by putting $y = 1 + \bar{\gamma}_i x$

$$= \int_{1+\bar{\gamma}_i \eta_{\rm th}}^{\infty} \log_2(y) \left(1 - e^{\eta_{\rm th} - \frac{y-1}{\bar{\gamma}_i}}\right)^n e^{\eta_{\rm th} - \frac{y-1}{\bar{\gamma}_i}} \times \frac{1}{\bar{\gamma}_i} \, dy$$

using the binomial theorem

$$= \sum_{r=0}^{n} \binom{n}{r} \frac{(-1)^r e^{(r+1)\left(\eta_{\rm th} + \frac{1}{\bar{\gamma}_i}\right)}}{\bar{\gamma}_i \ln 2} \int_{1+\bar{\gamma}_i \eta_{\rm th}}^{\infty} \ln(y) e^{-\frac{r+1}{\bar{\gamma}_i} y} \, dy$$

by integration by parts

$$= \sum_{r=0}^{n} \binom{n}{r} \frac{(-1)^r}{(r+1)\ln 2} \left[\ln(1 + \bar{\gamma}_i \eta_{\rm th}) + e^{(r+1)\left(\eta_{\rm th} + \frac{1}{\bar{\gamma}_i}\right)} \times E_1\left((r+1)\left(\eta_{\rm th} + \frac{1}{\bar{\gamma}_i}\right)\right)\right]$$

where $E_1(x) = \int_{x}^{\infty} \frac{e^{-t}}{t} \, dt$

$$Q_n(\eta_{\rm th}, \bar{\gamma}_i) = \frac{\partial I_n(\eta_{\rm th}, \bar{\gamma}_i)}{\partial \eta_{\rm th}} = \sum_{r=0}^{n} \binom{n}{r} \frac{(-1)^r}{\ln 2} e^{(r+1)\left(\eta_{\rm th} + \frac{1}{\bar{\gamma}_i}\right)} \times E_1\left((r+1)\left(\eta_{\rm th} + \frac{1}{\bar{\gamma}_i}\right)\right).$$

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Two-Hop Opportunistic Scheduling in Cooperative Cellular Networks

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***Abstract*—Due to the tradeoff between capacity and fairness in a wide variety of networks, increasing one objective may deteriorate the other. This paper investigates the possibility of improving capacity and fairness at the same time, specifically in two-hop cellular networks. First, we prove that an achievable capacity region can be enlarged by using relay, i.e., the capacity and fairness tradeoff relationship is alleviated. To achieve the Pareto-efficient boundary of this enlarged capacity region, an appropriate scheduling algorithm should be developed. Thus, second, we propose a generalized opportunistic scheduling algorithm for relaying mode that can improve both capacity and fairness. Furthermore, we propose a heuristic algorithm with low complexity and signaling overhead for relaying mode. Extensive simulations under various configurations demonstrate that the proposed algorithm not only increases the throughput of each user but also effectively alleviates unfairness among users.**

***Index Terms*—Capacity, cellular networks, cooperative relaying, fairness, opportunistic scheduling.**

I. Introduction

Multihop relaying has emerged as a promising technique in wireless networks, and there has been an upsurge of interest in deploying relays into legacy cellular systems, such as IEEE 802.16j [2]. The rationale of relays is that the path loss can be significantly reduced by breaking a long (or weak) single-hop link into several short (or strong) multihop links. Along with the fundamental analysis of the relaying system [3], several practical applications have been widely studied.

For capacity enhancement, the optimal relay deployment strategies [4] and several resource allocation algorithms for relaying [5], [7] have been proposed in cellular networks. Coverage extension (i.e., filling coverage holes due to shadowing and overcoming low signal-to-interference-plus-noise ratio at cell edges) has also been investigated in mobile relaying [6]. Cooperative relaying has attracted much attention as an effective technique [8], [9] to improve end-to-end throughput since it can perform like multiple-input–multiple-output techniques, even without multiple antennas, which require additional costs at a terminal. In [11], the authors developed an analytical model for the two-hop mobile relay to capture the relationship between capacity and probability of out-of-coverage. Although many studies have been focused on the improvement of capacity and coverage of cellular

Manuscript received June 7, 2011; revised May 15, 2012; accepted June 20, 2012. Date of publication July 23, 2012; date of current version November 6, 2012. This work was supported in part by the Defense Acquisition Program Administration and Agency for Defense Development. This paper was presented in part at the IEEE Global Communications Conference (GLOBECOM) 2007, Washington, DC, November 26–30. The review of this paper was coordinated by Dr. D. Zhao.

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Digital Object Identifier 10.1109/TVT.2012.2209691

networks by relaying [4]–[9], [11], very few attempts have been made for comprehensive analysis of the relaying effect on the capacity and fairness tradeoff relationship, i.e., increasing one objective may deteriorate the other.

There exists a scheduler that provides flexible tradeoff between capacity and fairness [12], but it is applicable only in the cellular system without relaying. In [5], authors provide a resource allocation algorithm considering throughput and fairness for downlink OFDMA cellular fixed-relay networks, but it achieves fair behavior just by stabilizing user queues in a special case such as all users having the same mean arrival rates and the same quality-of-service requirements. In this paper, we systematically analyze that enabling a relay functionality in each mobile station (MS)[1] can enlarge an achievable capacity region, which results in the alleviation of tradeoff between capacity and fairness in cellular networks. Thereafter, we propose an optimal relay selection and opportunistic scheduling algorithm that can achieve the Pareto-efficient boundary of this enlarged capacity region. Furthermore, we propose a heuristic algorithm with low computational complexity and signaling overhead for relaying.

II. System Model

Network Model: We consider a wireless cellular network of one base station (BS) and multiple MSs. Denote by $\mathcal{K}$ a set of MSs in the cell. All MSs are assumed to cooperate with each other and can relay others' data packets. In this approach, relaying is performed by a direct communication between two MSs via mobile-to-mobile connection [6], [10], [11] without an installation of fixed relay stations. A single broadband channel is shared by all MSs in a time-division multiple-access manner, i.e., there can be at most one user's transmission in a cell at each time slot. A full buffer traffic model, in which there are infinite data packets in the queue for each user, is used for best-effort traffic. It is worthwhile mentioning that our model can be applied to both uplink and downlink cases.

At the beginning of the time slot, the BS receives a direct channel gain g_k^D between the BS and each MS k and a relay channel gain vector $G_k^R = [g_{1k}^R, \ldots, g_{Kk}^R]$ from each MS k, where g_{ik}^R is the relaying channel gain between the relay node, MS i, and MS k. Channels may be time varying and modeled by some stationary ergodic random process with finite state index set $\mathcal{M}$. We assume that channel gains are constant during a time slot but may be varying over time slots. In each time slot t, both direct channel gains between the BS and MSs and relaying channel gains among MSs are one of the possible channel states $m \in \mathcal{M}$.

We assume that, for a given direct channel gain at time t, the data rate for MS k from the BS in downlink case (or to the BS in uplink case) follows Shannon's additive white Gaussian noise capacity given by

$$R_k^D(t) = \log_2\left(1 + \frac{g_k^D(t)P_{TX}}{N}\right) \tag{1}$$

where P_{TX} is the transmit power, N is the additive white Gaussian noise, and $g_k^D(t)$ is the direct channel gain of downlink (or uplink). We refer to $R_k^D(t)$ as the data rate of a direct link between the BS and MS k. Throughout this paper, we use the term "single-hop scheme" as a method that only utilizes a direct link to transmit data.

[1]Either an MS or an even fixed relay station can relay data packets for one another. The difference between these two types of relaying architecture is summarized in [10]. In this paper, we limit the discussion to the case of mobile relaying (up to two-hop), e.g., peer-to-peer transmission in cellular networks [6], [11].

Now let us define a concept of *triangular link*, which is composed of the BS, one MS (destination or source node), and another MS (a relay node). The relay node is used to improve the data rate between the BS and MS. To calculate the data rate of a triangular link, we adopt a conventional two-phase time-division method as in [9]. In the first phase, a source encodes the message and transmits it to a relay. In the second phase, the relay retransmits the message to the destination. This relaying method is a kind of decode-and-forward scheme [6]–[9], where the relay demodulates, decodes, reencodes, and forwards the received signal from the source. We assume that two phases are orthogonally separated in a time domain, and a ratio between two phases can be unrestrictedly adjusted. Then, the data rate of a triangular link is given by

$$R_{ik}^{\triangle}(t) = \max_{0\le\phi\le1} \min\left\{\phi\log_2\left(1+\frac{g_i^D(t)P_{TX}}{N}\right),\right.$$
$$\left.(1-\phi)\log_2\left(1+\frac{g_{ik}^R(t)P_{TX}}{N}\right)\right\} \tag{2}$$

where MS k is a destination or a source node, and MS i is a relay node. Time fraction $\phi \in [0, 1]$ is allocated to the transmission phase between the BS and relay node i, which can be the first or second phase whether uplink or downlink, and the remaining time fraction $1 - \phi$ is allocated to the transmission phase between relay i and MS k. The data rate of triangular link can be maximized by allocating more time portion to the phase that has lower data rate. Even if we adopt other cooperative methods, such that [6]–[9] are used instead of the two-phase time division method, most aspects of our results will still hold by simply modifying the data rate equation in (2).

Effective Data Rate: By comparing the data rates through a direct link and triangular links for all possible relays from (1) and (2), the BS determines the best link for each MS as follows:

$$R_k^E(t) = \max_{i\in\mathcal{K}\setminus\{k\}}\left\{R_k^D(t), R_{ik}^{\triangle}(t)\right\}. \tag{3}$$

We call $R_k^E(t)$ as an *effective data rate*, which means the highest data rate that MS k can achieve through the direct link or triangular link at time t. For channel state m, we can also define the *effective data rate* and direct data rate of MS k as $R_{k,m}^E$ and $R_{k,m}^D$, respectively.

Observation 1: If the two-phase time-division method in [9] is used, the *effective data rate* defined in (3) has three properties.

1) For every channel state m, $R_{k,m}^E$ is greater than or equal to $R_{k,m}^D$.
2) For every channel state m, $\max_{k\in\mathcal{K}}\{R_{k,m}^E\}$ is the same as $\max_{k\in\mathcal{K}}\{R_{k,m}^D\}$.
3) When $R_{i^*k}^{\triangle}$ is greater than R_k^D, the *effective data rate* R_k^E can increase larger as relaying channel gain $g_{i^*k}^R$ becomes larger, but it is upper bounded by R_{i*k}^D, where i^* is the best relay node of MS k.

The properties can be easily proved by the definition, and proofs are provided in [18].

Problem Definition: We shall start by presenting a general utility maximization problem in the cooperative cellular networks. Our objective is to find a throughput vector $\mathbf{T} = (T_1, T_2, \ldots, T_K)$ corresponding to a specific opportunistic scheduling policy that maximizes the sum of long-term utilities of MSs over a long-term achievable capacity region C

$$\mathbf{P}: \quad \max_{\mathbf{T}\in C}\sum_{k\in\mathcal{K}} U(T_k). \tag{4}$$

In modeling users' satisfaction, we adopt the generalized α-proportional fair utility function introduced in [14], where

$U(T_k) = (T_k)^{1-\alpha}/(1-\alpha)$ when $\alpha \neq 1$, and $U(T_k) = \log(T_k)$ when $\alpha = 1$. Note that we can encompass the various tradeoff between fairness and capacity by simply adjusting the parameter $\alpha \geq 0$. As α grows, the scheduler becomes more fair. For example, sum capacity is maximized when α is zero; however, max-min fairness can be achieved when α goes to infinity.

III. Achievable Capacity Region

In this section, we give an explicit characterization of the achievable capacity regions $C \subseteq \mathbb{R}_+^K$ for both the single-hop scheme and the relay scheme. We denote Π as the set of all possible stationary resource allocation policies. For a given channel state $m \in \mathcal{M}$, a stationary resource allocation policy $\pi = (\pi_m, m \in \mathcal{M}) \in \Pi$ has a fixed portion of time slots for each MS. It means that π_{mk}, which is the kth value of π_m, is the portion of time slots for MS k when the channel state is m, and also, $\sum_{k\in\mathcal{K}} \pi_{mk} \leq 1$.

Let C_Π be the achievable capacity region, i.e., the set of all long-term average throughput vectors that can be obtained by using a stationary resource allocation policy $\pi \in \Pi$. For both the single-hop and relay schemes, the achievable capacity region of each scheme can be expressed as follows:

$$C_\Pi^D = \left\{ \mathbf{T}^D = \left(T_1^D, \ldots, T_K^D\right) \Big| T_k^D = \sum_{m\in\mathcal{M}} \theta_m \pi_{mk} R_{k,m}^D, \quad k = 1, \ldots, K \; \forall \pi \in \Pi \right\}$$

$$C_\Pi^E = \left\{ \mathbf{T}^E = \left(T_1^E, \ldots, T_K^E\right) \Big| T_k^E = \sum_{m\in\mathcal{M}} \theta_m \pi_{mk} R_{k,m}^E, \quad k = 1, \ldots, K \; \forall \pi \in \Pi \right\} \tag{5}$$

where θ_m is the probability of channel state m, and $\sum_{m\in\mathcal{M}} \theta_m = 1$. The achievable capacity region C_Π^D is proven to be a convex set in [13]. Moreover, the convexity of C_Π^E can be proved in a similar way.[2] In addition to the convexity, two achievable capacity regions have the following property:

Proposition 1: The achievable capacity region C_Π^E is a superset of C_Π^D under the same channel condition $\theta_m \; \forall m \in \mathcal{M}$, and it is a proper superset if there exists any user who has better effective data rate than direct data rates for some channel states.

Proof: Any throughput vector achieved by stationary resource allocation policy $\tilde{\pi}^D$ in capacity region C_Π^D can also be achieved by stationary resource allocation policy $\tilde{\pi}^E$ of the relay scheme such that $\tilde{\pi}_{mk}^E = \tilde{\pi}_{mk}^D \times (R_{k,m}^D / R_{k,m}^E \; \forall m, k$. It is a valid policy since $(R_{k,m}^D / R_{k,m}^E) \leq 1$ from Observation 1-1, so $C_\Pi^D \subseteq C_\Pi^E$ holds.

Assume that $\hat{\pi}^D$ achieves throughput vector $\hat{\mathbf{T}}^D$, which is one of the boundary points of capacity region C_Π^D in the single-hop scheme. If each MS uses the *effective data rate*, instead of the direct data rate under the same resource allocation policy $\hat{\pi}^D$ and the same channel condition $\theta_m \; \forall m \in \mathcal{M}$, then we can obtain throughput vector $\hat{\mathbf{T}}^E$ of the relay scheme such that $\hat{T}_k^E \geq \hat{T}_k^D$ for all k since $\hat{T}_k^E = \sum_{m\in\mathcal{M}} \theta_m \hat{\pi}_{mk}^D R_{k,m}^E$, $\hat{T}_k^D = \sum_{m\in\mathcal{M}} \theta_m \hat{\pi}_{mk}^D R_{k,m}^D$, and $R_{k,m}^E \geq R_{k,m}^D$ by Observation 1-1. If there exists some channel state m such that $R_{k,m}^E > R_{k,m}^D$, then $\hat{T}_k^E > \hat{T}_k^D$. Since $\hat{T}_k^D$ is the boundary point of capacity region C_Π^D, $\hat{\mathbf{T}}^E$ is not contained in capacity region C_Π^D, so $C_\Pi^D \subset C_\Pi^E$ holds. ■

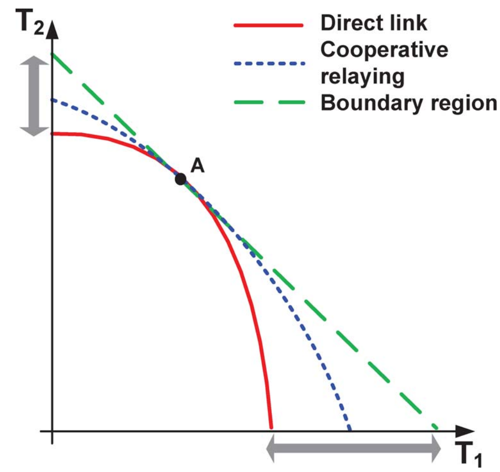

Fig. 1. Variation of the achievable capacity region of two-user networks according to the relaying channel gain. Each axis means the throughput of each user. It becomes larger as the relaying channel gain increases. At the extreme, the boundary of the region becomes a straight line, where the x- and y-intercepts of the straight line are equal to $\sum_{m\in\mathcal{M}} \theta_m \max_{k\in\mathcal{K}}\{R_{k,m}^E\}$.

In other words, with the relaying, any MS can achieve a throughput, which is greater than or equal to that of the case without relaying. Moreover, there are some characteristics of the achievable capacity region for the relay scheme.

Observation 2: Capacity region C_Π^E for the relay scheme has the following interesting properties, as shown in Fig. 1.

1) Some of the boundary points in C_Π^D remain unchanged in C_Π^E.
2) Capacity region C_Π^E can be more enlarged when the relaying channel gains are higher.
3) Capacity region C_Π^E cannot be enlarged more than a capacity region, whose axes are $\sum_{m\in\mathcal{M}} \theta_m \max_{k\in\mathcal{K}}\{R_{k,m}^E\}$, even if the relaying channel gains go to infinity.

These three properties come from Observation 1 and the definition of the capacity region, and proofs are provided in our technical report [18]. Since the achievable capacity region of the relay scheme is greater than that of the single-hop scheme, the achieved throughput vector using *triangular link* can surpass the capacity and fairness tradeoff relationship in the single-hop scheme. To obtain the throughput vector in the enlarged region, an appropriate scheduling policy needs to be developed.

IV. Scheduler Design

A. Optimal Opportunistic Scheduler Using Relaying

In the single-hop scheme case, Stolyar [13] showed that the achieved throughput vector obtained by a gradient scheduling algorithm is a solution of the problem $\mathbf{P}$, i.e., the boundary point of capacity region C_Π^D in (5). We first design an optimal scheduler that solves problem $\mathbf{P}$ when triangular links can be utilized when the achievable capacity region is expanded to $C_\Pi^\triangle$. The optimal scheduler should jointly determine the following:

- *User selection*: Which MS will be selected?
- *Relay selection*: Whether the selected MS will utilize a neighbor relay node or not? If yes, which relay node should be utilized?

[2] For a given channel state m, set $C_{\pi_m}^E$ is convex since it is a convex combination of $R_{k,m}^E$ with coefficients π_{mk}. Thus, the capacity region C_Π^E, which is a convex combination of components in convex set $C_{\pi_m}^E$, is also convex.

With the help of the gradient scheduling algorithm in [13], we propose an optimal scheduling policy.

Optimal scheduler

Relay selection algorithm: The best candidate relay node for MS k at time t, which is denoted by $i_k^*(t)$, is selected as follows:

$$i_k^*(t) = \arg \max_{i \in \mathcal{K} \setminus \{k\}} R_{ik}^{\triangle}(t) \qquad \forall k \in \mathcal{K}. \tag{6}$$

User selection algorithm: At each time slot t, the scheduler selects user $k^*(t)$

$$k^*(t) = \arg \max_{k \in \mathcal{K}} \frac{R_k^E(t)}{[T_k(t)]^\alpha} \tag{7}$$

where $R_k^E(t) = \max\{R_k^D(t), R_{i_k^* k}^{\triangle}(t)\}$, and the average throughput T_k is updated as follows:

$$T_k(t+1) = \begin{cases} (1-\beta)T_k(t) + \beta R_k(t), & \text{if } k = k^*(t) \\ (1-\beta)T_k(t), & \text{otherwise} \end{cases} \tag{8}$$

with a small constant $\beta > 0$.

It is worthwhile mentioning that the proposed optimal algorithm involves the best relay node selection process at each time slot to calculate the effective data rate $R_k^E(t)$. The scheduler selects a user who has the highest scheduling metric $R_k^E(t)/[T_k(t)]^\alpha$ such as (7). By selecting the user who has high *effective data rate* $R_k^E(t)$, the scheduler can be efficient, and by selecting the user who has low average throughput $T_k(t)$, the scheduler can achieve fairness. These two factors are combined by α in the scheduling metric $R_k^E(t)/[T_k(t)]^\alpha$, so that we can adjust tradeoff relation between capacity and fairness.

Proposition 2: The achieved average throughput vector $\boldsymbol{T}$ is the solution of problem $\boldsymbol{P}$ if the proposed scheduling algorithm in (6)–(8) is used at every time slot.

The proof of the aforementioned proposition is straightforward, following that in [13].

B. Heuristic Opportunistic Scheduler Using Relaying

Although the optimal scheduling algorithm described in the previous section can achieve maximum utility within the capacity region $C_\Pi^{\triangle}$, it incurs high complexity due to the best relay selection for each MS at each time slot. It also requires heavy channel estimation and feedback overhead since the relaying channel gain matrix $G^R = [G_1^R, \ldots, G_K^R]^t$ should be known to the BS. To obtain the relaying channel gain matrix G^R, every MS needs to broadcast its own pilot signal to measure channel state information among MSs. Furthermore, the MSs need to transmit this information to the BS. As a result, when the number of MSs is K, the numbers of required channel gains that need to be estimated and reported at each time slot in the relay and single-hop schemes are K^2 and K, respectively.

To reduce the complexity and overhead in the optimal algorithm, we utilize the idea of time-scale decomposition, where the best relay selection of each MSs is less frequently executed, e.g., every $T_R \gg 1$ slot, while the user scheduling is executed at every time slot. The proposed relay selection algorithm is given as follows:

TABLE I
FEEDBACK OVERHEAD AND COMPLEXITY OF THE PROPOSED SCHEMES AT EACH TIME SLOT

	Per-user feedback	Complexity
Optimal w/o relaying	1	K
Optimal w/ relaying	$1 + (K-1)$	K^2
Heuristic w/ relaying	$2 + (K-2)/T_R$	K^2/T_R

TABLE II
SIMULATION ENVIRONMENT

Parameter	Value
Number of users	30
Carrier frequency	2 GHz
User mobility	static or mobile (2 m/s or 20 m/s)
Cell Radius	2 km
Time slot duration	10 ms
Channel model	Path loss + Fast fading + Slow fading
Path loss model	16.5 + 37.6 log(distance (m)) [dB]
Slow fading	Log-normal distribution with standard deviation 8 dB
Fast fading	Rayleigh fading
Transmit Power	BS : 20 W, MS : 2 W

Long time-scale relay selection algorithm: The best relay node of MS k for a *triangular link* at time t, $i_k^*(t)$, is selected as follows:

$$i_k^*(t) = \begin{cases} \arg \max_{i \in \mathcal{K} \setminus \{k\}} \overline{R}_{ik}^{\triangle}(t), & \text{if } t \bmod T_R = 0 \\ i_k^*(t-1), & \text{otherwise} \end{cases} \tag{9}$$

where $\overline{R}_{ik}^{\triangle}(t)$ is the average data rate of the *triangular link* during the T_R period.

In the proposed long time-scale relay selection algorithm, each MS still needs to estimate the relay channel gains, but it does not send them to the BS at every time slot. It only reports the average relay channel gains at every T_R slot. Consequently, the total amount of feedback for each MS can be significantly reduced. Table I summarizes the results of feedback overhead and complexity analysis. Such a simple heuristic algorithm will be shown to be efficient enough (near optimal) as long as the best relay remains unchanged for a longer period of time than the channel update period, e.g., nomadic or group mobility case. We will validate the effectiveness of our heuristic algorithm through extensive simulations.

V. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed algorithms under various configurations. We demonstrate that the relay scheme alleviates the capacity and fairness tradeoff in the single-hop scheme and compare optimal and long time-scale relay selection algorithms (heuristic) in mobile node scenarios. Parameters for simulation environment are summarized in Table II. We adopt Jain's fairness index $J = (\sum_{k \in \mathcal{K}} T_k)^2 / |\mathcal{K}| \sum_{k \in \mathcal{K}} (T_k)^2$ to evaluate fairness among users [15].

From Fig. 2, although there is a tradeoff between capacity and fairness (i.e., increasing one objective may deteriorate the other) in cellular networks no matter what scheduling algorithms are used, we can clearly see that the relaying helps alleviate the tradeoff relationship. In particular, compared to the single-hop scheme (i.e., optimal without relaying), there is a huge gain in capacity when α is large. On the other hand, there is a huge gain in fairness when α is small. The main reason

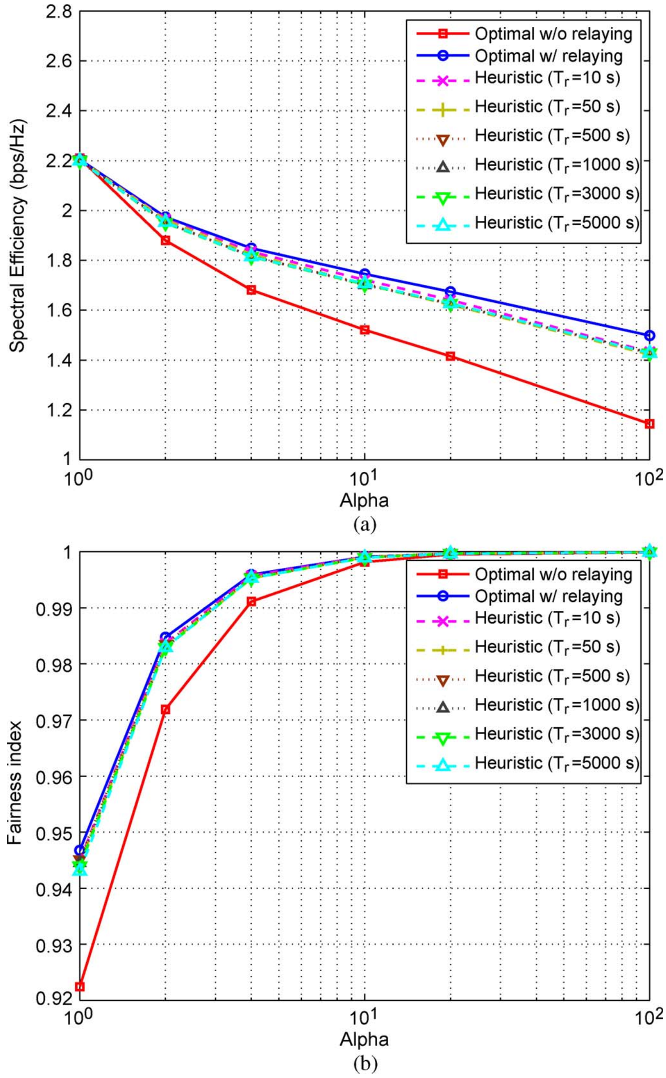

Fig. 2. Capacity and fairness comparison between a scheduling algorithm with only direct link and optimal/heuristic scheduling algorithms with triangular links. (a) Capacity versus alpha. (b) Fairness versus alpha.

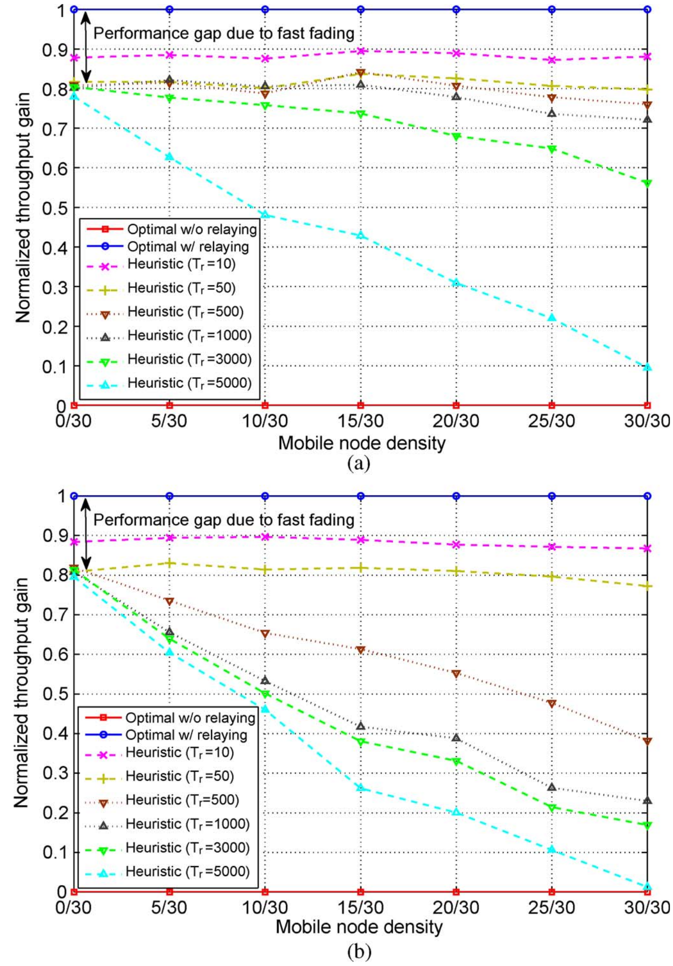

Fig. 3. Normalized throughput gains of heuristic algorithms when a mobile node density increases and $\alpha = 10$. (a) Low velocity (2 m/s). (b) High velocity (20 m/s).

the performance could be improved in the relaying scheme is that MSs who have low direct channel gains and instantaneous data rates can have chances to utilize triangular links with higher effective channel gains.

Fig. 3 shows the normalized throughput gain, which is the amount of throughput increase in the heuristic algorithm over that of the optimal algorithm with relaying. As the normalized gain approaches 1, the performance of the heuristic algorithm gets close to the optimum. In modeling users' mobility, we use the random waypoint model [16]. We ran simulations under various conditions, e.g., the fraction of mobile nodes among all static and mobile nodes, and the speed of nodes. We vary the density from $0(= 0/30)$ to $1(= 30/30)$ and the speed from low (2 m/s) to high (20 m/s).[3]

As the channel state varies by fast fading or mobility, the optimal relay may need to be changed. If the relay selection cannot keep up with the channel variation as the relay selection period gets longer, we cannot fully exploit the relaying gain. Even if all users are static, the optimal relay can be changed at each time slot due to fast fading effect. Therefore, the normalized gain decreases about 20% when all users are static (at 0/30 in the figures) if the relay selection period is greater than 50 time slots. As the mobile node density increases, the normalized gain tends to decrease. In particular, this becomes more severe when the relay selection period T_r is unreasonably long. This is because an inappropriate relay has to be still used until the next relay selection epoch, although the channel has already been varied due to mobility. Note, however, that we can bound the performance loss by choosing T_r that is small enough to keep up with the channel variation due to mobility. For example, we can achieve more than 75% of the relaying gain, regardless of the mobile node density, up to $T_R = 500$ in Fig. 3(a) of low velocity (2 m/s) and up to $T_R = 50$ in Fig. 3(b) of high velocity (20 m/s). If the relay selection period is small, compared to the degree of user mobility, the amount of feedback and complexity can be significantly reduced with bounded performance loss from fast fading. In practice, users who generate a considerable amount of traffic are likely to be more nomadic/static than mobile users. Therefore, in this case, the long time-scale relay selection algorithm is more effective.

[3]The coherence times for low- and high-speed mobile nodes are 37.5 and 3.75 ms, respectively. Note that the coherence time is inversely proportional to the velocity [17].

VI. Conclusion

In this paper, we have shown that the relay can enlarge the achievable capacity region in cellular networks, i.e., the relay scheme can alleviate the capacity and fairness tradeoff relationship of the single-hop scheme that uses direct links only. We have proposed an optimal algorithm that maximizes the sum of users' utility and achieves boundary points of the capacity region. Since the channel state feedback and the best relay selection for the optimal algorithm may cause much burden to the system, we have also developed an efficient heuristic algorithm that reduces the total amount of channel state feedback and complexity of the relay user selection. Extensive simulation results have verified that the proposed algorithms can increase the throughput of users and mitigate the unfairness problem by providing alternative links to users who have low direct channel gains, and the amount of feedback and complexity can be significantly reduced by the heuristic algorithm with a bounded performance loss due to not tracking the fast fading in the high-mobility regime.

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Semiblind Turbo Equalization Scheme for LTE Uplink Receiver

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***Abstract*—An advanced receiver scheme for long-term evolution (LTE) uplink is proposed. The scheme combines semiblind channel estimation and turbo equalization and is based on an approximate expectation–maximization (EM) algorithm. The receiver iterates between demodulation of the data symbols using frequency-domain soft interference cancelation, turbo decoding, and semiblind channel estimation that utilizes the soft symbols extracted from the turbo decoder output. It is shown that, using the proposed scheme, one can replace most of the dedicated pilots used in the current LTE scheme with data information and obtain significantly better performance with the same bandwidth. Moreover, an efficient implementation of the proposed algorithm utilizing the discrete/fast Fourier transform (DFT/FFT) properties used in the single-carrier orthogonal frequency-division multiplexing (SC-OFDM) scheme is presented.**

***Index Terms*—Channel estimation, long-term evolution (LTE), single-carrier orthogonal frequency-division multiplexing (SC-OFDM), turbo equalization.**

I. Introduction

This paper explores receiver scheme for single-carrier orthogonal frequency-division multiplexing (SC-OFDM) for long-term evolution (LTE) uplink with multiuser multiple-input–multiple-output (MU-MIMO) scheme.[1] The main difficulty with SC-OFDM, compared with OFDM, is the discrete Fourier transform (DFT) spreading of the information symbols, which prohibits the use of maximum-*a posteriori*-based demodulation and complicates both the demodulation and channel estimation. The conventional receiver for LTE uplink is therefore based on a pilot-aided channel estimation [1], followed by a per-subcarrier linear equalizer in the frequency domain. To improve the conventional receiver performance, turbo-based equalization schemes [2], [3] have been recently proposed. These schemes are based on iterative demodulation and turbo decoding where the data from the turbo decoder are soft mapped to symbols and used as *a priori* information in the next equalization iteration. Although these schemes improve the demodulation part, they are still limited by the quality of the channel estimation obtained from relatively small number of pilots. To improve the performance further, iterative semiblind channel estimation and demodulation schemes might be exploited (see, for example, [5], [11]–[13]) for single-carrier systems.

In this paper, we adapt the iterative channel estimation and equalization to LTE uplink systems. We propose an iterative scheme, encompassing 2-D (in frequency and time) channel estimation and turbo equalization, based on an approximate expectation–maximization (EM) algorithm. The receiver iterates between demodulation of the data symbols based on frequency-domain minimum mean square error

Manuscript received December 11, 2011; revised April 21, 2012, June 10, 2012 and July 16, 2012; accepted August 1, 2012. Date of publication August 7, 2012; date of current version November 6, 2012. The review of this paper was coordinated by Prof. C. Cozzo.

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Digital Object Identifier 10.1109/TVT.2012.2212212

[1] In this scheme, several users transmit to the base station using the same subcarriers in an uncorrelated manner; users separation is done by exploring the diversity receive antennas. Although the proposed receiver scheme is also suitable for single-user MIMO, for simplicity of notations, only MU-MIMO will be considered.