Maximizing Cooperative Diversity Energy Gain for Wireless Networks

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***Abstract*— We are concerned with optimally grouping active mobile users in a two-user-based cooperative diversity system to maximize the cooperative diversity energy gain in a radio cell. The optimization problem is formulated as a non-bipartite weighted-matching problem in a static network setting. The weighted-matching problem can be solved using maximum weighted (MW) matching algorithm in polynomial time $O(n^3)$. To reduce the implementation and computational complexity, we develop a Worst-Link-First (WLF) matching algorithm, which gives the user with the worse channel condition and the higher energy consumption rate a higher priority to choose its partner. The computational complexity of the proposed WLF algorithm is $O(n^2)$ while the achieved average energy gain is only slightly lower than that of the optimal maximum weighted-matching algorithm and similar to that of the $1/2$-approximation Greedy matching algorithm (with computational complexity of $O(n^2 \log n)$) for a static-user network. We further investigate the optimal matching problem in mobile networks. By intelligently applying user mobility information in the matching algorithm, high cooperative diversity energy gain with moderate overhead is possible. In mobile networks, the proposed WLF matching algorithm, being less complex than the MW and the Greedy matching algorithms, yields performance characteristics close to those of the MW matching algorithm and better than the Greedy matching algorithm.**

***Index Terms*— Cooperative diversity, matching algorithm, wireless networks, user mobility.**

I. INTRODUCTION

MULTIPLE-INPUT and Multiple-Output (MIMO) systems can exploit spatial diversity to achieve higher power and spectral efficiency. In situations when multiple antennas are impractical, cooperation among a group of users to transmit and relay the same signal can emulate a multiple transmit antennas environment to achieve spatial diversity gains. With the broadcast nature of the wireless channel, when a source transmits signals to a destination, neighboring users can also receive the signals. These neighboring users can relay the signals to the destination. In this way, the antennas of the source and the relaying users together form a multiple transmit antennas situation. A number of cooperative diversity (CD) schemes have demonstrated that cooperation can provide diversity gain to not only the users with worse channel quality but also those with better channel quality [1]–[7]. The performance of CD systems heavily depends on the inter-user channel condition. Given a group of users, if the inter-user transmissions are error free, the CD scheme can achieve full diversity order, which is equal to the number of terminals participating in the cooperation. In reality, inter-user channels are also erroneous, and inter-user transmission losses grow with the number of cooperating users, to the point that they can outweight the diversity benefits. In addition, implementation becomes more complex when more users cooperate as a group. Therefore, in this paper, we consider the cooperation between two users, *i.e.*, two sources relaying for each other.

On the other hand, wireless mobile devices are battery powered. It is important to minimize the energy consumption in order to maximize the time the wireless device can be functional without recharging or replacing the battery. Although cooperative diversity energy gain for a single group of users has become an active research topic, how much energy gain can be achieved for a network that employs a CD scheme, and how the diversity gain can be maximized for the whole network are still open issues. In wireless mobile networks, user mobility further complicates the grouping problem. The mobile users' velocities and moving directions can change over time, which affect the cooperative diversity gain of a pair of users. To the best of our knowledge, there is no research work reported in the literature on how to group mobile users.

Each individual user has its own preference in choosing its partner. The objective of an individual user (maximizing its own energy gain by cooperation) may conflict with the objective of the network (maximizing the energy gain of the whole network). For user mobility, the best grouping at the current time instant may not be the best at a future time instant. In this paper, our objective is to group active users in a radio cell, taking cell energy gain and user mobility into consideration. This problem requires the joint efforts from both the *physical layer*, which determines how a pair of users cooperate with each other, and the *network layer*, which determines how to group users in a radio cell. To solve the problem, we first focus on how to optimally group static users in a radio cell, and then study how to match users in a radio cell in the presence of user mobility.

Given the cooperative diversity energy gain of any pair of users, how to maximize it in a radio cell by optimally grouping all the active users can be formulated as a non-

Manuscript received November 5, 2005; accepted July 4, 2006. The associate editor coordinating the review of this letter and approving it for publication was A. Molisch. This work has been supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada under Grant No. RGPIN7779.

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Digital Object Identifier 10.1109/TWC.2007.05890.

bipartite maximum weighted-matching problem, which can be solved in polynomial time, $O(n^3)$. Another matching algorithm, called Greedy matching algorithm, which can be solved in polynomial time, $O(n^2 \log n)$, can achieve 1/2-approximation. Due to user mobility and intermittent traffic, the matching algorithm should be periodically executed in real time. Thus, it is important to reduce the computational and implementation complexity of the matching algorithm without compromising too much energy gain. We propose a Worst-Link-First (WLF) algorithm which gives the user with the worse channel condition and the higher energy consumption rate a higher priority to choose its partner. The computational complexity of the proposed WLF algorithm is $O(n^2)$. Later, we will show that the WLF is also easier to implement. In addition, we derive a theoretical upper bound of energy gain achievable by the matching algorithms.

With user mobility, the population size of a radio cell of the network varies with time, and frequently updating the matching will introduce significant overhead. We propose how to incorporate the mobility information in the matching algorithm to reduce the overhead. It is shown that, by intelligently incorporating user mobility, the maximum weighted-matching and the WLF matching algorithms can maintain high cell energy gain with reduced overhead.

The main contributions of this paper are three-fold. First, we formulate the problem of maximizing the cell energy gain in a radio cell as a classic non-bipartite maximum weighted-matching problem. Then, we study the performance of four matching algorithms, the MW algorithm, the Greedy matching algorithm, the proposed WLF algorithm and the benchmark random matching algorithm, and compare their computational complexity and the cell energy gain tradeoff. Second, we derive theoretical upper bounds of energy gain by cooperation in a radio cell. Third, we propose how to optimally group mobile users, taking user mobility into consideration.

The remainder of the paper is organized as follows. Section II presents the operational functions of the MW algorithm, the Greedy matching algorithm, the proposed WLF algorithm and the benchmark random matching algorithm. Section III describes the system model. Section IV gives analysis and numerical evaluation of the matching algorithms in a static network. How to group mobile users by considering mobility information is presented in Section V, followed by related work in Section VI. Concluding remarks and future research issues are given in Section VII.

II. Matching Algorithms

Choosing pairs of cooperating users is known as *matching* on graphs [10], [11]. Let $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ be a graph, where $\mathcal{V}$ is a set of vertexes and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is a set of edges between vertexes. Each mobile user in a cell is represented as a vertex. The $(i, j)^{th}$ edge, $e_{i,j} \in \mathcal{E}$, has a weight $w(e_{i,j})$, which equals the energy gained by cooperation between users i and j over no cooperation. If there is no cooperative energy gain, the two users will just use the non-cooperative scheme, and the weight of the edge linking them is zero. Thus, the weight is always non-negative, and a positive weight represents the energy gain of cooperation over no cooperation.

A subset $\mathcal{S}$ of $\mathcal{E}$ is called a *matching* subset if there are no two edges in $\mathcal{S}$ sharing the same vertex. The overall energy gain in the network is the sum of the positive weights of all edges in $\mathcal{S}$. For easy reference, the notations used throughout the paper are listed in Appendix I.

A. Maximum Weighted-Matching

Maximizing the energy gain by cooperation is equivalent to maximizing $w(\mathcal{S}) = \sum_{e_{i,j} \in \mathcal{S}} w(e_{i,j})$ among all possible matchings, which is a non-bipartite weighted-matching problem. The number of matchings with $|\mathcal{S}| = \lfloor \frac{n}{2} \rfloor!$ equals $n!/(2^{\lfloor \frac{n}{2} \rfloor} \lfloor \frac{n}{2} \rfloor!)$, which exponentially increases with n, where $n = |\mathcal{V}|$ is the cardinality of the set $\mathcal{V}$ or the number of users in the network. Comparing all possible matching by Brute Force search is very time consuming when the number of active users is large.

The maximum weighted-matching algorithm developed in [12] can yield the optimal solution for the non-bipartite weighted-matching problem in polynomial time, $O(n^3)$. This state-of-the-art algorithm can be used to obtain the highest energy gain in a wireless network.

B. Greedy Matching

The heuristic Greedy matching algorithm [13] can achieve 1/2-approximation:

Greedy Matching Algorithm:

1) The BS selects a user pair i and j such that energy gain $w(e_{i,j})$ is the largest among $w(e)$ for $e \in \mathcal{E}$. $e_{i,j}$ is added to the matching set.
2) Remove all edges incident to $e_{i,j}$ from $\mathcal{E}$.
3) Repeat 1) and 2) until the number of unmatched users is less than two.

The Greedy matching algorithm requires sorting the weights of all edges in $\mathcal{E}$, so its complexity is $O(n^2 \log n)$.

C. Worst-Link-First (WLF) Matching

With user mobility and intermittent traffic, the matching algorithm should be periodically executed in real time. Thus, it is important to further reduce the computational complexity of the matching algorithm without compromising too much energy gain.

Since the user with the worse channel quality (far from the BS) consumes more energy than the one with a better channel quality (near the BS) in a conventional transmission system, cooperation generally gives more energy gain to the far user than the near user. Therefore, when considering the radio cell, those users with worse channel quality and higher energy consumption rate should be given a higher priority. This motivates us to develop the following WLF matching algorithm.

WLF Matching Algorithm:

1) The BS selects an unmatched user i with the worst channel quality among all unmatched users.
2) The BS selects an unmatched user j such that the energy gain $w(e_{i,j})$ provided by the cooperation of user i and user j over no cooperation is the maximum one among

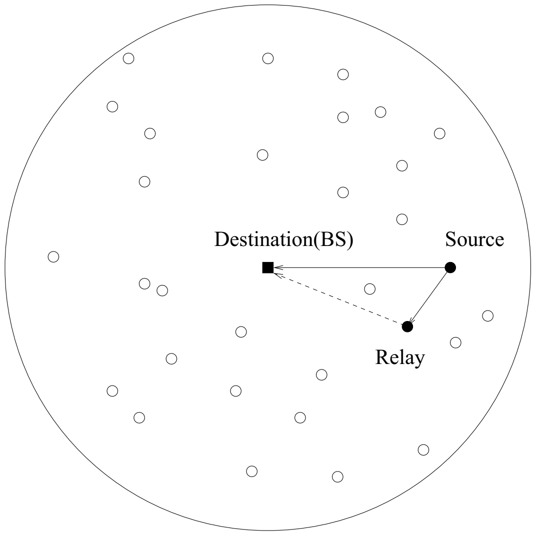
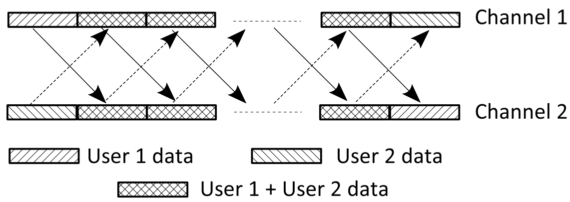
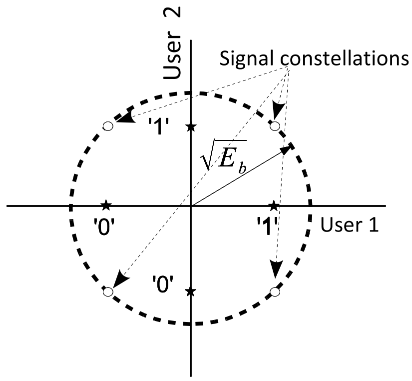


Fig. 1. System model.



(a) Frame format



(b) Signal constellations

Fig. 2. Transmission frame format and signal constellation of the CD scheme.

all $w(e_{i,k})$, where k is an unmatched user other than i. $e_{i,j}$ is added to the matching set.

3) Repeat 1) and 2) until the number of unmatched users is less than two.

The computational complexity of the WLF algorithm is $O(n^2)$.

D. Random Matching

The random matching algorithm is the simplest one and is used as the benchmark. The algorithm randomly selects an unmatched user i and matches it with another unmatched user j, until there are fewer than two unmatched users remaining. Although the computational complexity of the random matching algorithm is $O(n)$, due to the randomness in matching, a significant number of pairs cannot obtain positive energy gain by cooperation. Therefore, random matching provides very limited energy gain.

III. System Model

We study the performance of an infrastructure-based wireless network, *e.g.*, wireless cellular systems or infrastructure-based wireless LANs (WLANs). The BS of a radio cell, (or an access point in a WLAN) supports N mobile users, as shown in Fig. 1. We consider the scenario in which any user is capable of cooperating with another user, *i.e.*, cooperation between two active users.

Both the inter-user channels (channels between two users) and the channel between a user and the BS are assumed as quasi-static flat Rayleigh fading. Channel state information (CSI), *i.e.*, the variance of channel fading coefficient, is assumed available at the respective receivers. The users estimate the inter-user CSIs with their potential partners and forward them to the BS. If estimating inter-user CSIs is very time and power consuming by the mobile users, the BS can estimate the inter-user CSIs using the locations of the users and the path loss model available for the respective areas. Matching can be done by the BS according to the $n(n-1)/2$ CSIs, and the users can be grouped according to the matching results. Since cooperation is not always beneficial [7], a pair of users can choose not to cooperate if there is no cooperative diversity energy gain for them, and they communicate with the BS using a conventional non-cooperative scheme.

Two CD approaches have been reported in the literature: *amplify-and-forward* (relaying) and *regenerate-and-forward* (regenerative repeat). With the amplify-and-forward approach, the partner amplifies the signal received from the sender and retransmits it to the destination. These schemes require either complex transceiver for frequency division forwarding or large storage for time division forwarding. Thus, we focus on the regenerate-and-forward approach in which the partner detects the received signal and transmits the regenerated version to the destination.

Fixed regenerate-and-forward CD schemes based on orthogonal (or quadrature) signaling using QPSK modulation (BPSK symbols for each user information) have been studied in [7]. Briefly, in a symbol interval, each user transmits not only its own information, but also the partner's information received in the previous symbol interval. The transmission frame format and the signal constellation of the QPSK modulation scheme are shown in Fig. 2. With the fixed CD scheme, the partner always relays the information to the destination. In contrast, the partner of an adaptive CD scheme decides whether or not to forward the information based on the cyclic redundancy checksum (CRC) of the received frame of bits. Since the relay should store frames and check the CRC, and inform the BS whether the partner's bits should be relayed or not, additional processing and signaling are introduced. However, error performance of the adaptive CD scheme is generally superior to that of the fixed CD scheme, especially when the inter-user channel is highly erroneous. The cooperative energy gain with the fixed CD scheme reported in [7] and the adaptive

CD scheme reported in [8] are analyzed in this paper.

In general, wireless networks have a mixture of static and mobile users. In the following, the performance of the proposed matching algorithms will be analyzed and evaluated for a static-user network and a network with mixed static and mobile users.

IV. Performance in Static-User Network

Given the required BER of each user, we first calculate the energy consumptions with and without cooperation and the maximum energy gain for a pair of cooperating users. We then obtain the cell energy gain over a non-cooperative system, and its theoretical upper bounds.

A. Analysis

1) Energy Consumption of Non-cooperative Scheme: In signal transmission using a given modulation scheme over a Rayleigh fading channel, the bit error probability can be expressed as a function of SNR. The bit error probability of the non-cooperative (standard) BPSK scheme for user i can be written as [9]

$$P_e^i = \frac{1}{2}\left(1-\sqrt{\frac{\bar{\gamma}_i^{no}}{1+\bar{\gamma}_i^{no}}}\right), \tag{1}$$

where $\bar{\gamma}_i^{no} = \sigma_i^2 \frac{E_{b_i}^{no}}{N_0}$ is the SNR. $E_{b_i}^{no}$ is the energy expended in transmitting one bit using the non-cooperative scheme, σ_i^2 is the variance of the channel fading coefficient and N_0 is the one-sided power spectral density of additive white Gaussian noise. Therefore, to ensure the BER of user i to be no less than P_e^i, the minimal required bit energy is

$$E_{b_i}^{no} = \frac{N_0}{\sigma_i^2}\left[\frac{(1-2P_e^i)^2}{1-(1-2P_e^i)^2}\right]. \tag{2}$$

2) Energy Consumption of CD Schemes:

a) Fixed regenerate-and-forward CD scheme: For user i partnering with user j, the bit error probability with the fixed regenerate-and-forward CD scheme can be given as [7],

$$P_e^i = \frac{1}{2\bar{\gamma}_{i,j}}\frac{\bar{\gamma}_j}{\bar{\gamma}_i+\bar{\gamma}_j} + \frac{3}{4\bar{\gamma}_i\bar{\gamma}_j} + \frac{1}{2\bar{\gamma}_{i,j}}\frac{\bar{\gamma}_i-\bar{\gamma}_j}{(\bar{\gamma}_i+\bar{\gamma}_j)^2} - \frac{1}{2\bar{\gamma}_{i,j}}\frac{3}{4\bar{\gamma}_i\bar{\gamma}_j} \tag{3}$$

where $\bar{\gamma}_i = \sigma_i^2 \frac{2E_{b_i}^S}{N_0}$, $\bar{\gamma}_j = \sigma_j^2 \frac{2E_{b_j}^R}{N_0}$, and $\bar{\gamma}_{i,j} = \sigma_{i,j}^2 \frac{2E_{b_i}^S}{N_0}$. $E_{b_i}^S$ and $E_{b_j}^R$ are respectively the energies spent by the source (user i) and the relay (user j) in transmitting one bit for user i.

Let $k = E_{b_j}^R / E_{b_i}^S$. We can write (3) as

$$\begin{aligned} 0 \;=\; & P_e(E_{b_i}^S)^3 - \left[\frac{k\sigma_j^2 N_0}{4\sigma_{i,j}^2(\sigma_i^2+k\sigma_j^2)}\right](E_{b_i}^S)^2 + \frac{3N_0^3}{64k\sigma_{i,j}^2\sigma_i^2\sigma_j^2} \\ & - \left[\frac{3}{16k\sigma_i^2\sigma_j^2} + \frac{\sigma_i^2 - k\sigma_j^2}{8\sigma_{i,j}^2(\sigma_i^2+k\sigma_j^2)^2}\right] N_0^2 E_{b_i}^S. \end{aligned} \tag{4}$$

The above equation has a real solution for $E_{b_i}^S$, which can be expressed as a function of P_e^i, N_0, k, σ_i^2, σ_j^2 and $\sigma_{i,j}^2$:

$$E_{b_i}^S = f_1(P_e^i, N_0, k, \sigma_i^2, \sigma_j^2, \sigma_{i,j}^2). \tag{5}$$

$f_1(\cdot,\cdot,\cdot,\cdot,\cdot,\cdot)$ is a relatively complex function of its arguments. It can be solved numerically. Given $E_{b_i}^S$, $E_{b_j}^R$ can be found using $E_{b_j}^R = kE_{b_j}^S$. Thus, the energy required for user i in cooperation with user j, $(E_{b_i}^S + E_{b_j}^R)$, can be determined. Similarly, the energy required for user j in cooperation with user i, $(E_{b_j}^S + E_{b_i}^R)$, can be derived.

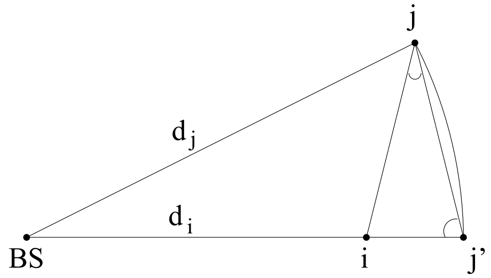


Fig. 3. Geographical setting of users for the derivation of upper bound.

b) Adaptive Regenerate-and-Forward CD Scheme: By considering cooperative and non-cooperative modes of the adaptive CD scheme in the high SNR regime, the bit error probability of user i can be written as

$$P_e^i = \left(1 - \frac{K_N}{2\bar{\gamma}_{i,j}}\right)\frac{3}{4\bar{\gamma}_i\bar{\gamma}_j} + \frac{K_N}{4\bar{\gamma}_{i,j}}\frac{1}{\bar{\gamma}_i} \tag{6}$$

where $K_N = \sum_{e_b=1}^{N} \frac{1}{e_b}$, N is the number of symbols in a frame and e_b is the number of bit errors between the transmitted and received frames. Equation (6) can be written as

$$0 = P_e^i(E_{b_i}^S)^3 - \frac{N_0^2}{16\sigma_i^2}\left[\frac{3}{k\sigma_j^2} + \frac{K_N}{\sigma_{i,j}^2}\right]E_{b_i}^S + \frac{K_N N_0^3}{64k\sigma_i^2\sigma_j^2\sigma_{i,j}^2} \tag{7}$$

Similar to the fixed CD scheme, the energy required for cooperative transmission can be expressed as a function of P_e^i, k, N, N_0, σ_i^2, σ_j^2 and $\sigma_{i,j}^2$.

3) Analytical Upper Bound: The cooperative diversity gain of the network depends largely on user deployment, *e.g.*, how many active users in the network, their locations, *etc*. A tight theoretical upper bound is important for quantifying the performance of different CD schemes and matching algorithms.

Network energy gain, which is the energy gain of a cell with user cooperation over a cell without user cooperation, is defined as

$$G_{CD} = 10\log_{10}\left(\frac{\sum_{i=1}^{N} E_{b_i}^{no}}{\sum_{i=1}^{K}(E_{b_i}^S + E_{b_i}^R) + \sum_{i=K+1}^{N} E_{b_i}^{no}}\right), \tag{8}$$

where the first K users are paired to have cooperation and the remaining $(N-K)$ users have no partners. Since $\sum_{i=1}^{N} E_{b_i}^{no}$ is a constant independent of matching, G_{CD} is maximized when $\sum_{i=1}^{K}(E_{b_i}^S + E_{b_i}^R)$ is minimized.

Consider user i located at distance d_i from the BS and user j at distance d_j from the BS. The average CSIs $\sigma_i^2 \propto d_i^{-\alpha}$, $\sigma_j^2 \propto d_j^{-\alpha}$ and $\sigma_{i,j}^2 \propto d_{i,j}^{-\alpha}$, where the path loss exponent α takes the value between 2 to 6. We first demonstrate that the energy gained by cooperation between users i and j is no larger than the energy gained by cooperation between users i and j', where user j' is located on the straight line beginning at the BS and passing through i, and the distance between j' and the BS is also d_j. Obviously, $E_{b_j}^{no} = E_{b_{j'}}^{no}$. For user i located anywhere between the BS and user j' (see Fig. 3),

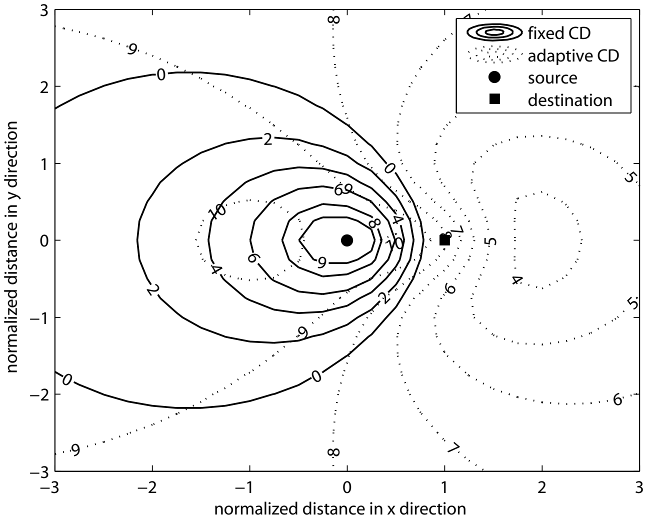


Fig. 4. Energy gain for a pair of users using fixed CD scheme and adaptive CD scheme.

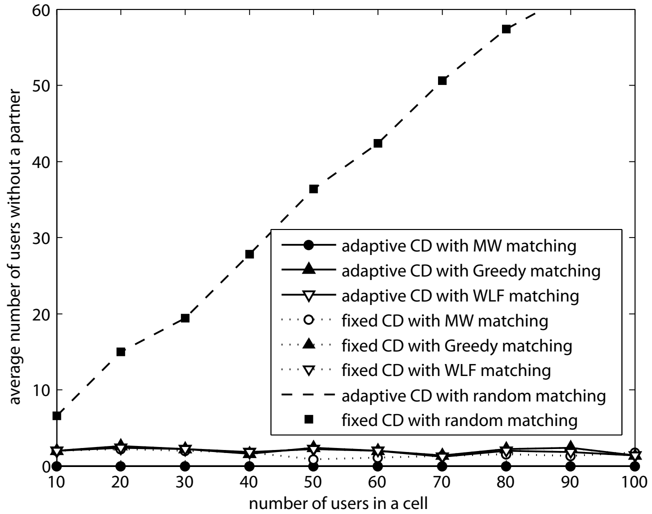


Fig. 5. Average number of users without a partner vs number of users in the cell.

$\angle ijj' < \angle ij'j$, and the distance between i and j is larger than the distance between i and j'. Therefore, $\sigma^2_{i,j} < \sigma^2_{i,j'}$. Consequently, given the BER requirements, the total energy consumption by cooperating users i and j' is smaller than that by users i and j.

Therefore, to obtain an upper bound of cell energy gain, it is sufficient to consider the one-dimensional case. That is, all users lie on the same straight line beginning at the BS, such that the distance between users i and j, $d_{i,j}$, equals $|d_i - d_j|$.

a) Fixed Regenerate-and-Forward CD Scheme: As an example, by substituting $k = 1$, $P_e = 10^{-3}$, $N = 128$, $N_0 = 1$ unit power/Hz, the CSIs in terms of distance, and $\alpha = 3$ into (5) and rearranging, we get $E^{no}_{b_i} + E^{no}_{b_j} - E^{S}_{b_i} - E^{R}_{b_j} - E^{S}_{b_j} - E^{R}_{b_i}$ in terms of d_i and d_j, which is maximized when $d_j = 0.85 d_i$ or $d_j = d_i/0.85$. It means that the most favorable matching for user i is a user located $0.85 d_i$ or $d_i/0.85$ away from the BS and on the line between user i and the BS. Therefore, to maximize the cooperative energy gain of the pair, $G_{i,j} = 10\log_{10}\left(\frac{E^{no}_{b_i}+E^{no}_{b_j}}{E^{S}_{b_i}+E^{S}_{b_j}+E^{R}_{b_i}+E^{R}_{b_j}}\right)$ should be maximized. For a given d_i, the maximum cooperative energy gain, $\max\{G_{i,j}\} = 9.63$ dB, is achieved when $d_j = 0.85 d_i$ or $d_j = d_i/0.85$.

It is noted that $\max\{G_{i,j}\}$ depends on the ratio of d_i and d_j only, and it is independent of the values of d_i and d_j. The upper bound on the cell energy gain can be achieved when all the users have cooperative partners ($K = N$ even number) and the cooperating pairs are located according to the ratio. Therefore, with the fixed CD scheme and other parameters, (α, k, P_e, N, N_0), as specified, (8) yields the upper bound of the network energy gain, which equals 9.63 dB. The energy gain contours are plotted in the Fig. 4: if the source node paired with a node located at the G dB contour, G dB cooperative energy gain can be achieved.

b) Adaptive Regenerate-and-Forward CD Scheme: Similarly, with the adaptive CD scheme, for a given d_i, $E^{no}_{b_i} + E^{no}_{b_j} - E^{S}_{b_i} - E^{R}_{b_j} - E^{S}_{b_j} - E^{R}_{b_i}$ is maximized when $d_j = 0.54 d_i$ or $d_j = d_i/0.54$. For a given d_i, the maximum cooperative energy gain, $\max\{G_{i,j}\} = 10.22$ dB, is achieved when $d_j = 0.54 d_i$ or $d_j = d_i/0.54$, and the upper bound of the cell energy gain with the adaptive CD scheme is 10.22 dB. Both the fixed and adaptive CD schemes have the same energy gain, 9.60 dB, when cooperative users are co-located and their inter-channel is error free. The energy gain contours with the adaptive CD scheme are also plotted in Fig. 4.

Comparing the contours of fixed CD and adaptive CD schemes in Fig. 4, since the fixed CD scheme is more sensitive to inter-user transmission errors, the cooperative energy gain for a particular user decreases quickly when the partner is far away from the user. For the adaptive CD scheme, the pair can still achieve quite significant energy gain even when they are far away from each other. As shown in Fig. 4, the cooperative region (in which a partner is located with certain dB cooperative energy gain) of the adaptive CD scheme is much larger than that of the fixed CD scheme.

B. Numerical Results

In this subsection, numerical results are presented for the four matching algorithms with both the fixed and adaptive CD schemes in a network with static users.

We generate a wireless network where the coordinates of the BS are $(0, 0)$. N users are randomly placed on a unit disk centered at the BS as given in Fig. 1, with their coordinates x and y uniformly distributed in $[-1, 1]$. The average CSIs are inversely proportional to d^{α}, where d is the distance between the sender and the receiver, and the path loss exponent α takes the value 3 in the simulation. The required BER is 10^{-3}.

Different user deployments are generated by using different random seeds. We assume that the BS can track the user locations, and thus determine their pair-wise distances and CSIs. From the CSIs, the average energy required for no cooperation and cooperation schemes are calculated, using (2) and (4), respectively. We change the number of active users in the network from 10 to 100 in order to consider both the low-density and high-density scenarios. The number of users without a partner and the average cell energy gains with the four matching algorithms are shown in Figs. 5 and

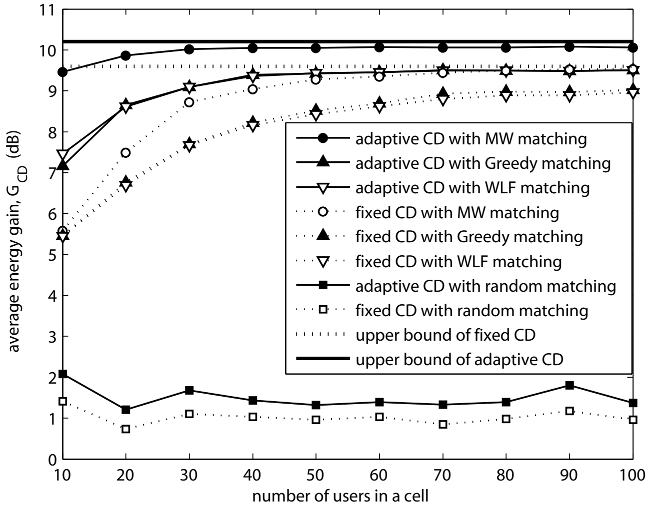


Fig. 6. Average energy gain.

6, respectively. All the results are obtained by averaging the performance parameters over 25 different user deployments.

As shown in Fig. 5, for both the fixed and the adaptive CD schemes with the MW, Greedy, and WLF matching algorithms, the number of users without a partner are independent of the number of active users in the network. Thus, the chance for a user without a partner is very low for a high-density network. On the other hand, with the random matching algorithm, the number of users without partner increases proportionally with the number of users in the network. This is because each user has a cooperative region, as shown in Fig. 4, only users in the cooperative region grouped together can obtain positive cooperative diversity gain. The probability of two randomly chosen users are within each other's cooperative region is constant, independent of the network density.

Fig. 6 shows that the average cell energy gains for the four matching algorithms. The gains of the MW, Greedy, and WLF matching algorithms increase with the number of users. This is because, as shown in Fig. 5, in a lower-density network, the chance for a user without a partner is higher, so the average cell energy gain is lower. To approach the analytical upper bound, the network should have a sufficiently large number of users, so every user can be grouped with an optimal partner. As shown in Fig. 4, the higher energy gain regions become smaller, so the energy gain of the cell increases slower when the number of active users is larger. In contrast, the random matching algorithm provides almost constant gain, independent of the number of users in the network.

From the numerical results, if a BS does not have the knowledge of the CSIs and just randomly matches users for cooperation, only about 1 dB or 1.5 dB cell energy gain over no cooperation can be achieved with the fixed CD scheme or the adaptive CD scheme, respectively. If the CSIs were available or could be estimated, the WM, Greedy, and WLF matching algorithms would achieve $5.5 \sim 9$ dB cell energy gain with the fixed CD scheme and $7 \sim 10$ dB cell energy gain with the adaptive CD scheme. In addition, the adaptive CD scheme outperforms the fixed CD scheme by about $1 \sim 2$ dB.

Although the WLF algorithm does not guarantee the worst case performance, extensive simulations demonstrate that, the performance of the WLF algorithm is close to that of the Greedy algorithm, and their average energy gains in a cell are about 1 dB less than that with the MW algorithm. The WLF algorithm is easier to implement than the MW and Greedy algorithms: the latter two require the matching gains of any pair of active users ($n(n-1)/2$ pairs) which are difficult to obtain. With the WLF, the BS can choose an unmatched active user with the farthest distance to the BS (or the worst channel condition to the BS) first. Then, according to Fig. 4, the BS selects an unmatched user in the high-dB-gain region to be its partner. In addition, the WLF algorithm can potentially be implemented in a distributed manner: each user chooses its desired partner; if there is any conflict, the user farther away from the BS (or has worse channel condition to the BS) has a higher priority. Due to space limitation, we do not further explore the distributed matching algorithm.

V. Performance in Mobile Networks

In mobile networks, user mobility complicates the matching problem. Since users may move in different directions at different velocities, and the velocities and directions change over time, their absolute and relative locations keep on changing. The currently best matching strategy may be less attractive or even no longer applicable after a while. Therefore, the matching algorithm should be periodically executed according to the current user locations and channel conditions.

A. *Matching Algorithms Considering Mobility*

Although more frequently updating the matching can more accurately track the locations and channel conditions of random and high-mobility users, it introduces significant overhead to not only the BS, but also the mobile users. Furthermore, mobile users need to synchronize with their new cooperative partners frequently. To reduce the overhead without significantly sacrificing performance, it is proposed to predict the future cooperative diversity energy gain of mobile users based on their current location and mobility information, and match users accordingly. How a BS detects the location and speed of active mobile users has been extensively studied in the literature, and the technologies have been used for E-911 service and other location dependent services.

The WLF matching algorithm considering mobility, which is periodically executed every T seconds, is as follows.

```
1  at time t, sort V according to CSIs
2  for each i ∈ V
3      MaxW = 0; partner(i) = 0
4      for (j = i+1; j < N; j++)
5          if v_j ∈ V
6              w(e_{i,j}) = f(w(e_{i,j}(t)), T)
7              if w(e_{i,j}) > MaxW
8                  partner(i) = j;
                   MaxW = w(e_{i,j})
9      remove i and partner(i) from V;
       add e_{i,partner(i)} to S
```

At time t, the set of N active users, $\mathcal{V}$, are sorted according to their channel conditions (CSIs), such that the user with the worst channel condition is considered first, as shown in Line

1. All users being grouped are removed from $\mathcal{V}$ (Line 9). For each unmatched user i, the BS calculates the cooperative diversity gain of i and another unmatched user j, $w(e_{i,j})$, (Lines 4, 5, 6). Note that $w(e_{i,j})$ is a function of $w(e_{i,j}(t))$ and T. $w(e_{i,j}(t))$ is the energy gain according to users i and j's current channel conditions or user locations (at time t). Assuming that the velocities and directions of i and j remain the same in the next T seconds, the BS can predict their future locations and channel conditions. $w(e_{i,j}(t+\delta))$ is the predicted energy gain according to the predicted user locations and channel conditions at time $t+\delta$. Function f in Line 6 calculates the average energy gain during t to $t+T$:

$$f(w(e_{i,j}(t)), T) = 1/T \int_t^{t+T} w(e_{i,j}(x))dx. \qquad (9)$$

To simplify the calculation, when T is small, $f(w(e_{i,j}(t)), T)$ can be approximated as $[w(e_{i,j}(t)) + w(e_{i,j}(t+T))]/2$. Similarly, the MW and Greedy algorithms can be modified by using the average cooperative diversity gain during $[t, t+T]$ as the weight.

There are certain implications that the system designers may consider. First, to reduce the overhead by lengthening T, the prediction of future user channel conditions and locations become less accurate, which will degrade the overall cell energy gain. Second, even if all active users keep their current velocities and directions for a long time, less frequently updating of the matching will also reduce the overall cell energy gain. This can be illustrated as follows. Observe l consecutive time slots, $t_1, t_2, ..., t_l$, where each slot has a very short duration ϵ. Assume that the user locations and channel conditions remain the same in each slot. If the maximum weighted-matching algorithm is executed at each slot, the energy gain in that slot will always be the highest among any matchings. Therefore, by executing the MW algorithm at each slot, the energy gain is always better than or equal to matching once for a period of l time slots. Third, if the matching algorithm is executed only once per T sec, and user mobility estimation is accurate, using $w(e_{i,j}) = f(w(e_{i,j}(t)), T) = 1/T \int_t^{t+T} w(e_{i,j}(x))dx$ in the MW algorithm also leads to optimal matching for overall energy gain of the cell during t to $t+T$. This is because the overall energy gain of the cell during t to $t+T$ is $\int_t^{t+T} \sum_{e_{i,j}\in\mathcal{S}} w(e_{i,j}(x))dx = \sum_{e_{i,j}\in\mathcal{S}} \int_t^{t+T} w(e_{i,j}(x))dx$, which is maximized using the MW algorithm.

B. Numerical Results

We consider a wireless mobile network in which the users are uniformly distributed over a $(4R)^2$ square area, as shown in Fig. 7. The BS is located at the center of the square, covering all active users in the disk centered at the BS with radius R. The mobile users move at constant velocities and the directions of motion are independent and identically distributed (i.i.d.) with uniform distribution in the range $[0, 2\pi)$. If a mobile user reaches the edge of the square, it will be bounced back and move with the same velocity. The velocity is a uniformly distributed random variable in the range $[0, V_{\max}]$. In the simulation, a user chooses a direction and a velocity, and moves in that direction (unless being bounced back) at the constant velocity for a time duration t_d, which is also uniformly distributed in the range $(0, t_{\max})$ slots. After t_d, the process repeats. The matching algorithm will be executed every T seconds. The grouped pairs will cooperate with each other till new matching results separate them, or when any of them moves out of the cell or when there is no longer any cooperative diversity gain between them. We use the following parameters in the simulations. The number of active users in the square area is 200. The normalized velocity V_{norm}, which is defined by $V_{norm} = \frac{V_{\max}T}{R}$, is set to 0, 0.25, 0.5, 0.75, 1, which cover the static, low mobility, and high mobility cases.

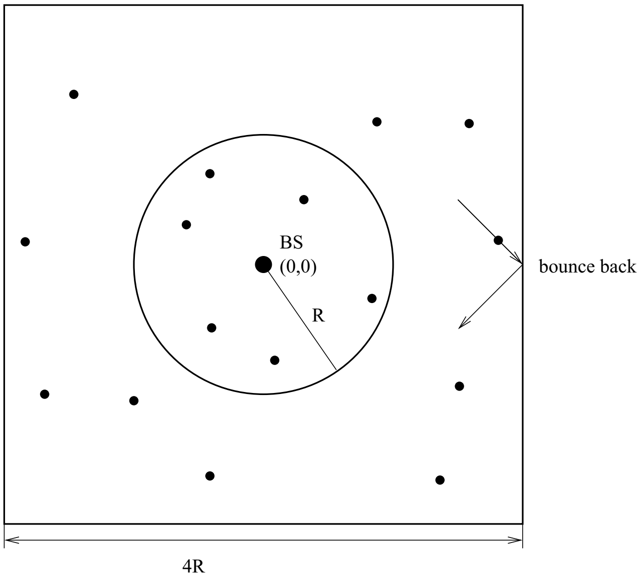


Fig. 7. Mobility model.

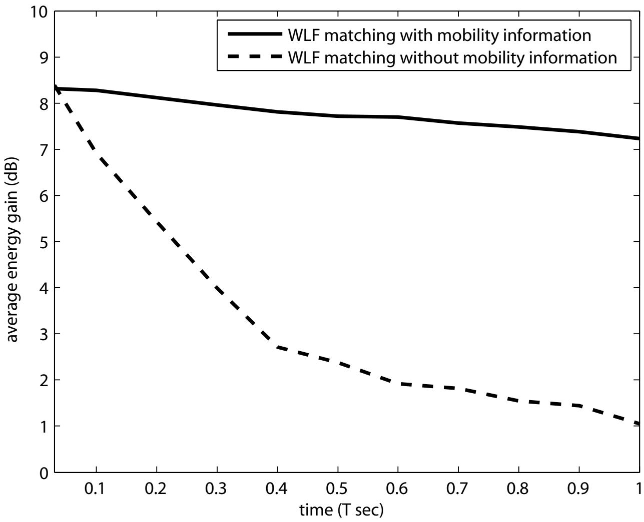


Fig. 8. Average energy gain of WLF matching with and without mobility information.

The energy gain achieved by the WLF matching algorithm for the adaptive CD scheme with and without mobility are shown in Fig. 8. It can be seen that for $V_{norm} = 1.0$, from the time after the matching ($t = 0$) to the time just before the next matching ($t = T$), the cell energy gain with the WLF algorithm without mobility information quickly drops from 9 dB to 1 dB. On the other hand, with the same user deployment, the WLF algorithm with mobility information maintains a high cell energy gain (above 7 dB). The simulation results confirm that if we intelligently apply the mobility information in the matching algorithm, a significant cell energy gain can be achieved for mobile networks. Similar results are obtained for both the adaptive CD scheme and the fixed CD scheme, with the MW, WLF and Greedy algorithms. In the following, we focus on matching algorithms with mobility information, and compare their performance metrics.

The percentage of in-cell users participating in the cooperation (specifically in the matching process) is approximately $(1-0.3V_{norm})$. In the low mobility situation ($V_{norm} < 0.25$), more than 90% of the in-cell users participate in the cooperation. It is reduced to 70% for the high mobility situation, i.e., $V_{norm} = 1$. On the other hand, the average energy gain decreases as V_{norm} increases, as shown in Fig. 9. With other CD scheme or matching algorithms, the same trend can be observed for the average energy gain versus V_{norm} curve. This is due to two factors. First, the percentage of participating users remaining in the cell for a given duration T decreases as V_{norm} increases. Second, with high mobility, even if the matching is ideal at the beginning of a slot, it becomes less favorable or even impractical at the end of the slot.

Fig. 9 demonstrates the tradeoff between the performance and overhead. If the BS updates the matching more frequently, *i.e.*, T is shorter, V_{norm} can be reduced and higher cell energy gain can be achieved; otherwise, the BS updates the matching less frequently with less overhead and less energy gain.

The simulation results show that the WLF algorithm outperforms the Greedy algorithm in mobile networks. The performance of the WLF and MW algorithms degrade gracefully when V_{norm} is higher, and the performance of Greedy matching algorithm degrades quickly with higher mobility. In addition, the adaptive CD scheme outperforms the fixed CD scheme by a larger margin with higher mobility. This is because, according to Fig. 4, the high gain area is much smaller with the fixed CD scheme than that with the adaptive CD scheme, so the partners easily move outside the high gain area with the fixed CD scheme.

VI. Related Work

At the physical layer, CD schemes have been extensively investigated in the literature [1]–[7]. Recently, the networking aspect of CD systems begins to get attention. How to choose relaying partners in infrastructure-based and ad hoc networks has become an active research topic [15]–[17]. In [15], a forwarding technique based on geographical location of the involved nodes is proposed. How to randomly select the relaying node via contention among receivers for ad hoc networks is also studied. In [16], selection of the best relay based on local measurements of the instantaneous channel conditions is presented. How to group users in CD systems in which the performance of matching algorithm, in terms of average outage probability, is first studied in [11]. However, how much energy gain can be maximized in a network remains unsolved. The network lifetime of wireless (static) sensor networks deploying a CD scheme, defined as the time until 1% of the nodes in the network die, is investigated in [18]. To the best of our knowledge, this paper is the first to systematically

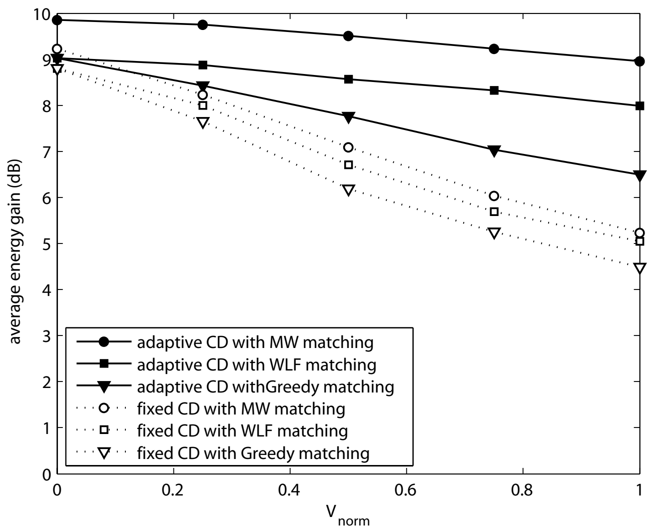


Fig. 9. Average energy gain vs. normalized velocity.

study the cell energy gain and matching algorithm computational complexity tradeoff in CD systems, and propose how to appropriately incorporate mobility information in matching algorithms for mobile networks.

Matching theory and algorithms have been extensively investigated in the past for other applications, *e.g.*, scheduling, assignment. Both the state-of-the-art algorithms to obtain the optimal matching, and approximation algorithms have been reported. The proposed WLF matching algorithm considers the fact that the nodes with worse channel condition generally get more benefits from the cooperation, which is not obvious in other applications. Furthermore, there are some characteristics which are unique in CD systems; thus, it is worth to re-investigate matching algorithms for this particular problem, and we anticipate more results in this interesting area.

VII. Conclusions

We have studied the energy gain provided by four matching algorithms, the MW, Greedy, random, and the proposed WLF matching algorithms, with computational complexity of $O(n^3)$,$O(n^2 \log n)$, $O(n)$, and $O(n^2)$, respectively, for both fixed and adaptive CD systems. We have further proposed how to optimally match mobile users considering user mobility. Simulation results demonstrate that, by intelligently applying user mobility information in the matching algorithm, high energy gain with moderate overhead is achievable in mobile networks. It is conjectured that our study provides insights into the tradeoff between matching overhead and energy gain in a wireless network, which is an important step toward practically deploying CD schemes in wireless networks. In this paper, we have considered the matching problem in a single-cell of a wireless mobile network. How to optimally match users in multi-cell systems with the effects of handoff and multiple access interference are under investigation.

Appendix I

1. α: path loss exponent of the wireless channel
2. $\bar{\gamma}_i^{no}$: average SNR, equal to $\sigma_i^2 E_{b_i}^{no}/N_0$
3. $\bar{\gamma}_i$: average SNR, equal to $\sigma_i^2 2E_{b_i}^{S}/N_0$
4. $\bar{\gamma}_j$: average SNR, equal to $\sigma_j^2 2E_{b_j}^{R}/N_0$
5. $\bar{\gamma}_{i,j}$: average SNR, equal to $\sigma_{i,j}^2 2E_{b_i}^{S}/N_0$
6. σ_i^2, $\sigma_{i,j}^2$: variance of the channel fading coefficient
7. $E_{b_i}^{no}$: energy consumption of transmitting a bit by user i using the non-cooperative scheme
8. $E_{b_i}^{S}$: energy consumption of transmitting a source's (user i) bit by user i using the cooperative scheme
9. $E_{b_i}^{R}$: energy consumption of relaying a bit at user i for the cooperative scheme
10. d_i: distance between user i and the BS
11. $d_{i,j}$: distance between user i and user j
12. $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$: a graph, where $\mathcal{V}$ is a set of vertexes and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is a set of edges between vertexes
13. $G_{i,j}$: energy gain of cooperation between users i and j
14. G_E: energy gain of the network with cooperation over that without cooperation (in dB)
15. P_e^i: the maximum tolerable bit error rate of user i
16. R: radius of the cell centered at the BS
17. $\mathcal{S}$: a *matching* subset of $\mathcal{E}$ if no two edges in $\mathcal{S}$ share the same vertexes
18. T: the period of matching algorithm being executed
19. $V_{\max}$: the max velocity of mobile users
20. V_{norm}: the normalized max velocity of mobile users
21. $w(e_{i,j})$: the energy gain by cooperation between the two users i and j over no cooperation

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