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Joint Cooperative Diversity and Scheduling in OFDMA Relay Systems

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***Abstract*— Motivated by joint cooperative diversity and scheduling (JCDS) in frequency-flat fading relay systems, this paper proposes JCDS for frequency-selective fading relay systems with an OFDMA technique. While JCDS for frequency-flat fading relay systems uses time-varying phase rotation at the relays, JCDS in this paper uses fixed cyclic delay times instead. This technique can be considered as an extension of cyclic delay diversity in a conventional MIMO-OFDM system to a multiuser relay system in order to gain both multipath diversity and multiuser diversity. It is shown that JCDS using fixed cyclic delay has significant gains in aggregate throughput while per-link throughput can be maintained when there are enough relays. The effect of delay spread to the required number of relays and to the throughput performance are shown by simulation.**

I. Introduction

Recently, relay systems and cooperative diversity have drawn enormous attention from the wireless research community [1], [2]. The key idea for cooperative diversity is to exploit spatial diversity from relays or users where each equipped with a single antenna. The diversity can be gained without multiple antennas neither at the source nor at the destination. Amplify-and-forward (AF) typed relay is of special interest since it only retransmits the received signals and thus has a low complexity transceiver [2].

In addition to spatial diversity, there has been an attempt to exploit multiuser diversity in the relay system [3]. Since the users see the channels differently, a scheduler can offer the user whose instantaneous SNR is highest to access the channel. Intuitively, the aggregate throughput of the system can be significantly improved when the number of users is large. If the channel is fast time-varying and users have the same average SNR, each user will have approximately equal chance to access the channel. However, if the channel is slowly time-varying, one user will occupy the channel for a long time while other users have to wait for in order to access the channel. This waiting time might exceed the delay constraint in practical systems. To address this problem, [3] proposed the so-called *joint cooperative diversity and scheduling* (JCDS) that uses the technique from [4] which introduced the technique of time-varying phase rotation at the relays. Originally, the time-varying phase rotation is exploited to generate time diversity from spatial diversity in a single-user relay system. This time-varying phase rotation essentially turns block fading channel into effectively time-varying channels and is necessary in order to achieve diversity when the relays do not know the channel gains from the relays to the destination [5].

The above mentioned technique is designed for frequency-flat fading channels. In frequency-selective channels, the situation is different since in addition to spatial diversity, the system also inherits multipath diversity. In conventional multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) systems, one neat technique in order to exploit multipath diversity is cyclic delay diversity (CDD) [6], [7]. CDD in the time domain results in phase rotation in the frequency domain. With multiple transmit antennas, CDD introduces more fluctuation among the subchannels and an outer coding can exploit this diversity in the frequency domain. One strong advantage of CDD is the fact that there is no change at the OFDM receiver so existing receivers can enjoy spatial diversity only by the change at the transmitter. Compared to space-time coding technique, CDD is also an attractive choice since CDD can be simply applied to any number of transmit antennas without significant complexity or rate loss. In the context of relay systems, some works are found on frequency-selective fading channels. [11] proposed an adaptive cooperative scheme to improve the error performance of an orthogonal frequency division multiple access (OFDMA) relay system while [12] addressed the resource allocation problem in an OFDMA relay system using graph theoretical approach. Recently, [13] proposed distributed delay diversity for an ad hoc wireless relay system and decision feedback equalizer at the receiver. Three equalization techniques which are distributed time-reversal, single-carrier and OFDM for distributed space-time block coding relay systems is proposed in [14].

In this paper, the CDD technique is applied to realize multipath diversity in an OFDM relay system. Instead of using time-varying phase rotation at each relay like [3], we apply a *fixed* cyclic delay at each relay to realize diversity in the frequency domain. With multiple users, each user will see a different channel condition at each subchannel. Thus, the scheduler can provide each subchannel to the user whose SNR is highest in each subchannel. With CDD, the fairness of

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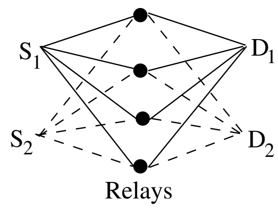

Fig. 1. System model

the channel scheduling is improved. Intuitively, this results in higher aggregate throughput while in order to maintain the quality of service (QOS) of each user, the number of relays must be high enough as will be shown. This work can also be considered as an extension of CDD in an OFDMA system in [9].

The paper is organized as follows. Section II discusses the system model. Section III introduces JCDS for OFDMA relay systems. Section IV shows the simulation results and discussion. Concluding remarks are given in section V.

Notations: Bold letters denote vectors or matrices. $(.)^T, (.)^*$ are transpose and conjugate, respectively. $E[.]$ denotes expectation and diag$(.)$ denotes a diagonal matrix with its arguments as diagonal elements. $|.|$ denotes an absolute value.

II. System Model

The communication system is composed of several source[1] -destination pairs with multiple relays in between. There is no direct path between each source-destination pair. The transmissions take place in two steps: first from sources to relays and second from the relays to destinations. These two step will be referred to as a one transmission cycle. Each source, each destination and each relay has only one antenna. Denote N_γ as the number source-destination pairs and N_μ as the number of relays. Fig. 1 shows an example of $N_\gamma = 2$ and $N_\mu = 4$ system. N_c-point OFDM modulation with guard interval (GI) insertion whose length is greater than the channel order is performed at the source while OFDM demodulation with GI removal is performed at the destination. Each source-destination pair is given a set of subcarriers that can be used from the scheduler who knows all the SNR information of all source-destination pairs. Note that each source transmits at the same time but with different sets of subcarriers, i.e., the transmission system in essentially an OFDMA system. Note also that all relays use the same set of subcarriers that has been given to a specific source to retransmit to its destination.

The channels are frequency-selective Rayleigh fading with the channel order L ($L + 1$ taps). All the channels are independent but are statistically similar. The lth tap channel complex impulse response from the γth source to the μth relay is $h^{\rm sr}_{\gamma,\mu}(l)$ and that from the μth relay to the γth destination is $h^{\rm rd}_{\gamma,\mu}(l)$. Both $h^{\rm sr}_{\gamma,\mu}(l)$ and $h^{\rm rd}_{\gamma,\mu}(l)$ are zero-mean complex Gaussian rv and their variances follow an exponential delay profile such that $E[|h^{\rm sr}_{\gamma,\mu}(l)|^2] = E[|h^{\rm rd}_{\gamma,\mu}(l)|^2] = \frac{e^{-l/\tau_{\rm rms}}}{\sum_{l=0}^{L} e^{-l/\tau_{\rm rms}}}$ where $\tau_{\rm rms}$ is a normalized rms delay spread. We assume the channels are quasi-static, i.e., the channels are constant during one OFDM symbol interval and change independently in the next OFDM symbol interval. We also assume that the relays know channel gains (transfer functions in the frequency domain) from all sources and the destination knows channel gains from its source and relays perfectly. In addition, perfect timing and synchronization are assumed.

[1]The terminologies 'user' and 'source' will be used interchangeably

Let us denote the channel transfer function of the subcarrier p from the γth source to the μth relay as $H^{\rm sr}_{\gamma,\mu}(p)$ and denote the channel transfer function of the subcarrier p from that relay to the destination as $H^{\rm rd}_{\gamma,\mu}(p)$. With these notations, $H^{\rm sr}_{\gamma,\mu}(p) = \sum_{l=0}^{L} h^{\rm sr}_{\gamma,\mu}(l)e^{-j2\pi lp/N_c}$ and $H^{\rm rd}_{\gamma,\mu}(p) = \sum_{l=0}^{L} h^{\rm rd}_{\gamma,\mu}(l)e^{-j2\pi lp/N_c}$.

The function of relays is to retransmit the received signal with the technique presented as follows. The structure of a relay is shown in Fig. 2. Now suppose that the subcarrier p is given to the $\bar{\gamma}$th source-destination pair (the dependent variable p in $\bar{\gamma}$ is omitted for conciseness). First, the relay performs GI removal of the received signal and the received signal is passed to the FFT processor. At the FFT output, the received signal of the pth subcarrier at the μth relay can be written as

$$y^{\rm r}_{\mu}(p) = H^{\rm sr}_{\bar{\gamma},\mu}(p)s_{\bar{\gamma}}(p) + w_\mu(p), \tag{1}$$

where $s_{\bar{\gamma}}(p)$ is a unit-energy symbol transmitted from the $\bar{\gamma}$th source and $w_\mu(p)$ is an independent complex white Gaussian noise at the μth relay. The noise variance at all relays is assumed to be σ_R^2. In order to equalize the transmit power, the received signal is multiplied by a relay gain

$$G_{\bar{\gamma},\mu}(p) = \sqrt{\frac{1}{N_\mu\left(|H^{\rm sr}_{\bar{\gamma},\mu}(p)|^2 + \sigma_R^2\right)}}. \tag{2}$$

This relay gain ensures that the total transmission power from all relays equal to one. After the multiplication, IFFT is performed and thus converts the signal from the frequency domain into the time domain. Next, the relay apply cyclic delay to the signal, i.e., at the μth relay the signal is delayed by Δ_μ and the portion of signal that is beyond the OFDM symbol length is transmitted at the beginning [6]. Notice that this cyclic delay is applied in the time domain. In this paper, a simple choice of Δ_μ is chosen as

$$\Delta_\mu = \text{the integer closest to } \frac{N_c}{N_\mu}\cdot(\mu - 1), \tag{3}$$

although an optimization of Δ_μ's may lead to throughput improvement [8]. Next, GI is inserted before the signal is transmitted from all relays simultaneously. We refer to this relay as an OFDM-AF relay with cyclic delay.

Since a cyclic delay in the time domain corresponds to a phase rotation in the frequency domain, the received signal at

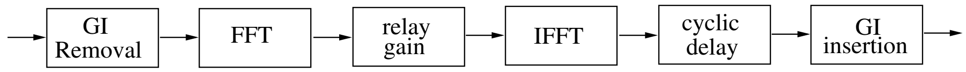

Fig. 2. The structure of a relay

the $\bar{\gamma}$th destination can be written as

$$\begin{aligned} y^{\mathrm{d}}_{\bar{\gamma}}(p) &= \sum_{\mu=1}^{N_\mu} H^{\mathrm{rd}}_{\bar{\gamma},\mu}(p) G_{\bar{\gamma},\mu}(p) y^{\mathrm{r}}_{\mu}(p) e^{-j\frac{2\pi\Delta_\mu p}{N_c}} + w_{\bar{\gamma}}(p) \\ &= \left(\sum_{\mu=1}^{N_\mu} H^{\mathrm{rd}}_{\bar{\gamma},\mu}(p) G_{\bar{\gamma},\mu}(p) H^{\mathrm{sr}}_{\bar{\gamma},\mu}(p) e^{-j\frac{2\pi\Delta_\mu p}{N_c}} \right) s_{\bar{\gamma}}(p) \\ &+ \sum_{\mu=1}^{N_\mu} H^{\mathrm{rd}}_{\bar{\gamma},\mu}(p) G_{\bar{\gamma},\mu}(p) e^{-j\frac{2\pi\Delta_\mu p}{N_c}} w_\mu(p) + w_{\bar{\gamma}}(p), \end{aligned} \tag{4}$$

where $w_{\bar{\gamma}}(p)$ is an independent complex Gaussian noise with variance σ^2 at the destination. Let $\boldsymbol{H}^{\mathrm{sr}}_{\bar{\gamma}}(p) = [H^{\mathrm{sr}}_{\bar{\gamma},1}(p) \dots H^{\mathrm{sr}}_{\bar{\gamma},N_\mu}(p)]^T$, $\boldsymbol{H}^{\mathrm{rd}}_{\bar{\gamma}}(p) = [H^{\mathrm{rd}}_{\bar{\gamma},1}(p) \dots H^{\mathrm{rd}}_{\bar{\gamma},N_\mu}(p)]^T$, $\boldsymbol{G}^{\mathrm{eff}}_{\bar{\gamma}}(p) = \mathrm{diag}\left(G_{\bar{\gamma},1}(p) e^{-j\frac{2\pi\Delta_1 p}{N_c}} \dots G_{\bar{\gamma},N_\mu}(p) e^{-j\frac{2\pi\Delta_{N_\mu} p}{N_c}} \right)$, and $\boldsymbol{w}(p) = [w_1(p) \dots w_{N_\mu}(p)]^T$. (4) can be represented compactly as

$$\begin{aligned} y^{\mathrm{d}}_{\bar{\gamma}}(p) &= \boldsymbol{H}^{\mathrm{sr}}_{\bar{\gamma}}(p)^T \boldsymbol{G}^{\mathrm{eff}}_{\bar{\gamma}}(p) \boldsymbol{H}^{\mathrm{rd}}_{\bar{\gamma}}(p) s(p) \\ &+ \boldsymbol{H}^{\mathrm{rd}}_{\bar{\gamma}}(p)^T \boldsymbol{G}^{\mathrm{eff}}_{\bar{\gamma}}(p) \boldsymbol{w}(p) + w_{\bar{\gamma}}(p). \end{aligned} \tag{5}$$

The last two terms in (5) are noise. Therefore, the SNR at the pth subcarrier can be defined as

$$\mathrm{SNR}_{\bar{\gamma}}(p) = \frac{\left| \boldsymbol{H}^{\mathrm{sr}}_{\bar{\gamma}}(p)^T \boldsymbol{G}^{\mathrm{eff}}_{\bar{\gamma}}(p) \boldsymbol{H}^{\mathrm{rd}}_{\bar{\gamma}}(p) \right|^2}{\sigma^2 + \sigma_R^2 \cdot \boldsymbol{H}^{\mathrm{rd}}_{\bar{\gamma}}(p)^T \boldsymbol{G}^{\mathrm{eff}}_{\bar{\gamma}}(p) \left(\boldsymbol{G}^{\mathrm{eff}}_{\bar{\gamma}}(p) \boldsymbol{H}^{\mathrm{rd}}_{\bar{\gamma}}(p) \right)^*} \tag{6}$$

Note that one can apply the phase rotation in the frequency domain directly (before IFFT is performed). However, using cyclic delay in the time domain is more appealing since it avoids complex multiplication with the received signal at each subcarrier.

III. Joint Cooperative Diversity and Scheduling

In a multiuser system, static scheduling is a conventional way to assign the resource to each user. For the system in this paper, static scheduling means OFDMA which assigns the subcarriers to each user equally in each OFDM symbol. This is the perfectly fair scheduling but the subcarrier resource is not used optimally. Another scheduling scheme is greedy adaptive scheduling which only assigns the channel to the best user. However, without phase rotation at the relays in frequency flat fading channels or without cyclic delay at the relays in the OFDMA relay system, the channels will not change much within one transmission cycle or within one OFDM system. This means only a small number of users or even a single user will have a chance to access the channel in a given transmission cycle or a given OFDM symbol while other users have to wait for the next transmission cycle whose

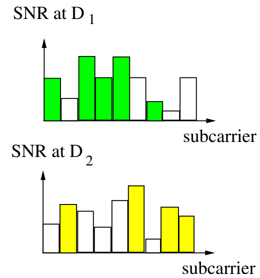

Fig. 3. Scheduling depending on the SNR at each subcarrier at the destination

channel conditions are favorable to them. This leads to an unacceptable outage performance from the user's point of view [3]. In this paper, adding cyclic delay at the relays will cause more channel fluctuation among the subcarriers. Therefore, it is more likely that all users will have a better chance to access the channels and that leads to lower outage from the user's point of view. Assuming an ideal scheduler, JCDS in an OFDMA relay system schedules the pth subcarrier to the source-destination pair whose SNR is highest, i.e.,

$$\bar{\gamma}(p) = \underset{\gamma \in \{1,\dots,N_\gamma\}}{\arg\max}\ \mathrm{SNR}_\gamma(p). \tag{7}$$

An example of JCDS in an OFDMA relay system is shown in Fig. 3. The shaded bars are the scheduled subcarriers

Note that the scheduler only needs to know the SNR at the destinations. There is no need to send channel gains or transfer functions to the scheduler.

A. Performance Measure

We adopt the performance measures from [3]. First, an aggregate throughput is defined as the total throughput of the system. If the aggregate throughput is high, it means the system uses the overall resource efficiently. Suppose we ignore the loss from GI, the aggregate throughput can be written as

$$C_{\mathrm{aggr}} = \frac{1}{2N_c} \sum_{p=0}^{N_C-1} \log_2\left(1 + \mathrm{SNR}_{\bar{\gamma}}(p)\right). \tag{8}$$

The unit of C_{aggr} is in bits per complex dimension. The factor $1/2$ in (8) accounts for the two transmission steps in one transmission cycle as described in section II.

Another performance measure is a per-link throughput which reflects the throughput that a user will experience in a given transmission cycle. The per-link throughput is defined as

$$C_{\text{per-link}} = N_\gamma \cdot \frac{1}{2N_c} \sum_{p \in \mathcal{P}} \log_2\left(1 + \mathrm{SNR}_\gamma(p)\right), \tag{9}$$

where $\mathcal{P}$ is the set of subcarriers that have been scheduled to the γth user. The factor N_γ accounts for a fair comparison

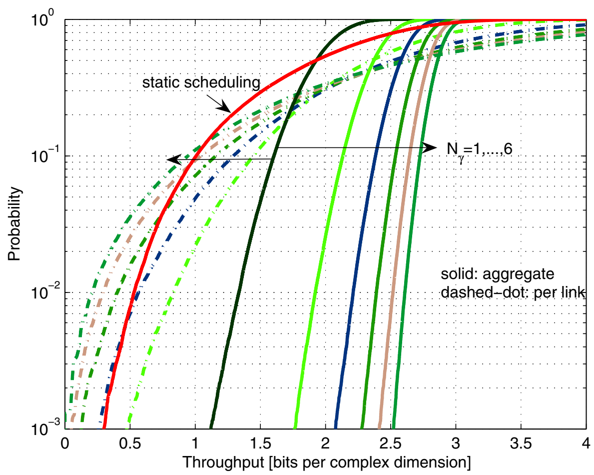

Fig. 4. CDF of aggregate and per-link throughput, $\tau_{\text{rms}} = 0.3$

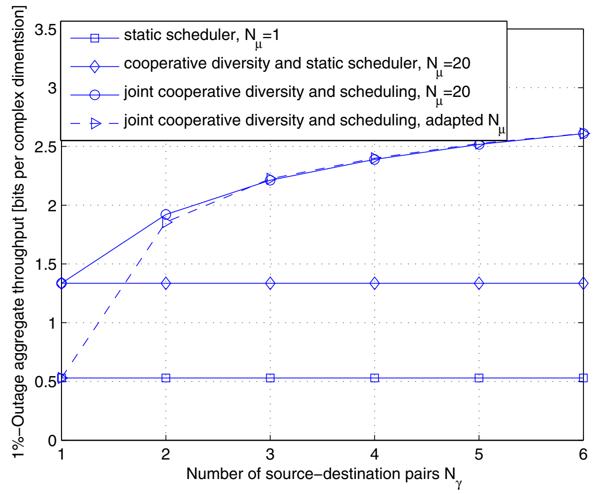

Fig. 5. 1% outage aggregate throughput comparison, $\tau_{\text{rms}} = 0.3$

between systems with different number of users. The per-link throughput is related to the quality-of-service (QOS) of the user that we need to maintain.

The aim of JCDS is to increase the aggregate throughput while maintaining the per-link throughput of each user [3]. We are interested in the outage performance of both performance measures. Specifically, CDF of C_{aggr},$C_{\text{per-link}}$ and 1% outage aggregate throughput will be plotted in the next section. 1% outage aggregate throughput guarantees that 99% of the aggregate throughput will be above the outage value.

IV. Simulation Results and Discussion

We evaluate the system with the number of source-destination pairs $N_\gamma = 1, \ldots, 6$. Two fading scenarios are defined from the parameters τ_{rms}. The first scenario has a relatively short delay spread $\tau_{\text{rms}} = 0.3$ corresponding to $L = 3$ and the second one has a relatively long delay spread $\tau_{\text{rms}} = 1.5$ corresponding to $L = 15$ [10]. The number of subcarriers is $N_c = 256$. We set the average SNR at the relay and at the destination to be the same at 20dB which is equivalent to $\sigma_R^2 = \sigma^2 = 0.01$. Physically, this means the distances from a source to all relays and the distance from all relays to its destination are equal.

Fig. 4 shows the cumulative distribution function (CDF) of the aggregate throughput and per-link throughput with JCDS in the short delay spread scenario. Aggregate throughputs are shown by solid lines while per-link throughputs are shown by dash-dot lines. The number of relays N_μ is fixed at 20. We also include the throughput of static scheduling in which the aggregate and per-link throughput are the same quantity [3]. The throughput value (x-axis) in which the probability (y-axis) is equal to 10^{-2} corresponds to the 1% outage throughput. The slopes of the curves also reflect the overall diversity gain. From Fig. 4, we can see that as the number of users increases, the aggregate throughput curves shift to the right and therefore the aggregate throughput increases. The aggregate throughput increases significantly from $N_\gamma = 1$ to $N_\gamma = 2$ while the gain decreases as N_γ gets higher. In contrast, the per-link throughput decreases as the number of users increases. That means JCDS is harmful to the QOS of each user. If we want to maintain the per-link throughput of JCDS to be at least equal to that of static scheduling, at 1% outage probability, it is seen that only less than or equal to 3 users can be present in the system. This is attributed to the fact that the number of relays is fixed at 20. The fluctuation which JCDS causes in the frequency domain is not enough to accommodate more users in one transmission cycle. As the number of users gets higher, there will be more users remaining in outage within a transmission cycle. As will be seen, if the number of relays is increased when number of users gets higher, JCDS can maintain the per-link throughput to be equal to the static scheduling case since more fluctuation can be generated with higher number of relays.

Fig. 5 shows the 1% outage aggregate throughput performance in the short delay spread scenario. We can see that in the case of cooperative diversity and static scheduling alone (using cyclic delay at the relays and fixed scheduling) already provides throughput improvement over static scheduling. The case of JCDS with fixed $N_\mu = 20$ shows significant throughput gains over the two previous schemes. At $N_\gamma = 6$, JCDS has about 5 times aggregate throughput gain over the static scheduling and about 2 times over the cooperative diversity with static scheduling. To maintain the per-link throughput, aggregate throughput with adapted N_μ is also plotted. The number of relays required to maintain the per-link throughput is shown in Table I. It is seen that the required number of relays increases with the number of users N_γ and is not linear at higher N_γ.

Next, let us consider JCDS in the the long delay spread case. Fig. 6 shows the CDF of the aggregate throughput and per-link throughput with JCDS. The number of relays is again fixed at 20. Similar observation as in Fig. 4 can be made in which the aggregate throughput increases as the number

TABLE I

THE NUMBER OF RELAYS REQUIRED TO MAINTAIN THE PER-LINK THROUGHPUT EQUAL TO STATIC SCHEDULING FOR $N_\gamma = [2\ 3\ 4\ 5\ 6]$

τ_{rms}	number of relays
0.3	[10 20 30 35 40]
1.5	[6 9 12 15 16]

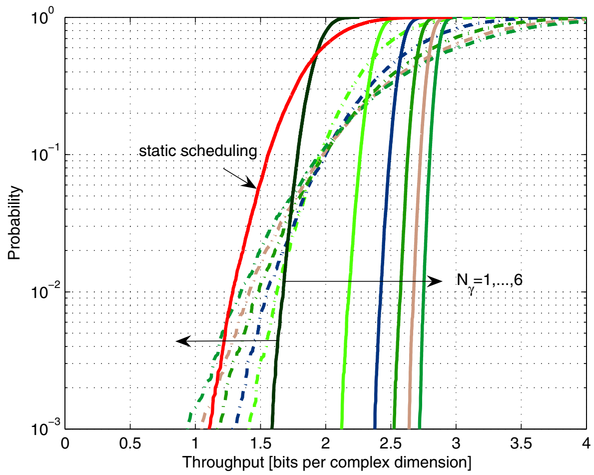

Fig. 6. CDF of aggregate and per-link throughput, $\tau_{\text{rms}} = 1.5$

of users increases while the per-link throughput decreases. Note, however, that with 20 relays, the per-link throughput for $N_\gamma = 6$ already exceeds that of static scheduling at 1% outage throughput. This is because long delay spread alone already creates much fluctuation in the frequency domain in which the system can accommodate more users in one transmission cycle. Therefore, we might speculate a smaller number of required relays to maintain the same per-link throughput as static scheduling. From Table I, we can see that the required number of relays is much lower in the case of long delay spread.

Fig. 7 shows the 1% outage aggregate throughput performance in the long delay spread scenario. The gain of cooperative diversity and static scheduling over static scheduling is smaller in this case. At $N_\gamma = 6$, the gains of the aggregate throughput of JCDS are about 2 times and 1.6 times over static scheduling and cooperative diversity and static scheduling, respectively.

V. CONCLUDING REMARKS

This paper applies the idea of cyclic delay diversity at the relays in order to achieve joint cooperative diversity and scheduling in OFDMA relay systems. Compared with the existing technique which uses time-varying phase at the relays in frequency flat fading channels, this paper applies fixed cyclic delay at the relays in frequency selective fading channels. Simulation results show that significant gain in aggregate throughput is achieved with higher number of users while we can maintain the QOS of each user when there is

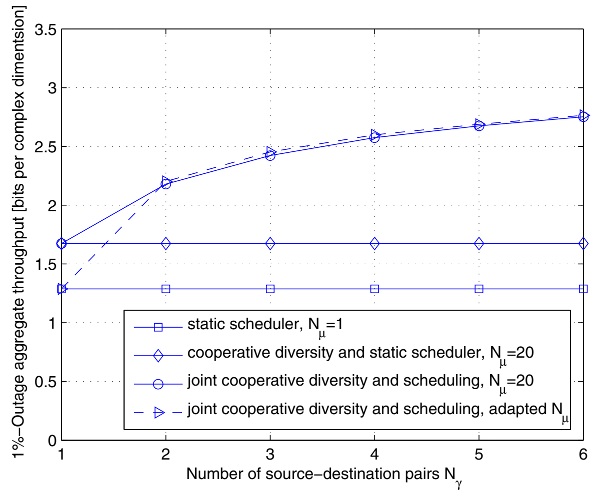

Fig. 7. 1% outage aggregate throughput comparison, $\tau_{\text{rms}} = 1.5$

sufficient number of relays. The results also show that in long delay spread channels, the required number of relays is smaller than in the short delay spread channels.

REFERENCES

[1] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity–Part I: System description," *IEEE Trans. Commun.,* vol. 51, pp. 1927-1938, Nov. 2003.

[2] J.N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inform. Theory,* vol. 50, pp. 3062-3080, Dec. 2004.

[3] A. Wittneben, I. Hammerström and M. Kuhn, "Joint cooperative diversity and scheduling in low mobility wireless networks," in Proc. *IEEE Globecom,* vol. 2, pp. 780-784, 29 Nov.-3 Dec 2004.

[4] I. Hammerström, M. Kuhn and A. Wittneben, "Cooperative diversity by relay phase rotations in block fading environments," in Proc. *Fifth IEEE Workshop on Signal Processing Advances in Wireless Communications,* pp. 293-297, July 2004.

[5] I. Hammerström, M. Kuhn and A. Wittneben, "Impact of relay gain allocation on the performance of cooperative diversity networks," in Proc. *IEEE Fall VTC 2004,* vol. 3, pp. 26-29, Sept. 2004.

[6] K. Witrisal, Y.-H. Kim, R. Prasad, and L.P. Ligthart, "Antenna diversity for OFDM using cyclic delays," in Proc. *8th Symp. on Commun. and Veh. Tech. (SCVT-2001),* pp. 13-17, Oct. 2001.

[7] A. Dammann and S. Kaiser, "Standard conformable antenna diversity techniques for OFDM systems and its application to the DVB-T system," in Proc. *IEEE Globecom,* pp. 3100-3105, Nov. 2001.

[8] G. Bauch, "Capacity optimization of cyclic delay diversity," in Proc. *IEEE VTC2004-Fall,* vol. 3, pp. 1820-1824, Sept. 2004.

[9] G. Bauch, "Orthogonal frequency division multiple access with cyclic delay diversity," in Proc. *ITG Workshop on Smart Antennas,* pp. 17-24, Mar. 2004.

[10] K. Witrisal, "OFDM air-interface design for wireless multimedia communications," *Ph.D. Dissertation,* Delft University of Technology, Apr. 2002.

[11] P.A. Anghel and M. Kaveh, "Relay assisted uplink communication over frequency-selective channels," in Proc. *Fourth IEEE Workshop on SPAWC,* pp. 125-129, 15-18 June 2003.

[12] G. Li and H. Liu, "Resource allocation for OFDMA relay networks," in Proc. *38th Asilomar Conf. on Signals, Systems and Computers,* vol. 1, pp. 125-129, Nov. 2004.

[13] S. Wei, D.L. Goeckel and M.C. Valenti, "Asynchronous cooperative diversity," *IEEE Trans. Wireless Commun.,* vol. 5, pp. 1547-1557, June 2006.

[14] H. Mheidat and M. Uysal, "Equalization techniques for space-time coded cooperative systems," in Proc. *IEEE VTC2004-Fall,* pp. 1708-1712, Sept. 2004.