exponent	α=3.5
	Shadowing loss standard deviation	σ=7.0(dB)
	Type of fading	Frequency-selective block Nakagami-Rice and Rayleigh
	K factor of Nakagami-Rice	K=10dB
	Power delay profile (PDP) shape	L=16 - uniform

N_{mbs}=4 distributed antennas are selected for up/downlink transmissions (TDD is assumed). In the case of STBC-TD, the sum of instantaneous path gains between each distributed antenna and U=2 UE antennas is computed and then, N_{mbs}=4 distributed antennas are selected for each UE from N_{macro}=7 distributed antennas in a descending order of the sum of instantaneous path gains. On the other hand, in the case of MMSE-SVD, the instantaneous path gain between each distributed antenna and each UE antenna is computed and then, N_{mbs}=4 distributed antennas are selected for each UE antenna in a descending order of instantaneous path gains.

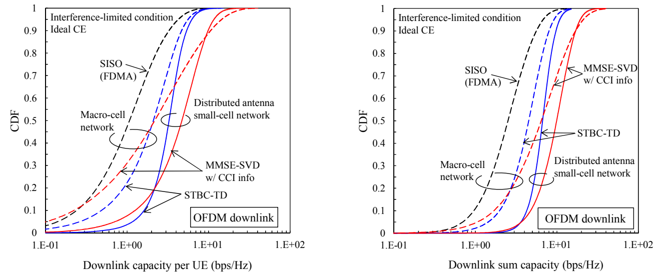
Multi-access scheme for the signal transmission using STBC-TD is frequency-division multiple access (FDMA). N_c=128 subcarriers are divided to 2 subcarrier-blocks and a different block is assigned to each of U=2 UEs. On the other hand, for the transmission using MMSE-SVD, all N_c=128 subcarriers are shared by U=2 UEs. Frequency-selective fading channel having an L=16-path uniform power delay profile (PDP) is assumed as well as shadowing loss and path loss. The channel is assumed to be Nakagami-Rice channel with K=10dB when the distance between distributed antenna and UE is shorter than $R/\sqrt{7}$, otherwise the channel is assumed to be Rayleigh channel, where R denotes the macro-cell radius.

Assuming an interference-limited condition, the distributions of uplink/downlink capacities are obtained by Monte-Carlo computer simulation. CCI from 7 adjacent macro-cells is taken into account to compute the uplink receive MMSE weight for STBC-TD and the downlink transmit and uplink receive MMSE weights for MMSE-SVD. However, since MRT-FDE is used for downlink using STBC-TD, the knowledge of CCI is not needed to compute the MRT-FDE weight. Perfect knowledge of CCI is assumed.

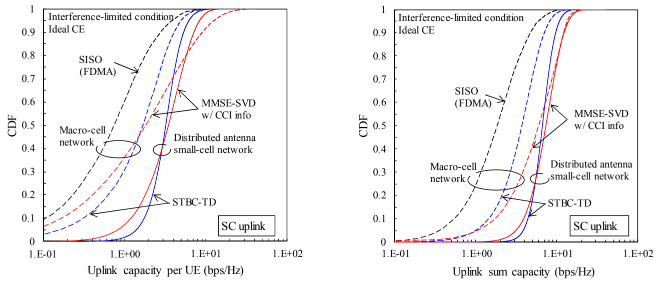
A. Single-user STBC-TD and multi-user MMSE-SVD

The link capacity distribution obtained by computer simulation is plotted in Fig. 7. Also plotted is the single-input single-output (SISO) case in a macro-cell network. The use of 7 co-located antennas improves the link capacity. Further improvement of the link capacity is achieved by deploying N_{macro}=7 antennas over a macro-cell area. Comparison between STBC-TD and MMSE-SVD shows that MMSE-SVD lowers the outage probability at a high link capacity region of around 5 bps/Hz, while STBC-TD lowers the outage probability at a low link capacity region of around 1 bps/Hz.

Downlink capacity comparison between MMSE-SVD with and without taking into account CCI (w/ and w/o CCI info in the figure) and BD-SVD [15] is shown in Fig. 8. It can be seen from the figure that, in a multi-macro-cell environment, although MMSE-SVD w/o taking into account the CCI provides lower capacity than BD-SVD, it provides higher capacity if the CCI is taken into account.



(a) OFDM downlink



(b) SC uplink

Fig. 7. Link capacity distribution.

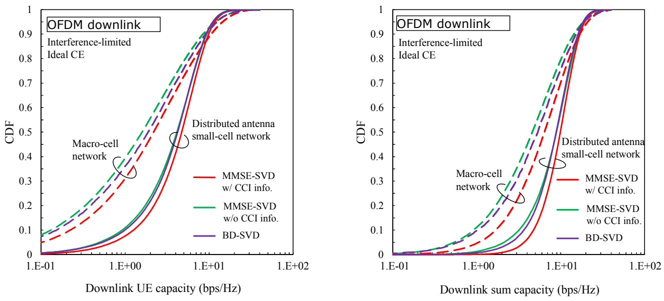


Fig. 8. Comparison between MMSE-SVD and BD-SVD.

B. Blind SLM

How blind SLM reduces the PAPR of SC signal with STBC-TD is plotted in Fig. 9. The uplink SC signal using N_c/U=64 subcarriers and 16 QAM data modulation is considered. The phase rotation in the phase rotation sequences is randomly chosen from 0, 2π/3, and 4π/3 radians. It is seen from Fig. 9 that increasing the number M of phase rotation sequences can reduce the PAPR more. TD-SLM can reduce the PAPR more than FD-SLM for the same value of M. This is because the resulting phase-rotated signals obtained from TD-SLM are in a bounded set of 16×3=48 patterns when using 16QAM, while the signal constellation after applying the phase rotation according to FD-SLM widely scatters. In the cases of N_{ue}=2, blind TD-SLM using block-by-block minimization criterion can achieve the same PAPR performance as single-antenna transmission case. Blind TD-SLM with M=256 can reduce the PAPR of SC signal by 3.6 dB, i.e., the PAPR becomes 1 dB lower than that of OFDM.

The uncoded average bit error rate (BER) performance of blind SLM is plotted in Fig. 10. For comparison, the BER performances with side information (the perfect knowledge of phase rotation sequence index) are also plotted. Although blind TD-SLM provides slightly degraded BER performance than TD-SLM with side information when N_{ue}=1 (no STBC-TD), blind TD-SLM achieves BER performance close to TD-SLM with side information when STBC-TD is used.

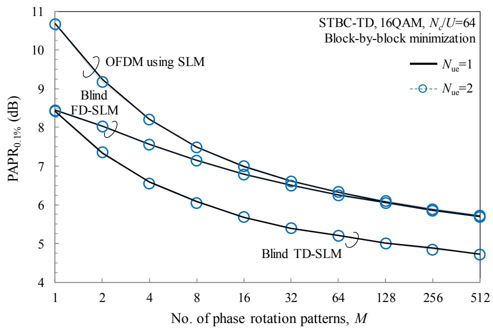


Fig. 9. PAPR of uplink SC signal with STBC-TD.

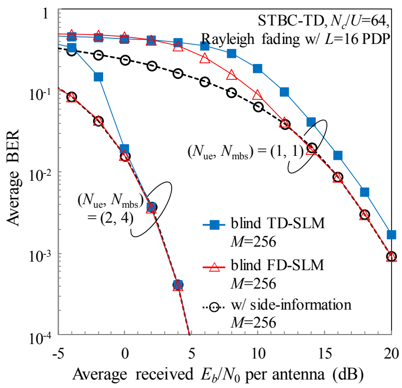


Fig. 10. BER performance of SC signal transmission with STBC-TD and blind SLM.

V. Conclusions

In this paper, the recent advance in cooperative distributed antenna transmission (CDAT) was provided. Specifically, single-user STBC-TD, multi-user MMSE-SVD, and blind SLM were presented. The effectiveness of CDAT was confirmed by computer simulation. It was shown that the distributed antenna small-cell network can significantly improve the link capacity compared to centralized antenna network. In this paper, the perfect knowledge of CSI was assumed. The channel estimation for CDAT is left as our important future study. An application of blind SLM to the OFDM downlink transmission using MMSE-SVD and the computational complexity reduction of blind SLM are also left as our future study.

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