The Resource-Optimized Differentially Modulated Hybrid AF/DF Cooperative Cellular Uplink Using Multiple-Symbol Differential Sphere Detection

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***Abstract*—In multiuser cellular uplinks, cooperating mobiles may share their antennas in order to achieve transmit diversity by formig a virtual antenna array (VAA) in a distributed fashion. In this paper, based on the minimum BER criterion, we investigate cooperating-user-selection (CUS) and adaptive-power-allocation (APA) for two types of differentially modulated cooperative cellular uplinks requiring no channel state information (CSI) at the receiver, namely, for the differential-amplify-and-forward (DAF) and the selective differential-decode-and-forward (DDF) assisted systems. They both employ multiple-symbol differential sphere detection (MSDSD) to combat rapid-fading-induced performance degradation. More specifically, we investigate the cooperative-protocol-selection (CPS) of the uplink system in conjunction with a beneficial CUS as well as the APA scheme in order to further improve the achievable end-to-end performance, leading to a resource-optimized hybrid AF/DF cooperative system.**

***Index Terms*—Cooperative cellular uplink, cooperative resource optimization, , hybrid cooperative protocol, multiple-symbol differential sphere detection.**

I. Introduction

MULTIPLE antenna aided diversity techniques [1] substantially mitigate the deleterious effects of fading, hence improving the end-to-end system performance, which is usually achieved by multiple co-located antenna elements at the transmitter and/or receiver. However, it is often impractical for the mobile to employ a large number of antennas for the sake of achieving a diversity gain due to its limited size. Fortunately, in multi-user wireless systems cooperating mobiles may share their antennas in order to achieve uplink transmit diversity by forming a *virtual antenna array* (VAA) in a distributed fashion [2], [3]. On the other hand, in order to avoid channel estimation for a VAA-aided system, which may impose both an excessive complexity and a high pilot overhead, especially in mobile environments associated with relatively rapidly fluctuating channel conditions, differentially encoded transmissions combined with non-coherent detection requiring no channel state information (CSI) at the receiver becomes an attractive design alternative, leading to differential modulation assisted cooperative communications [4].

Manuscript received May 01, 2009; revised July 02, 2009. First published July 14, 2009; current version published August 26, 2009. This work was supported by the EPSRC as part of the Core 4 Research Programme of the Virtual Centre of Excellence in Mobile and Personal Communications. The associate editor coordinating the review of this manuscript and approving it for publication was Dr. Min Dong.

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Digital Object Identifier 10.1109/LSP.2009.2027661

It is widely recognized that a full spatial diversity can be achieved by the differentially modulated cooperative system employing either the differential-amplify-and-forward (DAF) [4] or the selective differential-decode-and-forward (DDF) protocol [2]. Recently, cooperative resource optimization, in terms of the power allocation and the relay selection, was proposed in [5] for cooperative systems based on the outage probability criterion. By contrast, in this paper, an appropriate cooperative-protocol-selection (CPS) as well as a matching cooperative resource allocation are proposed based on a minimum bit error rate (BER) criterion for the differentially modulated cooperative uplink, where multiple cooperating mobile stations (MSs) are roaming in the area between a specific MS and the base station (BS), in order to achieve a desirable end-to-end BER performance.

II. System Model

As depicted in Fig. 1, we consider a U-user cooperation-aided cellular uplink system, where signal transmission involves the broadcast phase-I and the relay phase-II. In both phases, any of the well-established multiple access schemes can be employed by the users to guarantee orthogonal transmission among them. In this paper, TDMA is considered for the sake of simplicity. Furthermore, due to the symmetry of channel allocation among users, we focus our attention on the information transmission of the source MS seen in Fig. 1, which potentially employs $\mathcal{P}_{\rm cand} = (U-1)$ relay stations (RSs) in order to achieve cooperative diversity. Without loss of generality, we simply assume the employment of a single antenna for each terminal, and a unity total power P shared by the collaborating mobiles for transmitting a symbol. Thus, by assuming that M_r RSs are activated out of a total of $\mathcal{P}_{\rm cand}$, we have $P = P_s + \sum_{m=1}^{M_r} P_{r_m}$, where P_s and P_{r_m} $(m = 1, 2, \ldots, M_r)$ are the transmit power employed by the source MS and the mth RS, respectively. For the sake of simple analytical tractability, we assume that the sum of the distances D_{sr_u} between the source MS and the uth RS, as well as that between the uth RS and the BS, which is represented by D_{r_ud}, is equal to the distance D_{sd} between the source MS and the BS. Furthermore, by considering a path-loss exponent of v[6] (we use $v = 3$ to simulate a typical urban area), the average normalized channel power gain $\sigma_{i,j}^2$ at the output of the channel can be computed according to the inter-node distance $D_{i,j}$ as $\sigma_{i,j}^2 = D_{i,j}^{-v}$, $i, j \in \{s, r_u, d\}$.

Differential modulation is employed to avoid channel estimation at both the RS and the BS. For the sake of mitigating the impairments imposed by the time-selective channels on the differential transmission, packet-based user-cooperation is carried out. Thus, the source MS broadcasts a packet constituted of L_p DPSK symbols during phase-I, while the BS and the RSs

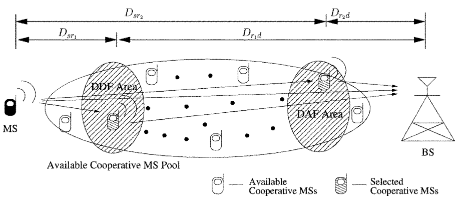

Fig. 1. Cooperation-aided cellular uplink using cooperating-user-selection.

receive and store it. In the ensuing phase-II, the DAF or the selective DDF scheme is employed by the RSs, which is the differentially modulated version of the protocol of [2]. Finally, in order to mitigate the performance degradation induced by the mobility of the RSs, multiple-symbol differential sphere detection (MSDSD) [7], [8] is employed at all the terminals in our cooperative cellular uplink scenario.

III. Performance Analysis

It was demonstrated in [7], [8] that the performance of the cooperative system employing the MSDSD in a challenging rapidly-fading environment closely approaches that achieved by its conventional differential detection (CDD) aided counterpart in a more benign slow-fading channel, provided that the observation window size N_{wind} is sufficiently high. Hence, in the ensuing subsections our performance analysis of both the DAF- and DDF-aided systems employing the MSDSD in rapidly-fading channels may be interpreted as the performance analysis of a CDD-assisted differentially modulated cooperative system operating in slow-fading channels.

A. Theoretical Analysis of the DDF-Aided Cooperative Uplink

In the selective DDF-aided cooperative uplink, some of the M_r RSs may not actively participate in the relaying phase for the sake of avoiding the potential error propagation imposed by the error-infested imperfect signal recovery. By simply assuming that the transmission packet length is sufficiently high with respect to the channel's coherent time, the worst-case packet loss ratio (PLR) at the mth RS can be expressed as

$$P_{\mathrm{PLR}_m}^{\mathrm{upper}} = 1 - (1 - P_{\mathrm{SER}_m})^{L_p} \tag{1}$$

for a given packet length L_p, where the symbol error rate (SER) P_{SER_m} at the mth RS can be calculated as [9]

$$P_{\mathrm{SER}_m} = \frac{M-1}{M} + \frac{|\rho_m| \tan(\frac{\pi}{M_c})}{\xi(\rho_m)} \left[\frac{1}{\pi} \arctan\left(\frac{\xi(\rho_m)}{|\rho_m|}\right) - 1\right] \tag{2}$$

where ρ_m and the function $\xi(x)$ can be written as $\rho_m = (P_s\sigma_{sr_m}^2/N_0)/\left(1 + P_s\sigma_{sr_m}^2/N_0\right)$ with N_0 denoting the noise variance, and $\xi(x) = \sqrt{1 - |x|^2 + \tan^2(\pi/M)}$, respectively. Then, based on the $P_{\mathrm{PLR}_m}^{\mathrm{upper}}$ expression of (1), the average end-to-end BER upper bound of a DDF-aided cooperative system can be obtained. For simplicity, we consider the system where only $M_r = 1$ cooperating user is activated to parcipate in relaying the signal from the source MS to the BS as an example. Under the assumption that the BS combines the signals received from all the M_r RSs as well as that from the direct link, the conditional end-to-end BER, $P_{\mathrm{BER}|\gamma^b}^{\mathrm{DDF}}$, is upper-bounded by the

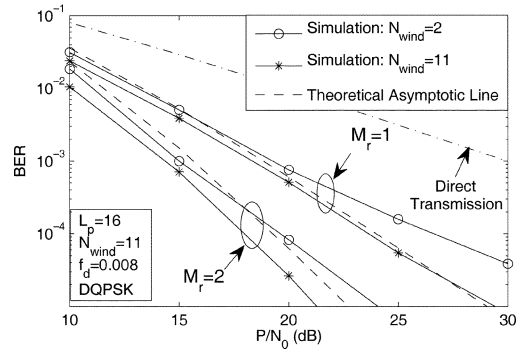

Fig. 2. BER performance of the DQPSK modulated selective DDF-aided cooperative cellular systems having M_r activated RSs in a Rayleigh fading channel associated with $f_d = 0.008$ and $v = 3$.

weighted summation of the two-component conditional BERs corresponding to the scenarios Φ_1^1 and Φ_2^1 as[1]

$$P_{\mathrm{BER}|\gamma^b}^{\mathrm{DDF}} \gtrapprox (1 - P_{\mathrm{PLR}_1}^{\mathrm{upper}}) P_{\mathrm{BER}|\gamma_{\Phi_1^1}^b}^{\Phi_1^1} + P_{\mathrm{PLR}_1}^{\mathrm{upper}} P_{\mathrm{BER}|\gamma_{\Phi_2^1}^b}^{\Phi_2^1} \tag{3}$$

where

$$P_{\mathrm{BER}|\gamma_{\Phi_i^1}^b}^{\Phi_i^1} = \frac{1}{2^{2L}\pi} \int_{-\pi}^{\pi} f(a, b, M_r + 1, \theta) e^{-\alpha(\theta)\gamma_{\Phi_i^1}^b} d\theta \tag{4}$$

in which

$$f(a, b, L, \theta) = \frac{b^2}{2\alpha(\theta)} \sum_{l=1}^{L} \binom{2L-1}{L-l} \left[(\beta^{-l+1} - \beta^{l+1}) \times \cos\left((l-1)\left(\theta + \frac{\pi}{2}\right)\right) - (\beta^{-l+2} - \beta^l) \cos\left(l\left(\theta + \frac{\pi}{2}\right)\right)\right]. \tag{5}$$

Additionally, we have $\alpha(\theta) = b^2(1 + 2\beta\sin\theta + \beta^2)/2$ and $\beta = a/b$, where the parameters a and b are the modulation-dependent factors defined in [10].

On the other hand, since in our performance analysis the maximum-ratio-combining (MRC) scheme is assumed to be employed at the BS to combine the signals potentially forwarded by multiple RSs and the signal transmitted from the source MS prior to the CDD, the received SNR per bit after the MRC stage is simply the sum of that of each combined path, which is expressed as

$$\gamma_{\Phi_1^1}^b = \gamma_{sd}^b + \gamma_{r_1 d}^b, \quad \gamma_{\Phi_2^1}^b = \gamma_{sd}^b. \tag{6}$$

Therefore, the unconditional BER of the scenario Φ_1 can be computed by averaging the conditional BER over the fading distribution of the SNR per bit at the output of the MRC with the aid of its PDF $p_{\gamma_{\Phi_1^1}^b}(\gamma)$ as follows [11]:

$$P_{\mathrm{BER}}^{\Phi_1^1} = \int_{-\infty}^{\infty} P_{\mathrm{BER}|\gamma_{\Phi_1^1}^b} \cdot p_{\gamma_{\Phi_1^1}^b}(\gamma) d\gamma \tag{7}$$

$$= \frac{1}{2^{2L}\pi} \int_{-\pi}^{\pi} f(a, b, L = 2, \theta) \mathcal{M}_{\gamma_{\Phi_1^1}^b}(\theta) d\theta \tag{8}$$

[1]More explicitly, Φ_1^m is defined as the first scenario, when the mth activated RS perfectly recovers the information received from the source MS and thus transmits the differentially remodulated signal to the BS. By contrast, Φ_2^m is defined as the second scenario, when the mth activated RS fails to correctly decode the signal received from the source MS and hence remains silent during the relaying phase

where the joint MGF of the received SNR per bit recorded at the BS for the scenario Φ_1^1 under the assumption of Rayleigh fading channels is expressed as

$$\begin{aligned}\mathcal{M}_{\gamma^b_{\Phi_1^1}}(\theta) &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{-\alpha(\theta)(\gamma^b_{sd}+\gamma^b_{r_1d})} p_{\gamma^b_{sd}}(\gamma_{sd}) p_{\gamma^b_{r_1d}}(\gamma_{r_1d}) d\gamma_{sd} d\gamma_{r_1d} \\ &= \frac{N_0^2}{\left[(N_0+\alpha(\theta)P_s\sigma^2_{sd})(N_0+\alpha(\theta)P_{r_1}\sigma^2_{r_1d})\right]} \qquad (9)\end{aligned}$$

with $p_{\gamma^b_{sd}}(\gamma_{sd})$ and $p_{\gamma^b_{r_1d}}(\gamma_{r_1d})$, respectively, denoting the PDF of the received SNR per bit for the direct link and for the relay-to-destination link. In parallel, the unconditional BER of the scenario Φ_2^1 can be obtained as

$$\begin{aligned}P_{\mathrm{BER}}^{\Phi_2^1} &= \int_{-\infty}^{\infty} P_{\mathrm{BER}|\gamma^b_{\Phi_2^1}} \cdot p_{\gamma^b_{\Phi_2^1}}(\gamma) d\gamma \qquad (10) \\ &= \frac{1}{2^{2L}\pi}\int_{-\pi}^{\pi} f(a,b,L=1,\theta)\mathcal{M}_{\gamma^b_{\Phi_2^1}}(\theta) d\theta \qquad (11)\end{aligned}$$

where the MGF of the received SNR per bit recorded at the BS for the scenario Φ_2 is written as

$$\mathcal{M}_{\gamma^b_{\Phi_2^1}}(\theta) = \int_{-\infty}^{\infty} e^{-\alpha(\theta)\gamma^b_{sd}} p_{\gamma^b_{sd}}(\gamma_{sd}) d\gamma_{sd} = \frac{N_0}{N_0+\alpha(\theta)P_s\sigma^2_{sd}}. \qquad (12)$$

Finally, in the light of (3), the unconditional worst-case end-to-end BER can be computed as

$$P_{\mathrm{BER}}^{\mathrm{DDF}} \lessapprox (1-P_{\mathrm{PLR}_1}^{\mathrm{upper}})P_{\mathrm{BER}}^{\Phi_1^1} + P_{\mathrm{PLR}_1}^{\mathrm{upper}} P_{\mathrm{BER}}^{\Phi_2^1}. \qquad (13)$$

Similarly, the BER upper bound can also be attained for the selective DDF-aided system using $M_r > 1$ RSs. For example, when $M_r = 2$, the end-to-end BER is upper-bounded by the sum of the average BERs of four scenarios as

$$\begin{aligned}&P_{\mathrm{BER}}^{\mathrm{DDF}} \\ &\lessapprox (1-P_{\mathrm{PLR}_1}^{\mathrm{upper}})(1-P_{\mathrm{PLR}_2}^{\mathrm{upper}})P_{\mathrm{BER}}^{\Phi_{11}} + P_{\mathrm{PLR}_1}^{\mathrm{upper}}(1-P_{\mathrm{PLR}_2}^{\mathrm{upper}})P_{\mathrm{BER}}^{\Phi_{21}} \\ &\quad + (1-P_{\mathrm{PLR}_1}^{\mathrm{upper}})P_{\mathrm{PLR}_2}^{\mathrm{upper}}P_{\mathrm{BER}}^{\Phi_{12}} + P_{\mathrm{PLR}_1}^{\mathrm{upper}}P_{\mathrm{PLR}_2}^{\mathrm{upper}}P_{\mathrm{BER}}^{\Phi_{22}} \qquad (14)\end{aligned}$$

where the four scenarios are defined as $\Phi_{11} = \{\Phi_1^1, \Phi_1^2\}$, $\Phi_{21} = \{\Phi_2^1, \Phi_1^2\}$, $\Phi_{12} = \{\Phi_1^1, \Phi_2^2\}$, $\Phi_{22} = \{\Phi_2^1, \Phi_2^2\}$.

It is not unexpected, as revealed by Fig. 2, that the resultant asymptotic line may not accurately approximate the true BER performance of a DDF-aided system employing the CDD in a rapidly fading environment, but nonetheless, adequately captures the dependency of the BER on the P/N_0 ratio for systems employing the MSDSD associated with $N_{\mathrm{wind}} > 2$.

B. Theoretical Analysis of the DAF-Aided Cooperative Uplink

Since the theoretical BER expression of the DAF-aided cooperative system employing the MRC and CDD schemes has already been derived in [12], we will not repeat the detailed derivation here, we simply provide the final result as follows:

$$P_{\mathrm{BER},high-snr}^{\mathrm{DAF}}(a,b,M_r) \lessapprox \frac{F(a,b,M_r+1)N_0^{M_r+1}}{P_s\sigma^2_{sd}} \times \prod_{m=1}^{M_r} \frac{P_{r_m}\sigma^2_{r_m,d} + P_s\sigma^2_{sr_m}Z_{r_m,min}}{P_sP_{r_m}\sigma^2_{sr_m}\sigma^2_{r_md}} \qquad (15)$$

where $F(a,b,L)$ and $Z_{r_m,min}$ are given by [12, eq. (20) and eq. (22)], respectively.

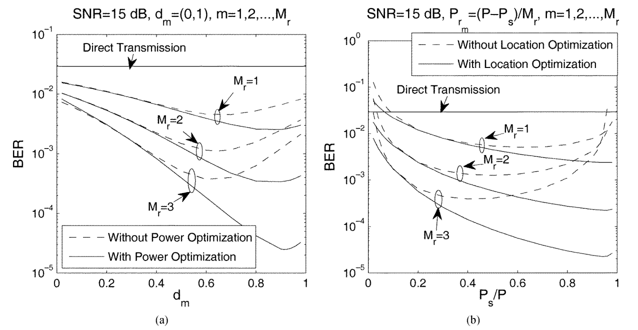

Fig. 3. Power and RS location optimization for DQPSK modulated DAF-aided cooperative cellular systems having M_r activated RSs in a Rayleigh fading channel associated with $v = 3$. The BER was computed from (15). (a) Adaptive power allocation. (b) Relay location optimization.

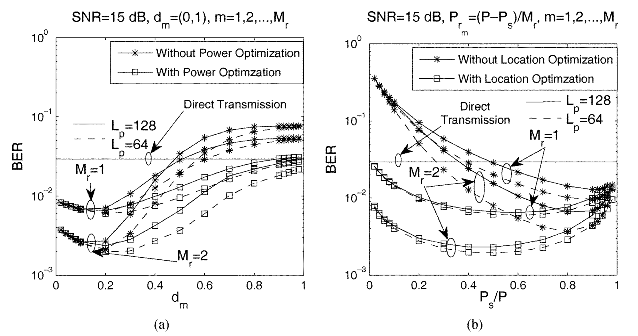

Fig. 4. Power and RS location optimization for the DQPSK modulated DDF-aided cooperative cellular systems having M_r activated RSs in a Rayleigh fading channel associated with $v = 3$. The BER was computed from (13). (a) Adaptive power allocation. (b) Relay location optimization.

IV. Resource-Optimized Differentially Modulated Hybrid Cooperative Cellular Uplink

A. Resource Optimization for the Cooperative Uplink

With the aid of the theoretical BER bound expressions of (13) and (15) derived for the DDF- and DAF-assisted cooperative uplinks, respectively, both the transmit power and the RS locations can be optimized by using the minimum BER criterion. Specifically, the optimized location of the cooperating users, expressed in terms of the normalized distance $d_m = D_{sr_m}/D_{sd}, (m = 1, 2, \ldots, M_r)$ between the source MS and the RS, which is the one minimizing (13) or (15), can be found numerically for a given power allocation $c_m = P_{r_m}/P_s$, and vice versa. Hence, in order to attain the globally optimum location, an iterative power-versus-RS-location optimization process can be performed. Based on the observation that the achievable BER is proportional to the distance between the RS and the optimum location, as indicated in Figs. 3(a) and 4(a), our proposed cooperating-user-selection (CUS) scheme simply chooses the available MS roaming closest to the off-line-computed optimum location. Then the adaptive-power-allocation (APA) is carried out accordingly.

B. Comparison of the DAF- and DDF-Aided Uplinks

Observe in Figs. 3 and 4 that significant performance gains can be achieved by the APA or CUS scheme for both the DAF- and DDF-aided systems. Owing to lack of space, our observations are summarized in a comparative manner in Table I.

TABLE I
COMPARISON BETWEEN THE DAF- AND DDF-AIDED COOPERATIVE CELLULAR UPLINKS WITH REFERENCE TO FIGS. 3 AND 4

	DAF-Aided Uplink	DDF-Aided Uplink
Overall Performance	Better when SR link quality is poor	Better when SR link quality is good
Overall Complexity	Relatively low, no decoding at RSs	Relatively high, decoding and re-encoding at RSs
Performance's Sensitivity to Source-Relay Link Quality	Relatively moderate	Strong
Performance's Sensitivity to Packet Length L_p	Insensitive	Strong without CUS, minor with CUS
Desirable RS Locations	Near the BS	Near the source MS
Desirable Transmit Power for the Source MS	About 88% of the total power	About 60% of the total power
Worst Case Performance (Bad Resource Allocation)	Slightly better than the non-cooperative system	Signi cantly worse than the non-cooperative system
Importance of CUS and APA	Equally important	CUS is signi cantly more important

TABLE II
RESOURCE ALLOCATION FOR THE HYBRID COOPERATIVE UPLINK

M_r	P/N_0 (dB)	$[P_s,\ P_{r_1},\ P_{r_{M_2}}]$	$[d_1,\ d_2]$
2	10	$[0.702,\ 0.202,\ 0.096]$	$[0.26,\ 0.86]$
	20	$[0.702,\ 0.202,\ 0.096]$	$[0.31,\ 0.86]$
	30	$[0.702,\ 0.202,\ 0.096]$	$[0.31,\ 0.91]$

C. Resource-Optimized Hybrid Cooperative Cellular Uplink

In the light of the complementarity of the two relaying mechanisms as revealed by their comparison in Section IV-B, a more flexible cooperative scenario can be created in order to enhance the performance, where the cooperating MSs roaming in different areas between the source MS and the BS may be activated and the relaying schemes employed by each activated RS may be adaptively selected, while maintaining a moderate complexity. For the sake of simplicity, let us now consider the hybrid cooperative cellular uplink employing the joint CPS and CUS scheme, as portrayed in Fig. 1, where $M_r = 2$ cooperating MSs roaming in the preferred DDF- and DAF-RS-area are activated. The particular cooperative protocol employed by the activated RSs is determined according to the specific area which they happen to be situated in. In order to make the most of the complementarity of the DAF and DDF schemes, it may be assumed that one of the cooperating MSs is activated in the preferred area of the DAF-RS, while the other from the "DDF-area", although naturally, there may be more than one cooperating MSs roaming within a specific desirable area. Then, under the assumption that the first selected cooperating MS is roaming in the "DDF-area", while the second one is roaming in the 'DAF-area' of Fig. 1, the cooperative resource allocation is optimized as shown in Table II based on the minimum BER criterion. Due to lack of space, the derivation of the theoretical BER for the hybrid cooperative system is omitted, which is similar to that in Section III. As expected, Table II reveals that the "DDF-area" and the "DAF-area" are still located in the vicinity of the source MS and the BS, respectively. Additionally, the majority of the total transmit power, i.e., about 70%, should be allocated to the source MS, while $2/3$ of the remaining power should be assigned to the cooperating MS roaming in the "DDF-area".

The BER performance of our proposed hybrid cooperative cellular uplink, where $M_r = 2$ out of $\mathcal{P}_{\text{cand}} = 8$ cooperating MSs are activated, is portrayed in comparison to that of its DAF- and DDF-aided counterparts in Fig. 5. Remarkably, as demonstrated by Fig. 5, the hybrid cooperative system outperforms both the DAF- and DDF-aided systems across a wide SNR range of our interest, regardless of whether the joint-CPS-CUS-APA scheme is employed.

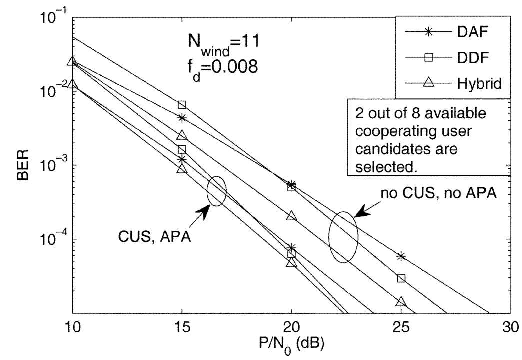

Fig. 5. Performance improvement by the joint CPS and CUS for the DQPSK modulated user-cooperative cellular uplink employing the MSDSD in a Rayleigh fading channel associated with $f_d = 0.008$ and $v = 3$, where two out of eight cooperating user candidates are activated.

V. CONCLUSION

In this paper, the theoretical performance analysis of both the DAF- and selective DDF-aided cooperative systems was first carried out, based on which we investigated the resource allocation of the DAF- and selective DDF-aided cooperative cellular uplinks in a comparative way. For the sake of enhancing the achievable end-to-end performance, a resource-optimized hybrid cooperative system was proposed by exploring the complementarity of the DAF and DDF schemes.

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