Joint Cooperative Diversity and Scheduling with Distributed Transmit Beamforming in OFDMA Relay System

Salma Ait Fares, Fumiyuki Adachi and Eisuke Kudoh
Depart. of Electrical and Communication Engineering, Tohoku University
6-6-05, Aza-Aoba, Aramaki, Aoba-ku, 980-8579, Sendai, Japan
E-mail: aitfares@mobile.ecei.tohoku.ac.jp, adachi@ecei.tohoku.ac.jp, kudoh@m.ieice.org

Abstract—**Cooperative relay diversity and adaptive scheduling for active source/destination pairs in OFDMA-based relay network can significantly improve the reliability of data transmission over wireless fading channels as well as enhance the aggregate and per-link throughputs. However, in slow-varying fading channel, this technique suffers from low per-link throughput since some users with highest SNR at the destination access the channel for a long period while others will have to wait until their channel condition improves. In this paper we propose joint transmit beamforming and fixed cyclic delay diversity (CDD) at the relay nodes to enhance the transmit signals from relays to the destination link and to improve the perlink throughput performance. Combining transmit beamforming with CDD approach creates more fluctuation among subcarriers resulting in time-varying SNR at each destination. Therefore, the scheduler can now successfully provide more chance to users to have access to the channel by allocating subcarriers to users whose SNR are highest and thus the per-link throughput is enhanced. Simulation results show that the system performance using the proposed method increases significantly compared with the other previously proposed cooperative diversity techniques.**

Keywords-component; Cooperative relaying network, Transmit beamforming, Cyclic delay diversity, Scheduling, OFDMA.

I. INTRODUCTION

In multiuser system, OFDMA based relay networks [1-4] have recently received much renewed research interest and recognized as enabling techniques to achieve greater coverage and capacity by exploiting multiuser diversity and allowing efficient sharing of limited resources such as spectrum and transmit power among multiple users. At a particular instant of time, and since several users' channels fade differently, the scheduler offer different users the access to the channel based on their channel conditions. In fast-varying fading scenario, if the users have the same average SNR at their destinations, they will have approximately the same chance to access the channel. However, in slow-varying fading scenario, some users with highest SNR at the destination will access the channel for a long time while unfortunately others have to wait until their channel condition improves.

For such slowly time-varying channel environment, joint cooperative diversity and scheduling (JCDS) technique has been recently proposed in [1-4] to improve the capacity performance. The authors in [1-2] introduced a time-varying phase rotation in time domain at relay nodes by multiplying each transmit relay signal by a specific phase rotation. This later creates a time-variant relay fading channel which can be exploited to provide opportunity for every user to be scheduled. For frequency selective fading channel, [3-4] have extended the JCDS technique by introducing a cyclic delay diversity (CDD) at the relay nodes in OFDMA system. Using CDD technique, additional fluctuation among the sub-carriers is produced and as a result the scheduler can successfully provide more chance to users to have access to the channel by allocating subcarriers to users whose SNR are highest.

The performance of the JCDS depends as well on the cooperative diversity technique used at relay nodes. It has been shown in [5] that using single Amplify and Forward (AF) relay, second order diversity can be achieved. But, it is not necessary evident to achieve higher order diversity by using several AF-relays. For instance, if some relays receive noisy signals then the noises contained in these received signals are also amplified during a retransmission process. Without any further signal processing; except amplification relay gain, these noisy signals may distort the received signal at the destination and hence diversity order is reduced. With proper processing of the received signals at the relay nodes, the performance of the JCDS system may perform better by improving the quality of communication links between relays and destinations. For this aim, several algorithms have been proposed in literatures known as cooperative distributed transmit beamforming (DTB) for single carrier frequency [6-8].

In this paper, we will introduce the DTB approach to JCDS OFDMA-based relay network in multi source-destination pair's environment where this technique has not been investigated and we will show its potential in order to increase the diversity order and the system throughput performance. The optimal transmit beamforming can be derived that maximizes the SNR [6-8] at each destination for each subcarrier. By jointly employing the JCDS with DTB, the *aggregate throughput*, defined as the total throughput in the given physical resources, is enhanced. On the other hand, the *per-link throughput*, defined as the user throughput in a given transmission cycle, is not significantly improved, since this performance measure is depending on how many subcarriers are allocated to the user during a given transmission cycle.

To tradeoff a small quantity of the aggregate throughput in return for significant improvement in the per-link throughput, we introduce also the fixed CDD approach at relay stations to our proposed JCDS-DTB. In multi source-destination pairs system, combining DTB with CDD at relay nodes creates more fluctuation among subcarriers resulting in time-variant SNR at each destination and consequently gives more opportunity to users to access to the channel.

The rest of the paper is organized as follows. Section II introduces the proposed JCDS using mutually DTB and CDD in OFDMA-based relay network in multi source-destination

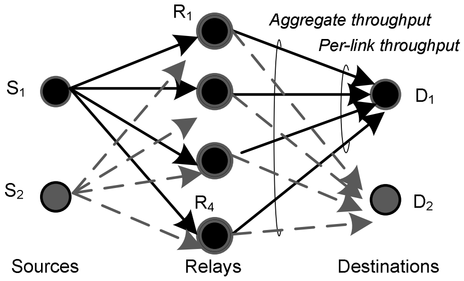


Figure 1. Multi source-destination pairs via relay routes.

pairs system. Section III evaluates the proposed method by computer simulation. Finally, Section IV concludes the paper. Notation: The bold letter denotes vector while the one with subscript *m* denotes matrix. Small and capital letters denote the element in time and frequency domain, respectively.

II. JCDS WITH DISTRIBUTED TRANSMIT BEAMFORMING AND CYCLIC DELAY DIVERSITY

A. System Model

Consider a wireless system composed of M user-destination pairs. R relays are assisting the communication link. Each source needs to communicate with its own destination with the help from these relays. We assume the destinations are far away from sources and there are no direct paths between source-destination pairs. Fig. 1 illustrates an example of the system model with two source-destination pairs (M=2) using four relays (R=4). We assume that the relays operate in duplex mode where in the first time slot, they receive the OFDM signals from sources that are transmitting simultaneously but with different non-overlapping sub-channels (i.e., a set of OFDM subcarriers), while in the second slot they forward concurrently their received signals to destinations. The channels are assumed time-invariant over one OFDMA block and i.i.d. frequency selective Rayleigh fading with the channel order L. The *l-th* path complex channel impulse response from the *i-th* source to the *r-th* relay and from the *r-th* relay to the *i-th* destination are denoted by $h_{i,r}(l)$ and $g_{r,i}(l)$, respectively. Both $h_{i,r}(l)$ and $g_{r,i}(l)$ are zero mean complex Gaussian random and their variances follow an exponential delay profile such as $E\left[\left|h_{i,r}\right|^2\right] = E\left[\left|g_{r,i}\right|^2\right] = e^{-l/\tau_{rms}} / \sum_{l=0}^{L} e^{-l/\tau_{rms}}$.

The structure of the OFDMA signal transmitted from user U_i is depicted in Fig.2 where N_c represents the N_c-point (I) FFT in the OFDMA transmitters and receivers, N_{ci} is the number of subcarriers allocated to the user U_i, where the remaining subcarriers (N_c-N_{ci}) are padded (e.g., zero padding) and N_{GI} is the guard interval (GI) length and assumed to be longer than the maximum channel delay spread.

After removing GI and applying FFT transform the received signal of the *p-th* subcarrier at the *r-th* relay is given by

$$Y_r(p) = \sqrt{P_s} \cdot H_{i,r}(p) \cdot S_i(p) + \eta_r(p),\ r = 1,\cdots,R. \quad (1)$$

where $S_i(p)$ is a unit-energy data symbol transmitted from user U_i ($1 \le i \le M$) whose subcarrier p has been assigned by the scheduler, P_s is the transmit power used by the user U_i, $H_{i,r}(p)$ is the channel gain of the subcarrier p from the *i-th* user to the *r-th* relay and $\eta_r(p)$ is the AWGN's in the corresponding channels with variance σ_R^2. Before forwarding the received signals to the destination, the relays may perform some signal processing as shown in Fig.3 (a, b, and c), such as jointly AF and CDD proposed in [4], jointly AF and DTB or jointly AF, DTB and fixed CDD as will be studied in the following.

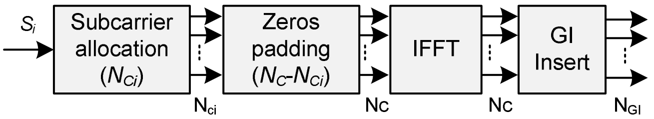


Figure 2. Transmit OFDM signal structure and subcarrier allocation scheme.

Using AF relay scheme, the relay normalizes its received signal by multiplying it with a relay gain given by

$$\beta_{i,r}(p) = 1 \Big/ \sqrt{P_s \cdot \left|H_{i,r}(p)\right|^2 + \sigma_R^2},\ r = 1,\cdots,R. \quad (2)$$

With channel order equal to L, the channel gain $H_{i,r}(p)$ at the *p-th* subcarrier can be written as

$$H_{i,r}(p) = \sum_{l=0}^{L} h_{i,r}(l) \cdot e^{-j2\pi lp/N_c}. \quad (3)$$

The output of the transmit beamforming can be expressed by

$$Y_r^{TB}(p) = \beta_{i,r}(p) \cdot W_{TB,r}(p) \cdot Y_r(p),\ r = 1,\cdots,R, \quad (4)$$

where $W_{TB,r}(p)$ represents the weight element of the *p-th* subcarrier at the *r-th* relay.

The received signal at the *i-th* destination after performing FFT is written as

$$Y_i(p) = \sum_{r=1}^{R} G_{r,i}(p) \cdot S_{Rr}(p) + \gamma_i(p), \quad i = 1,\cdots,M. \quad (5)$$

where $S_{Rr}(p)$ is the *p-th* subcarrier component of the OFDMA signal transmitted from the *r-th* relay, $G_{r,i}(p)$ denotes the channel gain at the p-th subcarrier from the *r-th* relay to the *i-th* destination, calculated using (3) by replacing $h_{i,r}(l)$ by $g_{r,i}(l)$, and $\gamma_i(p)$ is the AWGN's with variance σ_D^2.

By substituting (1) and (4) into (5), we obtain

$$Y_i(p) = \sqrt{P_s} \cdot S_i(p) \cdot \boldsymbol{a}(p) \cdot \boldsymbol{W}_{TB}^H(p) + \upsilon_i(p), \quad (6)$$

where $\boldsymbol{a} = \left[\beta_{i,1} \cdot H_{i,1} \cdot G_{i,1}, \ldots, \beta_{i,R} \cdot H_{i,R} \cdot G_{i,R}\right]$, (7)

$$\upsilon_i = \boldsymbol{\eta} \cdot \boldsymbol{A_m} \cdot \boldsymbol{W}_{TB}^H + \gamma_i, \quad (8)$$

$$\boldsymbol{A_m} = diag\left[\beta_{i,1} \cdot G_{i,1}, \ldots, \beta_{i,R} \cdot G_{i,R}\right], \quad (9)$$

$\boldsymbol{W}_{TB}^H = \left[W_{TB,1}^*, \ldots, W_{TB,R}^*\right]^T$, $(\cdot)^*$ is the conjugate and $\boldsymbol{\eta} = [\eta_1, \ldots, \eta_R]$.

To ensure that all relays transmit data with total energy P_r, the transmit beamforming weight vector should satisfy

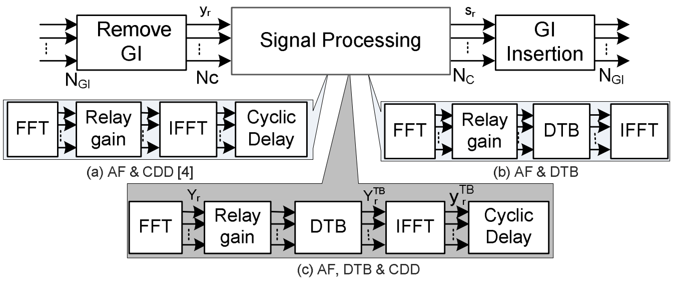
$$\boldsymbol{W}_{TB} \cdot \boldsymbol{W}_{TB}^H = P_r. \quad (10)$$

From (6), the instantaneous SNR of the p-th subcarrier at the i-th destination can be expressed as

$$SNR_i(p) = P_s \cdot \frac{\boldsymbol{W}_{TB}(p) \cdot \boldsymbol{a}^H(p) \cdot \boldsymbol{a}(p) \cdot \boldsymbol{W}_{TB}^H(p)}{\boldsymbol{W}_{TB}(p) \cdot \boldsymbol{\Omega}_{\mathrm{m}}(p) \cdot \boldsymbol{W}_{TB}^H(p) + \sigma_D^2(p)}, \quad (11)$$

where $\boldsymbol{\Omega}_{\mathrm{m}} = \sigma_R^2 \cdot \boldsymbol{A}_m^H \cdot \boldsymbol{A}_m$. (12)

Let define $\boldsymbol{\Omega}_{1\mathrm{m}} = \boldsymbol{\Omega}_{\mathrm{m}} + \frac{\sigma_R^2}{P_r} \cdot I_{R\times R}$ and since



(a) AF & CDD [4]

(b) AF & DTB

(c) AF, DTB & CDD

Figure 3. Relay node structure using different cooperative techniques.

$\boldsymbol{W}_{TB} \cdot \boldsymbol{W}_{TB}^{H} = P_r$ is assumed in (10), (11) can be written as

$$SNR_i(p) = P_s \cdot \frac{\boldsymbol{W}_{TB}(p) \cdot \boldsymbol{a}^{H}(p) \cdot \boldsymbol{a}(p) \cdot \boldsymbol{W}_{TB}^{H}(p)}{\boldsymbol{W}_{TB}(p) \cdot \boldsymbol{\Omega}_{1\text{m}}(p) \cdot \boldsymbol{W}_{TB}^{H}(p)}. \qquad (13)$$

From (13), the source destination channel capacity of the *p-th* subcarrier for the *i-th* user is given by

$$C_{i,p}(p) = \frac{B}{2N_c} \cdot log_2\big(1 + SNR_i(p)\big), \qquad (14)$$

where B is the total bandwidth. It can be seen from (14) that in order to maximize the aggregate channel capacity, each destination's SNR should be maximized at each subcarrier. Therefore, we develop in the following section a transmit beamforming technique that maximizes the SNR at each destination and for each subcarrier.

B. Derivation of the ditributed transmit beamforming weight

To combat fading effects and then improve the link level performance, the distributed spatial diversity created by the relay nodes can be effectively exploited using a transmit diversity weight technique. In this paper, we develop the optimal weight vector that maximizes the SNR given by (13), i.e. determine the transmit beamforming vector such that

$$\boldsymbol{W}_{TB} = arg\ \underset{\boldsymbol{W}}{max}\left(\frac{\boldsymbol{W} \cdot \boldsymbol{a}^{H} \cdot \boldsymbol{a} \cdot \boldsymbol{W}^{H}}{\boldsymbol{W} \cdot \boldsymbol{\Omega}_{1\text{m}} \cdot \boldsymbol{W}^{H}}\right). \qquad (15)$$

The weight optimization criterion expressed by (15) is in the form of Rayleigh quotient, and can be derived by solving the generalized Eigen-value problem [7] and [8]. Hence, for any weight vector $\boldsymbol{W}_{\text{TB}}$, we have

$$SNR_i \leq \lambda_{max}, \qquad (16)$$

where λ_{max} is the largest Eigen-value of $\left(\boldsymbol{\Omega}_{1m}^{H/2}\right)^{-1} \boldsymbol{a}^{H} \boldsymbol{a} \left(\boldsymbol{\Omega}_{1m}^{1/2}\right)^{-1}$. The equality holds if

$$\boldsymbol{W}_{TB}(p) = c \cdot \boldsymbol{a}(p) \cdot \boldsymbol{\Omega}_{1m}^{-1}(p), \qquad (17)$$

where $c = 1/\sqrt{|\boldsymbol{a} \cdot \boldsymbol{\Omega}_{1m}^{-1}|^{2}}$. (18)

By using this derived optimal transmit beamforming that maximizes the SNR, the aggregate channel capacity is significantly enhanced while in parallel the per-link capacity is not much improved and in particularly in slow-varying fading scenario. To overcome this problem one can introduce a phase rotation at the relay nodes to create time varying fading channel and hence the scheduler will offer opportunity to more users to get channel access.

In this paper, we applied the CDD approach in the time domain (after IFFT transform) at relay nodes as shown in Fig.3.c to perform a phase rotation in frequency domain. Hence, after performing IFFT transform at the *r*-th relay, the output of the CCD block is given by

$$y_r^{CDD}(l) = y_r^{TB}(l - \Delta_r),\ r = 1, \cdots, R, \qquad (19)$$

where $y_r^{TB}(l)$ represents the *l-th* element of the IFFT of the $Y_r^{TB}(p)$ signal and Δ_r represents the cyclic delay value used at the *r-th* relay. Δ_r is selected as a fixed circular shift cyclic delay given by

$$\Delta_r = Int\left(\frac{N_c}{R} \cdot (r - 1)\right), r = 1, \cdots, R \qquad (20)$$

where *Int*(x) represents the nearest integer function of x.

Subsequently by using the CDD approach, the instantaneous SNR given in (13) is expressed currently as

$$SNR_i(p) = P_s \cdot \frac{\boldsymbol{W}(p) \cdot \boldsymbol{a}^{H}(p) \cdot \boldsymbol{a}(p) \cdot \boldsymbol{W}^{H}(p)}{\boldsymbol{W}(p) \cdot \boldsymbol{\Omega}_{1m}(p) \cdot \boldsymbol{W}^{H}(p)}. \qquad (21)$$

where

$$\boldsymbol{W}(p) = \boldsymbol{W}_{TB}(p) \cdot diag\big(\boldsymbol{a}_1(p)\big), \qquad (22)$$

and

$$\boldsymbol{a}_1(p) = \left[e^{-j\frac{2\pi p \Delta_1}{N_c}}, \cdots, e^{-j\frac{2\pi p \Delta_R}{N_c}}\right]. \qquad (23)$$

An adaptive scheduling in OFDMA-based relay network is adopted to allocate the subcarriers to each source based on SNR channel assignment approach. This adaptive scheduler allocates the *p-th* subcarrier to the *i-th* user destination pair with the highest SNR such that

$$U_i(p) = arg\ max_{i\epsilon\{1,\cdots,M\}}\big(SNR_i(p)\big),\ p\ \epsilon\ \{1, \cdots, N_c\}. \qquad (24)$$

Two significant measured performances, highlighted in Fig.1, are studied, the *aggregate throughput* and the *per-link throughput*. By ignoring the loss from GI, the aggregate throughput (in bit per complex dimension) is expressed by

$$C_{agr} = \frac{1}{2N_c} \cdot \sum_{p=0}^{N_c - 1} log_2\big(1 + SNR_i(p)\big). \qquad (25)$$

While the per-link throughput or average user throughput is defined by

$$C_{per-link} = M \cdot \frac{1}{2N_c} \cdot \sum_{p\epsilon\Gamma} log_2\big(1 + SNR_i(p)\big), \qquad (26)$$

where Γ is the set of subcarriers allocated to the *i-th* user and M represents the number of user-destination pairs.

It should be noticed from (25-26) that increasing the user-destination pairs increases the aggregate throughput while the per-link throughput is reduced since the number of allocated subcarriers for each user is largely reduced. Hence using our proposed JCDS with adaptive scheduling based on SNR channel assignment; a trade-off between aggregate throughput and per-link throughput is achieved and that guarantees the per-link throughout to have at least the same QoS as in the static scheduling (SS) where all users get an equal share of the allocated resources.

III. SIMULATION RESULTS

In this section, we compare the performance of the proposed JCDS using both DTB and fixed CDD with different cooperative diversity techniques such as JCDS with DTB, JCDS with AF and JCDS with fixed CDD where adaptive scheduling based on SNR channel assignment is employed.

This adaptive scheduler allocates the subcarriers to the source whose SNR is highest. Both techniques, JCDS-AF and JCDS-CDD, are using equal divided transmit power at relay stations, i.e., $P=P_r/R$. While, in JCDS-DTB the relays are using DTB under constraint of (10). We evaluate the system performance by taking the same simulation scenario presented in [3] for comparison purpose. In this scenario, two types of fading are studied, the flat fading where the normalized *rms* delay spread (τ_{rms}) is relatively short and equals to 0.3; corresponding to L=3, and the frequency selective fading where the normalized *rms* delay spread is relatively large and equal to 1.5; corresponding to L=15. The number N_c of subcarriers is equal to 256, R=20 and the average SNR at the relay and at the destination are defined to be the same 20dB which is equivalent to $\sigma_R^2 = \sigma_D^2 = 0.01$.

Fig. 4 illustrates the cumulative distribution functions (CDF) of the aggregate throughput, $P(C_{agr}$<throughput), and the per-link throughput, $P(C_{per\text{-}link}$<throughput) in short delay spread scenario ($\tau_{rms} = 0.3$) using our proposed method; i.e., JCDS with DTB and CDD for different user-destination pairs. Aggregate and per-link throughput's results are shown by solid and dashed lines, respectively. A comparison of the static scheduling with R=1 (single relay node), in which the aggregate throughput and per-link throughput are equal, is also studied. It should be noticed that when M=1 (single source-destination pair), the aggregate throughput is equal to the per-link throughput and the employed adaptive scheduler is equivalent to the static scheduling. Hence, from Fig. 4, by comparing the throughput using static scheduling and R=1 with that of our proposed method using M=1 and R=20, we can see clearly the cooperative relay diversity gain.

Furthermore, we can observe as well the user diversity effect in both aggregate and per-link throughputs. It is intuitively clear that when the number of users increases the aggregate throughput is improving since the scheduler switches to the user whose link is better. In contrast, the per-link throughput is decreasing when the number of source-destination pairs is getting higher. Thus the QoS of each source-destination pair is severely affected due to the reduced number of assigned subcarriers. In addition, at 1% outage per-link throughput, if we want to maintain the per-link throughput at least equal to that of static scheduling, it is seen that 5 users can be handled by this system.

Fig. 5 compares the 1% outage aggregate throughput and 1% outage per-link throughput, using different cooperative diversity and scheduling approach in short delay spread scenario in terms of the number M of source-destination pairs. Aggregate and per-link throughput's results are shown by solid and dashed lines, respectively. From this figure, and for aggregate throughput curves comparison, we notice that the aggregate throughput of all cooperative diversity techniques exceeds that of the static scheduling with R=1. In addition, the throughput using JCDS - DTB is the largest followed by JCDS with DTB & CDD and both of them significantly outperform the JCDS with DTB & CDD using static scheduling with R=20. Moreover, the aggregate throughputs obtained by using JCDS-CDD and JCDS-AF exceed that of using JCDS with DTB & CDD using static scheduling with R=20 when M>1 and M>3, respectively. However, for per-link throughput curves comparison in the same figure, we notice that the per-link throughputs of all cooperative diversity techniques are lower than those of the JCDS–(DTB & CDD) with R=20 and using static scheduling. This indicates the impact of the unfair SNR assignment relative to user throughput. In addition, the per-link throughput using JCDS-(DTB & CDD) is the largest followed by JCDS–CDD. The JCDS–(DTB & CDD) achieves the highest throughput while JCDS-DTB and JCDS-AF have the worst performance. By comparing aggregate and per-link throughputs of JCDS-(DTB & CDD) with JCDS–DTB, the proposed method JCDS–(DTB & CDD) sacrifices a small quantity of the aggregate throughput in return for significant improvement in the per-link throughput.

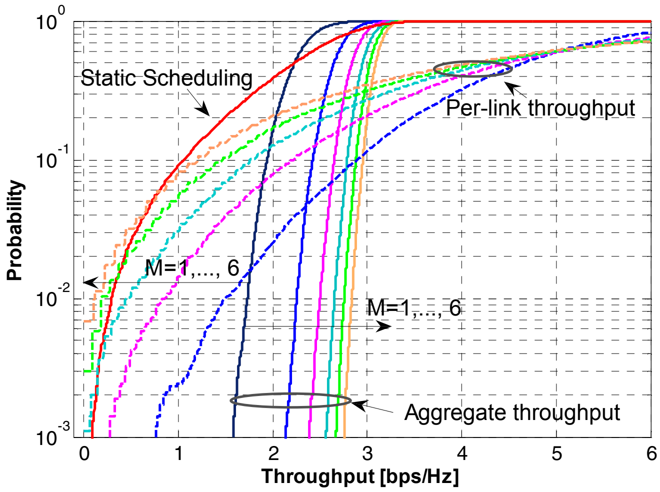


Figure 4. CDF of the aggregate and per-link throughput for short delay spread (τ_{rms}=0.3) using JCDS with DTB and CDD.

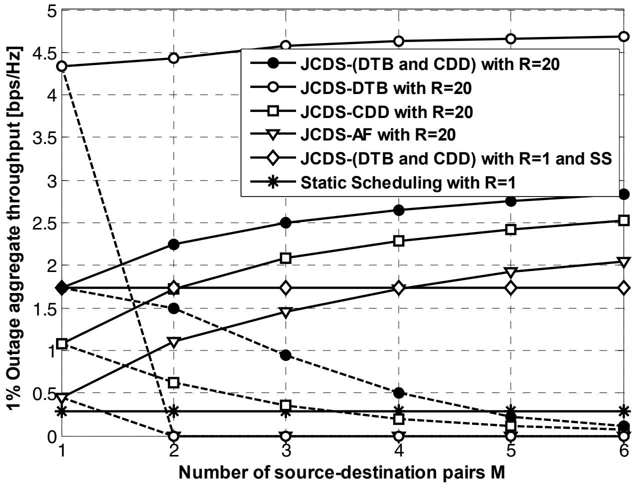


Figure 5. 1% outage throughput comparaison for short delay spread (τ_{rms}=0.3) using different cooperation diversity methods.

Using the same propagation environment but having long normalized delay spread ($\tau_{rms} = 1.5$), Fig. 6 illustrates CDFs of the aggregate throughput and per-link throughput using our proposed JCDS with DTB and CDD method for different

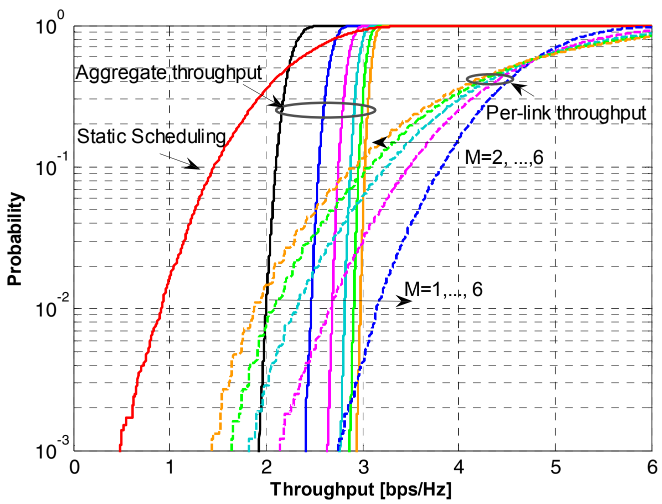


Figure 6. CDF of the aggregate and per-link throughput for long delay spread (τ_{rms}=1.5) using JCDS with DTB and CDD.

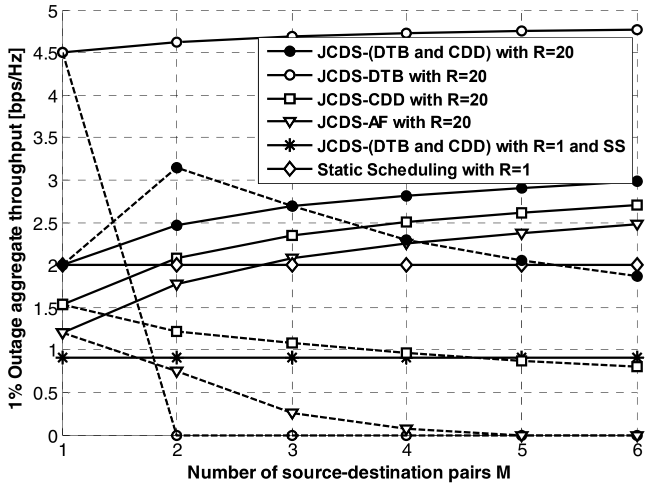


Figure 7. 1% outage throughput comparaison for long delay spread (τ_{rms}=1.5) using different cooperation methods.

number M of source-destination pairs. Similar observation given in Fig.4 can be provided herein regarding the cooperative diversity gain and user diversity gain which are positive on the aggregate throughput and negative on the per-link throughput. However, we notice that all per-link throughput curves exceed largely that of static scheduling with *R=1*. This can be explained by the higher multipath diversity in the large delay spread scenario where more fluctuation in frequency domain is provided and hence more users are scheduled.

Fig. 7 compares the 1% outage aggregate and per-link throughputs, using different cooperative diversity and scheduling approaches in long delay spread scenario ($\tau_{rms} = 1.5$) in terms of the number M of source-destination pairs. Aggregate and per-link throughput's results are shown by solid and dashed lines, respectively. From this figure, and for aggregate throughput curves comparison, the gain of the aggregate throughput using all JCDS techniques with static scheduling is smaller compared to short delay case ($\tau_{rms} = 0.3$). Also, the aggregate throughput of all cooperative diversity techniques exceeds that of the static scheduling. However, for per-link throughput curves comparison in the same figure, we notice that the per-link throughput of JCDS-(DTB& CDD) is the best followed by JCDS-CDD and both of them outperform that of static scheduling with R=1 irrespective to the number M of source-destination pairs. This result is due to the increase in frequency selectivity in such long delay spread channel. Moreover, the JCDS-(DTB & CDD) achieves highest throughput while JCDS with DTB provides the lowest throughput when M>1. When M=2, the JCDS- (DTB & CDD) achieves the highest throughput due to the increase in path and user diversities.

IV. CONCLUSION

In this paper, we studied the JCDS for active source/destination pairs in OFDMA-based relay system. We investigated the performance of the JCDS technique by introducing and developing a distributed transmit beamforming approach jointly with cyclic delay diversity (CDD) at the relay nodes. Combining transmit beamforming with fixed CDD approach creates more fluctuation among subcarriers and gives more opportunity to users to access to the channel and thus to increase considerably the diversity order and the throughput performance. Therefore, time-varying SNR at the destination is created and more users can be efficiently assigned by the scheduler. Simulation results show that the system performance using our proposed JCDS increases considerably compared with the other previously proposed cooperative diversity techniques.

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