An Iterative Resource Allocation Algorithm for Cooperative Multimedia Communications

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***Abstract*—Transmit diversity through user cooperation is an attractive proposal for performance enhancement in a mobile communication network. Given the availability of multiple transmission channels from multiple users, we are concerned with the channel, power and rate assignment scheme that offers the maximum capacity while satisfying the multimedia multi-rate requirements. Earlier cooperative schemes often assume that a central processing device is available to find the optimal or suboptimal solution. The corresponding high computing complexity, however, makes the implementation of an energy-efficient cooperative transmission not very practical. In this paper, we present a simple resource allocation scheme that enables each participant user to easily and independently find a near-optimal channel assignment matrix and power allocation vector under certain constraints. Our solution can be used for both mono-rate and multi-rate applications. It is optimal for the former case and gives near-optimal performance for the latter case.**

I. Introduction

Multiple-input/multiple-output (MIMO) techniques, in particular, transmit diversity, can be used to combat fading in a wireless environment. However, due to the size limitation, it is not very desirable for a mobile unit to have multiple antennas. In a multiuser communication scenario, nevertheless, transmit diversity can be realized through user cooperation that allow a user with no physical arrays to achieve the spatial diversity by exploring other users' antennas.

The concept of cooperative diversity was introduced in [1], [2] where a CDMA-based two-user cooperative communication scheme that allows a user to act as a relay to retransmit the estimated data of its partner's information in the highest possible uplink transmission rate. The simple relay technique was extended by [3] [4] to a variety of cooperative strategies. In [5], the outage and the ergodic capacity behavior of various cooperative protocols, e.g. detect-and-forward and amplify-and-forward protocols are derived. In addition, [6] considers a cooperative broadcast strategy with an objective to maximize the network lifetime.

Most of previous works concentrated on the improvement of the peer-to-peer link quality and presented some cooperative schemes without considering the implementation complexity. Zhu *et al.* [7] proposed a method to solve the problems about who should help whom and how to cooperate over a multiuser OFDM network. Although their algorithm leads to optimal performance, the associated computing complexity is relatively high for a mobile device.

Water-filling-like algorithms for optimal power allocation with prescribed error tolerance for various systems have been proposed [7][8][9]. These algorithms are basically exhaustive searches and there is no guarantee that the optimal solution can be found. In this paper we generalize the problem setting and present a very efficient iterative algorithm that is guaranteed to yield the optimal solution for mono-rate transmissions. For multiple rate applications, we need an extra step for channel assignment and the overall algorithm is proved to provide near optimal solution.

We assume a locally cooperative communication scenario in which the user terminals are located within a small neighborhood so that the inter-user distance is far smaller than than the terminal-to-base-station distance. Such a scenario occurs when a group of dual-mode handsets or PDAs are equipped with both WiFi and cellular capabilities and form a local area network (LAN). We assume that information/data can be exchanged within this LAN without error. Our solution provides efficient channel, power and rate assignment that achieve high capacity with minimum power or energy.

The rest of this paper is organized as follows. The ensuing section describes the assumed operation scenario and the problem of concern. We present the optimal mono-rate uplink transmission scheme and a near-optimal multimedia multirate scheme for locally cooperative communication in Section III. Performance of the optimal and the proposed schemes are compared in the same section. Numerical results and related discussion are presented in Section IV. Finally, some concluding remarks are given in the last section.

II. Scenario and Problem Statement

A. Scenario and assumptions

As the demand for higher data rate multi-media wireless communications increases it also becomes more and more important that one takes into account the energy-efficiency factor when designing an anti-fading transmission scheme for mobile terminals. Cooperative communication is an attractive alternative candidate technique as it offers the potential to

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achieve an enhanced performance-resource ratio through transmit diversity and improved inter-user resource allocation. We assume a locally cooperative communication scenario in which the user terminals are located within a small neighborhood so that the inter-user distance is far smaller than than the uplink (terminal-to-base-station) distance. The users who are willing to join in a cooperative communication mode form a cooperative communication network. When a user terminal decides to solicit for transmission aid, it broadcasts its requirement to its peers in the network. Upon receiving the request for cooperation, other network users will send their reply to inform the requester(s) the resources to be offered and their conditions. The resources includes available power, bandwidth, and perhaps time. For simplicity we shall convert these resources into the number of virtual orthogonal channels (VOCs) which can be used to access the base station of interest so that the resource condition of interest is the corresponding channel-gain-to-noise ratios.The number of VOCs includes the number of the orthogonal subcarriers [7] which are unused or any other forms of orthogonal channels like the number of eigen-channels in a MIMO wireless link.

We assume that there are N orthogonal (independent) Rayleigh-faded VOCs within the network and each virtual channel occupies the same bandwidth W during a fixed transmission time. Consequently, the number of VOCs can be expressed as $N = \sum_{i=1}^{K} m_i$, where m_i denotes the number of VOCs supplied by the ith user, and K represents the number of users in the cooperative network . The number of the transmission rates d is given by $d = \sum_{i=1}^{\hat{K}} n_i$ where n_i is the number of distinct transmission rates posted by ith user and $\hat{K}$ is the number of users (help-seekers) who have solicited their transmission cooperation requests. Obviously, $\hat{K} \leq K$. It is assumed that the mobiles who join locally cooperative communication network can perfectly acquire the allocation information/data from the desired users. The transmission rate r_i supplied by the ith virtual channel with the corresponding transmitted power p_i can be given by

$$r_i = W_i \log_2 \left(1 + \frac{p_i h_i}{\sigma_i^2}\right), 1 \leq i \leq N \tag{1}$$

where h_i and σ_i^2 denote the channel gain of the ith virtual channel and the thermal noise power respectively. It is assumed that the channel-gain-to-noise ratio h_i/σ_i^2(GNR) is known for all i.

B. Problem Formulation

The total uplink transmission rate is equal to the sum of individual VOC rates. To minimize the total transmitted power that achieves the various uplink rates constraints can be formulated as [7]

$$\min_{\mathbf{P},\mathbf{A}} \sum_{i=1}^{N} p_i \quad s.t. \quad \sum_{i=1}^{N} A_{j,i} r_i = R_j, \ 1 \leq j \leq d \tag{2}$$

where $\mathbf{p}$ denotes the power allocation vector whose ith coordinate p_i represents the ith VOC's transmitted power, r_i is the corresponding transmission rate and R_j is the required rate of the jth data type. The $d \times N$ binary channel assignment matrix $\mathbf{A} = [A_{ji}]$ is defined by $A_{ji} = 1$ if the ith VOC transmits the jth data type. Assuming that a VOC can only serve one data type, then A_{ji} is either 1 or 0 and $\mathbf{A}$ must satisfy

$$\sum_{j=1}^{d} A_{ji} \leq 1, \ \sum_{i=1}^{N} A_{ji} \geq 1, \ 1 \leq i \leq N, 1 \leq j \leq d \tag{3}$$

To solve the problem (2), we divide it into two subproblems. The first subproblem is to find the optimal $\mathbf{p}$ for a fixed channel assignment matrix $\mathbf{A}$. The second one is to find the optimal $\mathbf{A}$ that minimizes the total power.

III. Locally Cooperative Communication Schemes

In this section, we provide two algorithms to find solution for the problem (2). The first algorithm is to find the optimal $\mathbf{p}$ for mono-rate application within some iterations. It is more practical than the water-filling solution with the individual power constrains. The other one is the modified version of the above proposed algorithm for the multi-rate applications. It obtains a suboptimal channel assignment matrix $\mathbf{A}$ and power allocation $\mathbf{p}$ by taking the algorithm's realization into account without much performance loss.

A. Conventional Optimization Algorithm

The optimal solution can be obtained by a conventional two step procedure like that used in [7]. One first finds the optimal $\mathbf{p}$ for a fixed $\mathbf{A}$ by using the water-filling approach and then runs a greedy search for the optimal $\mathbf{A}$ that gives the minimum total transmitted power under all constraints. For a given channel assignment matrix, the problem of finding the optimal power allocation vector can be divided into d simple optimization subproblems given by

$$C(j) = \{i | 1 \leq i \leq N, A_{j,i} = 1\}$$

$$\min \sum_{i=1}^{N} p_i, \quad s.t \sum_{i \in C(j)} r_i = R_j, 1 \leq j \leq d \tag{4}$$

The minimum transmission power for each specific rate can be independently solved by the water-filling method. Thus, the optimal power and rate allocation of ith virtual channel can be given by

$$\hat{p_i} = \left(\lambda_j - \frac{\sigma_i^2}{h_i}\right)^+, \hat{r_i} = W_i \log_2 \left(1 + \frac{\hat{p_i} h_i}{\sigma_i^2}\right) \tag{5}$$

where x^+=max(x,0), and λ_j are Lagrange multipliers that satisfy.

$$\sum_{i \in C(j)} \hat{r_i} = R_j, 1 \leq j \leq d, \tag{6}$$

A greedy search is performed to find the optimal assignment matrix $A_{d \times N}$. We compute the minimum transmitted power for each desired rate by running the above water-filling method within d subproblems and calculating their sum as the minimum total power with respect to each given $A_{d \times N}$.

To implement this solution, each requester has to compute the optimal channel assignment matrix and power allocation vector and forward the result to the network participants. The optimization process is both complicated and time-consuming, especially if the numbers data rates (types) and virtual channels are large. Moreover, each requester has to perform the same (redundant) computation unless a protocol for deciding a designated user to perform the optimization is in place. In the next section we propose a simple and practical solution which has much reduced complexity with minimum performance loss.

B. Iterative Optimization Algorithm for Mono-rate requirement

In general, the power allocation optimal solution for the mono-rate requirement is the traditional water-filling solution. Thus, the optimal power and rate allocation of ith virtual channel can be given by

$$p_i = \left(\lambda - \frac{\sigma_i^2}{h_i}\right)^+, \quad r_i = W_i \log_2\left(1 + \frac{\hat{p}_i h_i}{\sigma_i^2}\right) \tag{7}$$

where x^+=max(x,0) and λ is the solution of the above problem subject to constraint that $\sum_{i=1}^{N} r_i = R$. Even with exhaustive search, the true optimal λ is hard to come by. We propose an iterative Lagrange-type algorithm. Unlike earlier proposals in which the channels to be excluded are found only after the optimal level λ is known, we first select some "bad" channels and then perform power allocation on the remaining "good" channels. The optimal solution can be easily found within a few iterations. Let us define the normalized channel capacity r by

$$C_i = W_i log_2(1 + \frac{h_i p_i}{\sigma_i^2}) = W_i log_2 e \cdot ln(1 + \frac{h_i p_i}{\sigma_i^2}) \tag{8}$$

$$r_i = \frac{C_i}{W_i log_2 e} = ln(1 + \frac{h_i p_i}{\sigma_i^2}) \tag{9}$$

where the subscript i denotes the ith channel, h_i, p_i, σ_i^2 are the corresponding channel gain, transmitted power, and noise power. We assume that $W_i = W = 1$ for simplicity. Furthermore, there are N virtual orthogonal channels available and these channels are sorted with descending channel gain. For the mono-rate case, (2) becomes

$$\min_{\mathbf{P}} \sum_{i=1}^{N} p_i \quad s.t. \quad \sum_{i=1}^{N} r_i = R, \tag{10}$$

where

$$r_i = ln(1 + \frac{h_i p_i}{\sigma_i^2}) = ln(1 + a_i p_i), \quad a_i = \frac{h_i}{\sigma_i^2} \tag{11}$$

To begin with, we release the constraint $0 \le p_i$ for all i and use Lagrange approach iteratively to find the optimal solution. Taking derivative of the following function with respect to r_i,

$$\begin{aligned} f(r_1, r_2, \cdot, r_N) &= (p_1 + p_2 + \cdot + p_N) \\ &\quad -\lambda(r_1 + r_2 + \cdot + r_N - R) \end{aligned} \tag{12}$$

we obtain

$$\frac{\partial f}{\partial r_i} = 0 \ \Rightarrow \ \frac{e^{r_i}}{a_i} = \lambda, \ i = 1, 2, \cdot, N, \tag{13}$$

Since

$$\lambda = \frac{e^{R/N}}{\hat{a}} \quad \text{and} \quad \hat{a} = (a_1 \cdot a_2 \cdots a_N)^{1/N} \tag{14}$$

we have

$$\begin{aligned} r_i &= ln(\lambda a_i) = ln(e^{R/N} \cdot \frac{a_i}{\hat{a}}) \\ &= \frac{R}{N} + ln(\frac{a_i}{\hat{a}}), \ i = 1, 2, \cdot, \cdot, N \end{aligned} \tag{15}$$

The process will repeat by modifying the number of channels involved until $0 \le r_i, \ \forall \ 1 \le i \le N$. The resulting algorithm that finds the optimal power allocation with rate constraint $r_i \ge 0$ is listed below.

Step 1:	Given h_i for $1 \le i \le N$, and R, set $x = N$.
Step 2:	Calculate the power and rate allocations by $a_i = \frac{h_i}{\sigma^2}, 1 \le i \le x$ $\hat{a} = (a_1 \cdot a_2 \cdots a_x)^{1/x}$ $r_i = \frac{R}{x} + ln(\frac{a_i}{\hat{a}})$
Step 3:	**If** the smallest rate $r_x \ge 0$ then end. **else** set $x = x - 1$ and go **Step 2**.

Table I: An Iterative Constrained Power Allocation Algorithm

C. A resource allocation algorithm for multi-rate transmissions

We now turn to the multimedia case. Similar to the conventional approach, the proposed algorithm consists of two main procedures.

In the first procedure, we perform channel assignment iteratively based on the idea that the strongest channel in each step should be assigned to transmit the data type that requires the largest bandwidth. In order to achieve the optimal performance, we use the iterative optimization algorithm for mono-rate in **Table I** under the constraint $R = \sum_{j=1}^{d} R_j$ to obtain an initial power/rate allocation. After that, we perform channel assignment, which is described in **Table II**, based on the above idea. A legitimate channel assignment matrix can usually be obtained in some iterations when $d \ll N$, which is often the case. However, there is a nonzero probability that (4) is not satisfied, in particular, $\sum_{i=1}^{N} A_{ji} = 0$ for some j. We then activate an iterated re-distribution process that starts with the data types that are carried by the maximum number of channels, i.e., $\arg\max_l \sum_{i=1}^{N} A_{li}$ to release some channels with lower GNRs for carrying those unserved low rate data.

The second procedure employs the iterative algorithm described before to obtains the optimal power/rate allocation for each data type. The complete algorithm is given in **Table II**.

IV. Numerical Results and Discussion

We report some simulated performance of the proposed resource allocation schemes in this section. For simplicity, we assume $\sigma_i = \sigma, \forall i$, which is a reasonable approximation unless the bandwidth is extremely large. We normalize the bandwidth of each VOC such that $W = 1$ and set the normalized noise power lever σ^2 to be 0.01.

In Fig. 1, it is shown that the proposed mono-rate scheme yields the exact optimal solution. Fig. 2 indicates that the multi-rate algorithm is capable of rendering near-optimal performance even when the number of data type increases. The both results from the above figures show the difference relative to the power is too minor to distinguish. Based on the above cause, Fig. 3 plots the excess power ratio in percentage against the transmission rate, where the former is defined as the difference between the actual required power and the power prescribed by the optimal solution normalized by the latter. It is shown that, for the dual rate ($d = 2$) system, there is no performance loss when the desired rate is less than one. Even if the desired rate increases to 3, the performance degradation is only 0.043%. In Fig. 4 we consider a triple-rate system with 8 VOCs $R_1 = 1$ and $R_2 = 2$. The result indicates that the proposed scheme still offers near-optimal performance for a relatively large range of R_3.

Exact optimal solution is not obtained since the channel assignment matrix in the proposed scheme does not necessarily lead to the optimal channel assignment solution. However, within the range of interest, the proposed algorithm suffers only minor degradation with respect to the optimal performance.

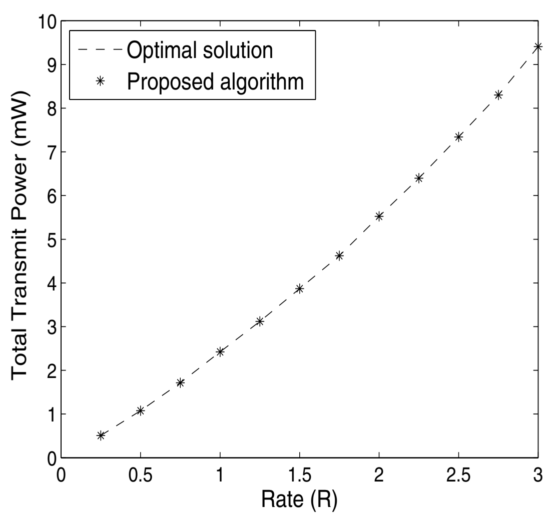

Fig. 1. Performance of the proposed mono-rate power allocation algorithm; $N = 32$, $W = 1$ and $d = 1$.

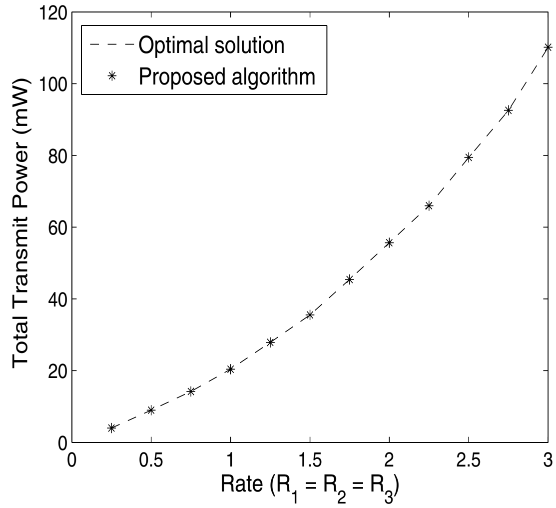

Fig. 2. Total transmit power with power constraint for a triple-rate system; $N = 8$, $W = 1$ and $d = 3$.

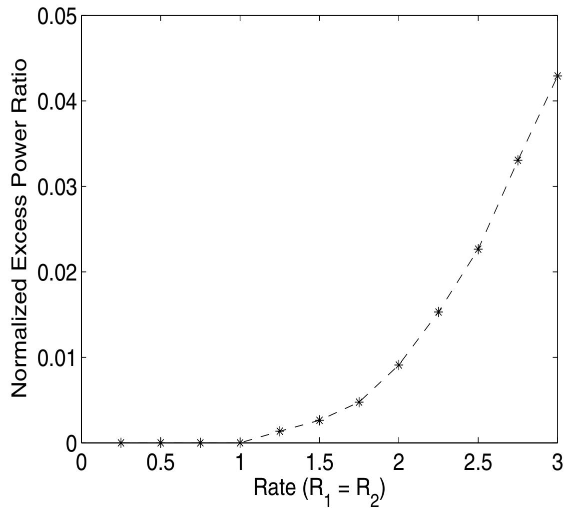

Fig. 3. Normalized excess power ratio versus desired rate with different cooperative schemes for $N = 8$, $W = 1$, and $d = 2$.

V. Conclusion

This paper presents a near-optimal radio resource allocation algorithm for multimedia communications. This algorithm can be applied to a locally cooperative communication system to enhance the energy/power efficiency for uplink multimedia transmission. It can also be used for single-user (most likely base stations) multi-channel transmission applications. The proposed scheme is simple and, more importantly, is capable of giving optimal (in the mono-rate case) or near-optimal (for the multi-rate cases) solution. Because of its simplicity, it becomes practical for a mobile device to directly compute the resource allocations such that uplink capacity can be maximized through a properly designed local cooperative communication protocol.

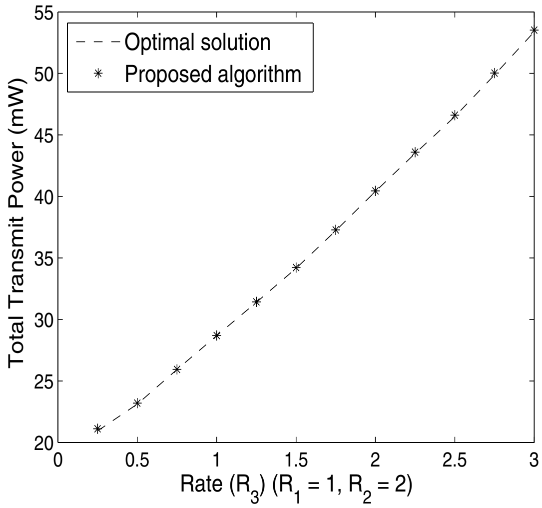

Fig. 4. Total transmit power versus desired transmission rate for a triple-rate system; $N = 8$, $W = 1$ and $d = 3$.

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Table II: An iterative resource allocation algorithm for cooperative communication.

Step 1: (Initialization) The cluster information N, d, h_i and R_j, $1 \le i \le N, 1 \le j \le d$ are received by all terminals within the cluster during the regular periodic broadcasting interval.

Step 2: (Gain sorting and initial rate computing) Arrange all VOC gains by decreasing order such that $h_1 > h_2 > \cdots > h_N$ and computes the rates of all VOC
$R = \sum_{j=1}^{d} R_j$
set mono-rate equal to R to run the proposed iterative algorithm in Table I
and obtain p_i and r_i for all i.

Step 3: (Preliminary channel assignment) Compute the preliminary channel assignment matrix $\mathbf{A}$ via
$C = \{i|1 \le i \le N, p_i > 0\}$
$C_{zero} = \{i|1 \le i \le N, p_i = 0\}$
set $R'_j = R_j$ for $1 \le j \le d$
for $i = 1 : size(C)$
  $j = \arg\max_{1 \le l \le d} R'_l$
  $A_{ji} \leftarrow 1,\ \ A_{k,i} \leftarrow 0$, for $1 \le k \le d, k \ne j$
  $R'_j \leftarrow R'_j - r_i$
end

Step 4: compute rate difference,
for $j = 1 : d$
  $C(j) = \{i|1 \le i \le N, A_{ji} = 1\}$
  $R_j - \sum_{i \in C(j)} r_i = \Delta R_j$
end

Step 5: modify the power allocation, set $D = 0$
for $j = 1 : d$
  if $\Delta R_j < 0$
    run the iterative algorithm for mono-rate for the jth data type
    with $\min \sum_{i \in C(j)} p_i, \quad s.t \sum_{i \in C(j)} r_i = R_j$
  end
  if $\Delta R_j > 0$
    $D = D + 1$
  end
end

Step 6: modify the channel allocation and its power allocation again
for $j = 1 : D$
  $J = \arg\max_{1 \le j \le d} \Delta R_j$
  run the mono-rate iterative algorithm
  with $\min \sum_{i \in C(J) \bigcup C_{zero}} p_i$,
  s.t $\sum_{i \in C(J) \bigcup C_{zero}} r_i = R_J$
  modify C_{zero} and set $\Delta R_J = 0$
end