Interactive Communication for Resource Allocation

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***Abstract*—For the resource allocation problem in a multiuser OFDMA system, we propose an interactive communication scheme between the base station and the users with the assumption that this system utilizes a rateless code for data transmission. We describe the problem of minimizing the overhead measured in the number of bits that must be exchanged required by the interactive scheme, and solve it with dynamic programming. We present simulation results showing the reduction of overhead information enabled by the interactive scheme relative to a straightforward one-way scheme in which each user reports its own channel quality.**

***Index Terms*—Resource allocation, interactive communication, dynamic programming.**

I. Introduction

Orthogonal frequency division multiple access (OFDMA) is widely used in modern downlink cellular systems. In a multiuser OFDMA system, resource allocation and link adaptation are crucial ingredients. Under resource allocation, each subcarrier needs to be assigned to a user by the base station, while under link adaptation a modulation and coding scheme must be selected for use for communicating to a user that enables it to reliably receive information.

Under many traditional resource allocation and link adaptation architectures, such as those utilized in the Long Term Evolution 3GPP standard, channel quality indicators are sent as uplink feedback, and these are utilized to determine which user should get which subcarriers as well as deciding the coding scheme. These channel quality indicators are often defined as the index of the highest rate modulation and coding scheme, among those that are possible to be selected by the basestation, that the user's associated downlink channel can currently support with a target block error probability. For instance, the modulation and coding schemes and associated channel quality indicator levels for the LTE standard are displayed in Table I as specified via Section 7.1 & 8.6 in [1] and discussed in [2], [3], [4], [5], [6], [7].

Once the base-station has decided which user to schedule on a particular collection of subcarriers, and which modulation and coding scheme to employ in its communication with them, it must signal this resource decision, both the subcarriers assigned and the modulation and code employed, on the downlink as overhead control information in addition to the data to be transmitted to the user itself.

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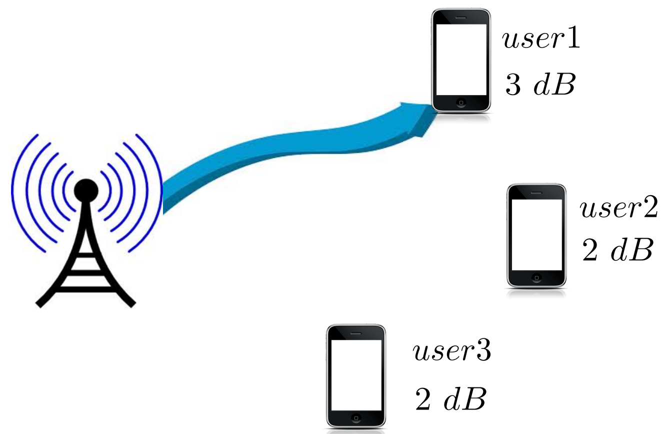

Fig. 1. We consider a resource allocation/link adaptation problem in which a basestation wishes to maximize the system spectral efficiency by scheduling the user with the highest channel quality.

These resource decisions control information, along with the channel quality indicator feedback utilized to make them, create control overheads in the multiuser OFDMA system that are surprisingly large, with the control information such as resource decisions and reference signals typically occupying roughly a quarter to a third of all downlink transmission in the LTE standard [8]. This overhead is growing significantly as cellular standards incorporate additional otherwise capacity improving features such as coordinated multipoint and carrier aggregation [9], [10], [11], [12], [13], [14]. Since time frequency resources utilized for control information must be taken from resources that could be used for data transmission, the problem of determining how to efficiently encode channel quality feedback from the view of both information theory and communication is important [15].

Meanwhile *Rateless coding*, also known as fixed-to-variable coding [16], can achieve performance close to channel capacity without requiring the explicit feedback of channel state information and use of adaptive modulation and coding in a single user system [17], [18]. These schemes operate by enabling the block length (in channel uses) for the modulation and coding to stretch or shrink based on the received channel

MCS	CQI	Modulation	Code rate	Spectral Efficiency	MCS	CQI	Modulation	Code rate	Spectral Efficiency
-	0	Out of range			15	9	16QAM	0.6015	2.4063
-	1		0.0761	0.1523	16			0.6425	2.5684
0	2		0.1171	0.2344	17			0.4277	2.5684
1			0.1533	0.3057	18	10		0.4550	2.7305
2	3		0.1884	0.3770	19			0.5048	3.0264
3			0.2451	0.4893	20	11		0.5537	3.3223
4	4	QPSK	0.3007	0.6016	21			0.6015	3.6123
5			0.3701	0.7393	22	12	64 QAM	0.6503	3.9023
6	5		0.4384	0.8770	23			0.7021	4.2128
7			0.5136	1.0264	24	13		0.7539	4.5234
8	6		0.5878	1.1758	25			0.8027	4.8193
9			0.6630	1.3262	26	14		0.8525	5.1152
10			0.3320	1.3262	27			0.8886	5.3349
11	7		0.3691	1.4766	28	15		0.9257	5.5547
12		16 QAM	0.4238	1.6953	29		QPSK		
13	8		0.4785	1.9141	30		16QAM	Reserved	Reserved
14			0.5400	2.1602	31		64QAM		

TABLE I
SUPPORTED MCS INDEX & ASSOCIATED CQI IN THE LTE STANDARD

quality in a manner that closely resembles H-ARQ. Rather than feeding back channel quality, the receiver only needs to indicate when it has successfully decoded as its feedback, which it learns through an outer error detection code.

However, once one passes back to a multiuser OFDMA context, it is again necessary to know who to schedule the blocks of subcarriers to, even if a rateless code is to be employed. If the base station in multiuser OFDMA system utilizes rateless codes and wishes to maximize the sum rate across users, the uplink feedback only needs to enable the basestation to learn which user has the best channel SNR (i.e. the highest capacity, Fig.1), but not the value of this best channel SNR. Hence the resource allocation feedback problem can be modeled as a distributed function computation problem, where the basestation must compute who among a series of users has the best channel quality from a series of messages sent by the users which initially know only their own channel qualities.

Interactive communication is the scheme that allows message passing forward and backward multiple times between two or more terminals [19]. It has been shown that interactive communication can provide substantial benefits over non-interactive codes in some distributed function computation problems [20].

In this paper, we consider the multiuser OFDMA systems that use rateless AWGN codes for downlink data transmission. Inspired by the ideas of selective multiuser diversity [21] (SMUD) scheme as well as the multi-predefined thresholds [22] scheme which is an extension of SMUD, we propose an achievable interactive communication scheme between the base station and the users that efficiently encodes the feedback necessary for the resource allocation and link adaptation problem. We show that there is a saving of overhead bits when interaction is utilized when compared with the straightforward one-way scheme in which each user feeds back its own channel quality.

II. PROBLEM MODEL

We consider the resource allocation problem for a single resource block (a collection of subcarriers which, owing to the parameters of the OFDMA system and the channel, have roughly the same channel fade) with a base station and N different users. The channel SNR between the base station and each user is modeled as an identical independent discrete random variable with support set $\mathscr{X} = \{a, \cdots, b\}$ and probability mass function $f_0(x)$, and is initially known to the associated users, and is fixed during the whole block of data transmission. To maximize the throughput, the basestation wishes to select the user with the highest channel quality to occupy the channel. In contrast to the traditional adaptive modulation and coding scheme, we assume the base station uses a rateless code for data transmission, hence, once a user is picked, we can almost achieve its channel capacity without

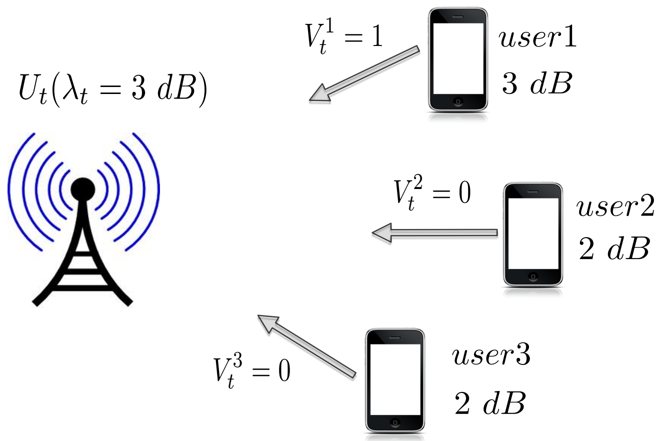

Fig. 2. One round illustration of the interactive scheme between BS and users

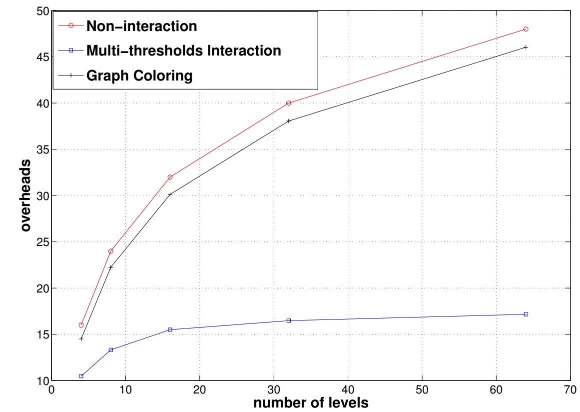

Fig. 3. Multi-thresholds interaction Vs. non interaction. The initial number of users is 8.

knowing the channel state at the transmitter. Therefore, the resource allocation problem is to determine who has the best channel. The basestation wishes to determine this information based on mutliple rounds of communication with the users. As depicted in Fig. 2, at round t, we will denote the message that the base station broadcasting to the users by U_t, and the message that the user i feeds back to the basestation V_t^i.

One achievable scheme to determine the best channel works as follows: at round t, the base station broadcasts a threshold λ_t to all users; for each user, if its channel SNR is above the threshold, it replies a 1, otherwise it replies a 0. Clearly, V_t^i will be no more than 1 bit. The whole process will stop at round T if there is only one user above the threshold λ_T or if there are multiple users above the threshold but the support set shrinks to 1 (which means all users have the same SNR level).

Additionally, again with the purpose of reducing overhead, we allow the users that must not be the best to stop replying, i.e. if one or more users replies a 1 during round t, then certainly all users replying 0 do not need to be involved in future rounds. We also argue that the base station's knowledge of the channel distribution will be more specific after each round of interactive communication. Bearing this in mind, we will let N_t denote the number of "online" users at round t.

III. Analysis

Our aim in this section is to determine the optimal choice of the thresholds in the interactive scheme in the sense of minimizing the average total amount of overhead that the scheme must incur.

A. Multi-threshold Interactive Communication Scheme

Given (at round t) channel CMF $F_t(x)$, PMF $f_t(x)$ and support set $\mathscr{X} = \{a_t, \cdots, b_t\}$, the base station determines and broadcasts an optimal threshold based on its knowledge of channel information and number of online users N_t. After receiving all feedbacks, the base station can renew the channel information for next round's communication. If more than one user replies a 1, then conditioned on all the information received thus far, the new channel distribution parameters for the active users are

$$\begin{aligned} a_{t+1} &= \lambda_t \\ b_{t+1} &= b_t \\ F_{t+1}(x) &= \frac{F_t(x) - F_t(\lambda_t)}{F_t(b_t) - F_t(\lambda_t)} \end{aligned} \tag{1}$$

While if all users reply 0, then conditioned on all the information received thus far at the basestation, the new channel distribution parameters for the active users are

$$\begin{aligned} N_{t+1} &= N_t \\ a_{t+1} &= a_t \\ b_{t+1} &= \lambda_t \\ F_{t+1}(x) &= \frac{F_t(x) - F_t(a_t)}{F_t(\lambda_t) - F_t(a_t)} \end{aligned} \tag{2}$$

At a given round, a user will stay active for the next round if it feedback a 1. Alternatively, if a user feeds back a 0, if the next threshold λ_{t+1} is lower than λ_t (which indicating that all users replied 0 at round t) it will stay active, otherwise this user becomes inactive. Owing to the symmetry regarding the knowledge the basestation has about the active users, the threshold for next round will be generated based on the renewed channel information and number of users remaining active.

Define R to be the total expected number of overhead bits exchanged when using the series of threshold levels $\lambda_1, \lambda_2, \cdots$, and define $R*$ to be the minimum expected number of overhead bits exchanged by using using the optimal threshold $\lambda_1^*, \cdots, \lambda_T^*$. It is clear that R^* will be a function of the initial number of users N_1 (all of whom are initially active) and channel distribution.

$$R^*(N_1, \{a_1, b_1\}, F_1(x)) \tag{3}$$

We observe that if policy $\lambda_1^*, \cdots, \lambda_T^*$ is the optimal choice of thresholds for initial condition N_1, $\{a_1, \cdots, b_1\}$ and $F_1(x)$

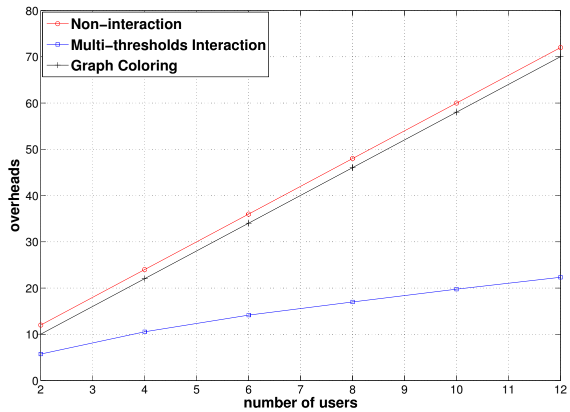

Fig. 4. Multi-thresholds interaction Vs. non interaction. The initial support set is $\{1, \cdots, 64\}$

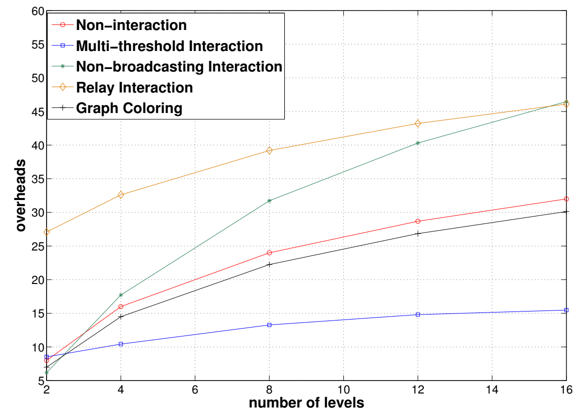

Fig. 5. A comparison of the three interactive schemes with 8 users

then the truncated policy $\lambda_t^*, \cdots, \lambda_T^*$ will be the optimal choice of thresholds for initial condition N_t, $\{a_t, \cdots, b_t\}$ and $F_t(x)$, and thus the problem has the form of a dynamic programming problem. In order to solve this problem, we begin with a a one round analysis in which we assume to we pick λ as the threshold for round t and that the thresholds after round t have been optimized already. Define $R_t(\lambda)$ as the sum of the overheads from round t to the end, then

$$R_t(\lambda) = H(\lambda_t|\lambda_1, \cdots, \lambda_{t-1}) + N_t + (F_t(\lambda))^{N_t} R^*(N_t, a_t, \lambda) + \sum_{i=1}^{N_t} (1 - F_t(\lambda))^i F_t(\lambda)^{N_t - i} \frac{N_t!}{i!(N_t - i)!} R^*(i, \lambda, b_t) \quad (4)$$

where the first item represents the minimum number of bits needed to let the users know the threshold in round t, the second item represents the total number of bits of feedback from the N_t users, and the remaining two items represent all possible cost after round t. The optimal choice of threshold at round t then must satisfy

$$\lambda_t^* = \operatorname*{argmin}_{\lambda} R_t(\lambda) \quad (5)$$

(4) and (5) together form a policy iteration algorithm[23] for this dynamic programming problem.

B. Thresholds Vs. Number of Users

Let us now consider several possible methods of encoding the threshold, and hence several possible values for the quantity $H(\lambda_t|\lambda_1, \cdots, \lambda_{t-1})$ in (4). The minimum information the BS needs to broadcast should be the conditional entropy of the threshold given all previous knowledges that the active users have. This side information includes the users own channel quality, however, we consider an upper bound where we only utilize the side information provided by the previous thresholds as the notation $H(\lambda_t|\lambda_1, \cdots, \lambda_{t-1})$ suggests.

For the purposes of comparison, and ease of the associated algorithm encoder design, let's also consider two additional coding strategies which are easy to implement. We will see that these two strategies also have lower overheads than the non-interaction scheme. The first strategy is to encode the threshold with no conditioning:

$$U_t = H(\lambda_t) = \log_2 |\mathscr{X}_t| \quad (6)$$

Motivated by the idea that the users may calculate the optimal choice of threshold themselves rather than receiving it, we provide the second strategy that the BS broadcasts the number of currently online users. Observe that the optimal policy λ^* at each round is determined by the information the BS has, including the number users N_t, the estimated distribution $f_t(x)$ and the support set $\mathscr{X} = \{a_t, \cdots, b_t\}$ of the channel distribution. We prove that it's enough to let the users calculate the threshold by broadcasting N_t by induction:

Proof: Each user has the channel pdf $f_1(x)$, $\mathscr{X}_1 = \{a_1, \cdots, b_1\}$ and its own channel SNR C_i. Hence the optimal threshold λ_1^* can be calculated after receiving the initial number N_1. The users will reply 1 bit feedback based on this threshold.

Suppose that the users successfully compute the threshold λ_{t-1}^* by the information N_{t-1}, f_{t-1} and $\mathscr{X}_{t-1} = \{a_{t-1}, \cdots, b_{t-1}\}$ in round t-1, then in round t the $\mathscr{X}_t$ will be renewed by the following rules:

$$\mathscr{X}_t = \begin{cases} \{\lambda_{t-1}^*, b_{t-1}\} & if\ N_t < N_{t-1} \\ \{a_{t-1}, \lambda_{t-1}^*\} & if\ N_t = N_{t-1}\ and\ \lambda_{t-1}^* > C_i \\ \{\lambda_{t-1}^*, b_{t-1}\} & if\ N_t = N_{t-1}\ and\ \lambda_{t-1}^* \leq C_i \end{cases} \quad (7)$$

Note that the user will turn off if $N_t < N_{t-1}$ and $\lambda_{t-1}^* > C_i$. The channel distribution $f_t(x)$ is easy to get once the support set has been renewed. Therefore, the threshold λ_t^* can be determined by the users. ■

IV. Results

Having identified the policy iteration form of the problem of minimizing the expected number of overhead control bits exchanged for the multi-thresholding method for determining the user with the best channel quality, we now pass to solving

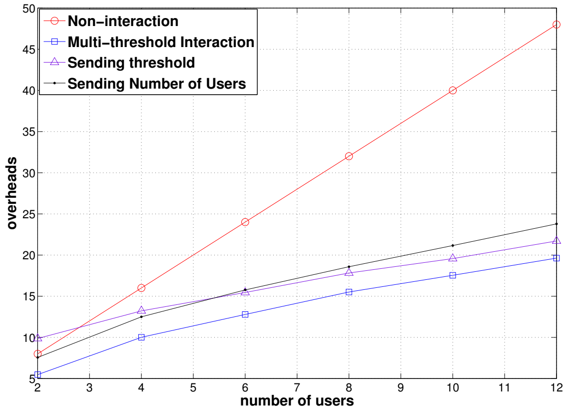

Fig. 6. A comparison of sending thresholds and sending number of users, fixing the initial support set to be $\{1, \cdots, 16\}$.

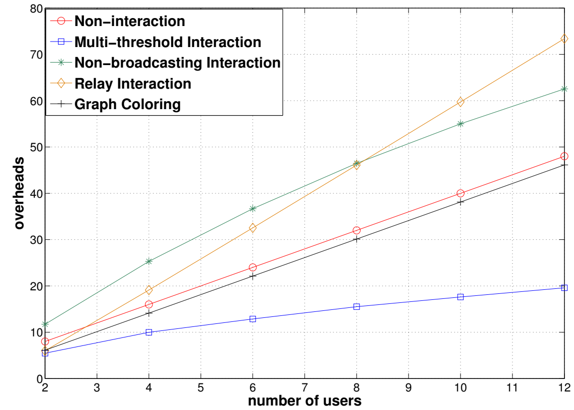

Fig. 7. A comparison of the three interactive schemes with 16 CQI levels

the policy iteration for the various methods of communicating the thresholds. (4) and (5) can be solved by iteration with the boundary conditions:

$$\begin{aligned} R^*(1, a, b) &= 0 \\ R^*(N, a, a) &= 0 \end{aligned} \tag{8}$$

The first boundary condition represents the situation that the user with highest SNR has been found, while the second boundary condition represents the situation that the support set shrinks to 1 and all the remained users have the same SNR level, we will stop our algorithm and pick any one of them since there will be no capacity loss. Uniform distribution of the channel SNR is used in simulation. Fig.3 shows the overheads of multi-thresholds interactive communication scheme Vs. non-interactive scheme with number of initial users to be 8 while Fig.4 shows with initial support set to be $\{1, \cdots, 64\}$. These first two plots consider the case where the basestation uses a number of bits equal to the conditional entropy of the threshold at time t given all the previous threshholds and initial information which include number of users N_1, channel pdf $f_1(x)$ and support set $\mathscr{X}_1 = \{a_1, \cdots, b_1\}$. We've also included for the purposes of comparison the minimal number of bits necessary to losslessly calculated the $\arg\max$ when there is no-interaction. This is slightly less than the non-interaction scheme, and is depicted by the black curve in Fig. 3 and Fig. 4, and can be calculated by coloring a characteristic graph based on the predefined $\arg\max$ function. Each user then sends its color by compressing it with a Slepian-Wolf like code[24]. From both figures we can see a huge saving of overhead can be achieved through interaction when trying to determine who has the best channel quality.

As mentioned in previous section, we also suggested two simple encoding strategies for the base station to broadcast which include Huffman encoding the threshold(with no conditioning on previous thresholds) and Huffman encoding the number of users. Fig.6 shows the number of bits that must be exchanged when these methods are used. The strategy of sending threshold outperforms the strategy of sending number of users in the situation that the initial number N_1 is large. When N_1 is small, the latter one shows better performance.

A. Compare with Some Other Interactive Schemes

As another interesting point of comparison, we compare our multi-thresholding scheme with another two interactive schemes. These two schemes are based on the assumption that each user has its own index so that the communication can follow the index order. Unlike the multi-threshold scheme in which messages can only be exchanged between basestation and users, we propose the first scheme as follows: User 1 transmit its channel SNR and index to user 2. User 2 then calculate the higher SNR between them and sent it with its index(the $\arg\max$) to user 3. Every user will sending the max and $\arg\max$ to the next one after receiving information from previous user and the last user will directly tell the base station the $\arg\max$. We call such a scheme the relay interaction scheme. The second interaction scheme (which is listed in[20] as an example to show that interaction can help in multi-terminal function computation problem) has a constraint that the BS can only talk to one user at a time. This scheme still starts from user 1 transmitting its channel SNR to the base station. The BS then forwards user 1's SNR to user 2. At round t, the BS will tell user t the maximum SNR among the first t-1 users, the user t will then compare it with its own channel quality and feedback the answer to the base station.The user with the best channel can be determined after this scheme. We call this scheme the non-broadcasting interaction scheme.(Fig. 8) For uniform distributed channel SNR, we can see the non-broadcasting scheme has better performance than multi-threshold scheme when there is only two users. For most of the cases, the multi-threshold scheme utilizes fewer overhead bits than the other two schemes, as is shown in Fig.5 and Fig.7.

V. Conclusions and Future Work

We considered the problem of designing resource allocation and link adaptation schemes for multiuser OFDMA systems

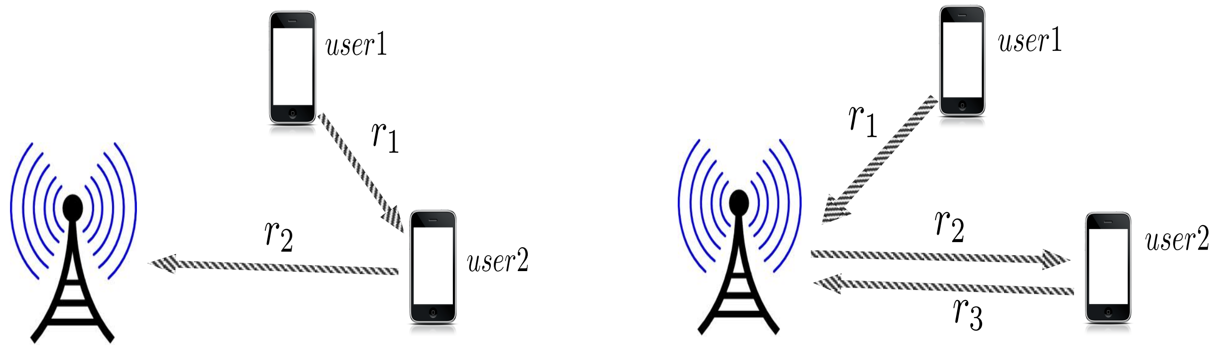

Fig. 8. System diagram of the relay interaction scheme and non-broadcasting interaction scheme

that utilizing rateless codes for downlink data transmission. Using principles from dynamic programming, we have derived a multi-threshold interactive communication scheme for the resource allocation problem, and demonstrated it to be superior in terms of the amount of overhead information required to the optimal non-interactive scheme based on graph coloring, as well as several other intuitive interactive schemes. The key approach here is to move away from thinking about channel feedback as quantization, and move instead toward only feeding back that information necessary to make multiuser scheduling decisions. We expect this approach to provide additional insight in other more complicate resource allocation and link adaptation models involving MIMO communications, and this is one important future direction for the work.

It is also evident that although we have optimized its expected amount of overhead through dynamic programming, the proposed multi-thresholding scheme is just an achievable scheme for the distributed interactive function computation. The expression of fundamental limits for general interactive communication problem has been given[19][20]. Another important direction we are pursuing for future work is to calculate these fundamental limits for the minimum amount of information that has to be exchanged in an interactive scheme to lossless determine the argmax, and comparing this with the expected number of bits required by our dynamic programming optimized approach.

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