DELAY-DIFFERENTIATED SCHEDULING IN A RANDOMIZED MIMO RELAY NETWORK

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ABSTRACT

The paper considers a randomized multiuser MIMO relay network with M sources. Each source and the destination node have multiple transmit/receive antennas. The R relay nodes have only one antenna transmit and receive antenna, and they pseudo-randomly vary the transmission signal, and generate a time-varying MIMO channel to the destination node. The destination schedules the transmissions of delay-differentiated services of the M sources. Both opportunistic and centralized scheduling policies are considered and it is seen that with both schedulers the resulting capacity is similar, and that delay differentiation is effective. Increasing the number of transmit and receive antennas reduces the scheduling gain considerably.

1. INTRODUCTION

The target of this paper is study how to use a cluster of very simple relay nodes in a MIMO wireless network so that total capacity is increased at the destination node. As an example, the source nodes could be the end-user devices and the destination node an access point or a base station, or vice versa. In between the sources and destinations, there are several relay nodes, that are used simultaneously or collaboratively by all sources.

The relay nodes are constructed as "semi-transparent" network elements with only minimal data processing capabilities. For example, they do not perform channel estimation, detection or decoding, but operate using a variant of an amplify-and-forward protocol. Ideally,they impact only the physical channel between source and destination, and the network and devices are unaware of their existence. Such methods are considered for SISO systems in [1, 6, 4].

This paper addresses efficient multiuser scheduling methods in a previously stated MIMO relay network. In particular, we consider delay-differentiated scheduling in which different sources have different (maximum) delay requirements. In addition, we consider delay constrained scheduling using well-known combinatorial optimization techniques such as the assignment algorithm [7]. As for motivation, channel-aware (opportunistic) scheduling and MIMO are the primary techniques for attaining high throughput in modern networks and their combined use needs to be controlled efficiently.

The paper is organized as follows. Section II introduces the relaying concept. Modern multimedia networks support different services with different delay requirements. Section III formalizes a scheduling scheme for channel-aware delay-differentiated scheduling, to be used in a randomized relay network. The proposed optimization approach to scheduling takes into account both efficiency and fairness. Section IV presents numerical results.

2. RANDOMIZED RELAY NETWORK

Channel variation is known to improve the performance of channel-aware scheduling [3]. Multiple relay nodes and random beamforming [5] can be used to artificially randomize a channel, to increase channel variations. Artificially induced channel variation via time-varying relay nodes are thus able to improve the performance of channel-aware schedulers even in low-mobility environments [1].

2.1 Signal model

The MIMO relay network considered in this paper comprises a source node with N_t transmit antennas, R single-antenna relay nodes, and a destination node with N_r receive antennas. A source node transmits a signal $\mathbf{x}$ through a $N_\mathrm{t} \times R$ MIMO channel $\mathbf{F}$ with power P, where R designates the number of relay nodes. Each relay node multiplies the signal with a relay-specific complex weighting coefficient w_r. These are collected to a diagonal matrix

$$\Lambda = \mathrm{diag}(w_1, ..., w_R). \tag{1}$$

The $N_\mathrm{r} \times R$ MIMO channel from the relay nodes to the destination is given by $\mathbf{H}$. In a two-hop amplify-and-forward network, the relays transmit at the same time and the destination receives

$$\mathbf{y} = \mathbf{H}\Lambda\mathbf{F}\mathbf{x} + \mathbf{H}\Lambda\mathbf{n}_r + \mathbf{n}_d \tag{2}$$

where the elements of complex Gaussian vector $\mathbf{n}_r$ designate noise with variance σ_r^2 at each relay node, and elements of $\mathbf{n}_d$ designate complex Gaussian noise with variance σ_d^2 at each destination antenna. The capacity with i.i.d. Gaussian sources (in terms of bits-per-channel-use (bpcu)) for the signal model (2) is [6]

$$\alpha = \frac{1}{2}\log_2 \det(\mathbf{I} + P\mathbf{H}\Lambda\mathbf{F}\mathbf{F}^\dagger\Lambda^\dagger\mathbf{H}^\dagger\mathbf{R}_{nn}^{-1}), \tag{3}$$

where the noise correlation matrix is

$$\mathbf{R}_{nn} = (\sigma_d^2\mathbf{I} + \sigma_r^2\mathbf{H}\Lambda\Lambda^\dagger\mathbf{H}^\dagger). \tag{4}$$

Factor $1/2$ in model (3) is due to two-hop relaying.

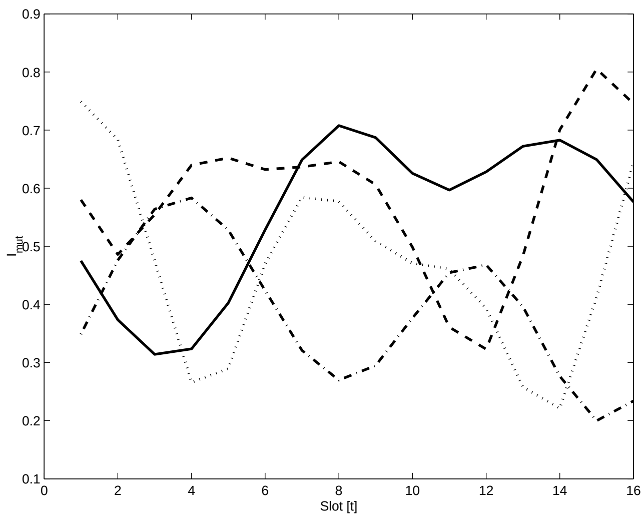

Figure 1: Example of time-varying mutual information for four sources in a $2 \times 4 \times 2$ network.

2.2 Randomization

The randomization is implemented via time-varying weighting coefficients $w_1, ..., w_R$. Formally, we simply write

$$\mathbf{y}[t] = \mathbf{H}\Lambda[t]\mathbf{F}\mathbf{x}[t] + \mathbf{H}\Lambda[t]\mathbf{n}_r[t] + \mathbf{n}_d[t] \quad (5)$$

to highlight that only the weighting matrix needs to vary in time (channel may or may not vary). The capacity is computed as above, and obviously it is also time-varying. Capacity at time t is denoted as $\alpha[t]$.

The weighting coefficients are used to control the transmit power and transmit phase of each relay node. There are several ways of determining the transmit power in order to make sure that an amplify-and-forward node transmits with some maximum power or that it does not amplify noise more than necessary. Here, we simply set the amplitudes to satisfy

$$|w_r| = \sqrt{\frac{P_2/R}{\sum_{n=1}^{N_t} |f_{r,n}|^2 + \sigma_r^2}} \quad (6)$$

where σ_r^2 designates the variance of each element of noise vector $\mathbf{n}_r$ and P_2 is the desired total transmit power of all R relay nodes. The phase of the weighting coefficient of relay r at time t is taken periodically from the phase of element $(r, t\text{mod}R)$ of a unitary matrix of dimension R. Denote this element by $u_{r,t\text{mod}R}$. Thus,

$$w_r[t] = \exp(\text{j}\arg(u_{r,t\text{mod}R}))\sqrt{\frac{P_2/R}{\sum_{n=1}^{N_t} |f_{r,n}|^2 + \sigma_r^2}}. \quad (7)$$

For example, we can choose the unitary matrix as an FFT matrix of dimension R.

3. SCHEDULING

In this section we consider multiuser scheduling in randomized relay network with M source nodes of which only one is allowed transmit during one slot. Let $\alpha_m[t]$ denote the capacity of user m at slot t.

The effect of randomization is apparent from Fig. 1. If the complex phasors in the relay units were static, the Shannon capacity would obviously be identical in each slot. In Fig. 1 the weights are changed for the other slots and a realization of time-varying capacity $\alpha_m[t]$ is plotted for four different sources, where each of the $M = 4$ sources have two transmit antennas and the destination node has two receive antennas. Clarly, in the static case, where the relay weights are the same in each slot, there is no benefit from channel-aware scheduling, when compared to round-robin. However, with pseudo-random phasors any channel-aware scheduler is likely to provide a performance benefit. The channel variation is affected by the number of activate relay nodes and their weights.

3.1 Delay-differentiation and opportunistic scheduling

We assume that the performance indicator used in scheduling is capacity (see equation 3) and a scheduler adopts a policy that guarantees each user tolerable delay performance. In [2] it is suggested that a simple modification of proportional fair scheduling [5] enables delay differentiation. [2] suggests that to determine the transmitting user at time t the following scheduling criterion can be applied:

$$\max_m \frac{\alpha_m[t]}{\bar{\alpha}_m[t]} \quad (8)$$

where $\alpha_m[t]$ is the Shannon capacity of user m at slot t and $\bar{\alpha}_m[t]$ is a scheduling threshold of user m at time t. Examples discussed in [2] suggest that the following simple scheduling threshold yields a good delay-throughput performance

$$\bar{\alpha}_m[t] = b_m[t]E(\alpha_m[t]) \quad (9)$$

where $b_m[t]$ is a delay discount factor that is set appropriately to reduce delays. Equations (8)-(9) imply the scheduling criterion:

$$m^* = \arg\max_m \log(\alpha_m[t]) - \log(E(\alpha_m)) - \log(b_m[t]). \quad (10)$$

The delay parameter of user m, $b_m[t]$, measures the delay-tolerance of m; $b_m[t]$ decreases as the delay deadline of user m becomes closer. Thus, the scheme schedules the least delay-tolerant user relative to the channel quality (ties resolved by tossing a coin).

3.2 Centralized scheduling

The solution above assumes that only channel history is known. In a pseudo-random network, it is in theory possible to device a jointly optimal scheduling policy. Let ϕ_m denote the portion of a time-window allocated to user m. Consider the scheduling of users over a time window of length T via the following linear programming problem (known as the transportation problem [7]):

$$\max \sum_t \sum_m \alpha_m[t] z_{m,t} \quad (11)$$

subject to

$$\sum_{t=1}^{T} z_{m,t} = \phi_m T, \forall m \quad (12)$$

$$\sum_m z_{m,t} = 1, \forall t, \quad (13)$$

$$z_{m,t} \geq 0, \forall m, t, \quad (14)$$

$$\sum_m \phi_m = 1. \quad (15)$$

Problem (11)-(15) can be solved efficiently applying transportation algorithm [7]. The variable $z_{m,t}$, when solved from above problem dictates which user becomes active in which slot, so that a given number of slots is allocated to different users. In the special case where $\phi_m = 1/T, \forall m$, the transportation problem is known as an assignment problem which can be solved various assignment algorithms (AA). If all (fairness) constraints are removed from problem (11)-(15), the solution corresponds to a max-capacity scheduler. If only the fairness constraints are kept, the solution corresponds to a round-robin (RR) scheduler.

4. PERFORMANCE

4.1 Scheduling gain

Consider first the performance gain due to channel-aware scheduling in a pseudo-random MIMO relay network with 10 users and 10 relay nodes. Each channel coefficient is i.i.d. Rayleigh and the transmit power for each source and for combined transmit SNR for all relay nodes is 0 dB. The number of MIMO antennas in source and destination is varied from 1 to 40. Fig. 2 depicts the capacity per channel use (cpcu) at destination using greedy or max-capacity (Max) scheduler, assignment method (AA) (see eqs. (11)-(15)) and round-robin (RR) scheduling. It is seen that the results in [3] are in line with those in Fig 2 in that the gain due to channel-ware scheduling diminishes when compared to round-robin scheduling as the number of MIMO antennas are increased. Assignment method provides fairness across users but it further reduces the scheduling gains. For the assignment method, the performance is close to max scheduler when only a few MIMO antennas deployed, whereas the performance approaches that of round-robin with a large number of MIMO antennas. This is again due to channel "hardening" [3], which makes all assignments approximately identical in terms of performance. Comparing to round-robin, the relative capacity improvement with channel-aware scheduler in a SISO system (one transmit and receive antenna) is almost 150% but reduces in a 4-antenna MIMO system to 35% and 22% with max and with AA schedulers, respectively.

4.2 Delay-differentiation

The assignment algorithm used in previous section guarantees that consecutive scheduling instant for any user are at most ten channel uses apart from each other. The max-capacity scheduler dispenses all delay guarantees but obtains higher channel utilization. With delay -differentiation different users have different delay preferences. Below, we consider the delay and channel utilization properties of a decentralized scheduler that is not able to make joint scheduling decision for all users over all time slots, since the future channel state are assumed to be unknown. Rather, it computes the scheduling decisions on-line and is effectively unaware that the time-varying channel is due to the use of pseudo-random relays.

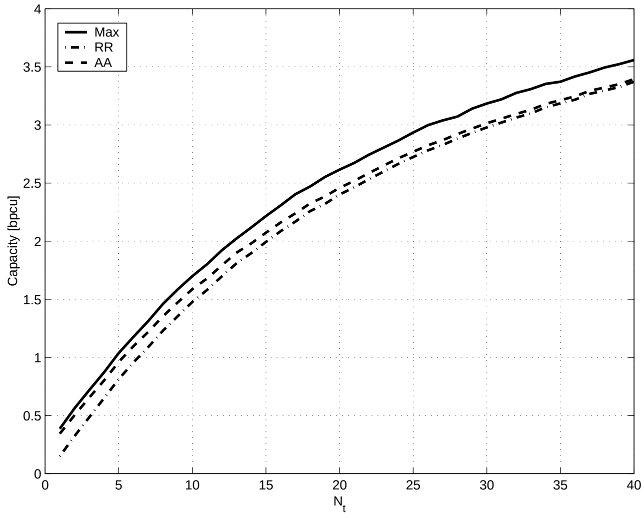

Figure 2: Shannon capacity per channel use in a randomized MIMO network with 10 relays and with N_t MIMO antennas in source and destination nodes.

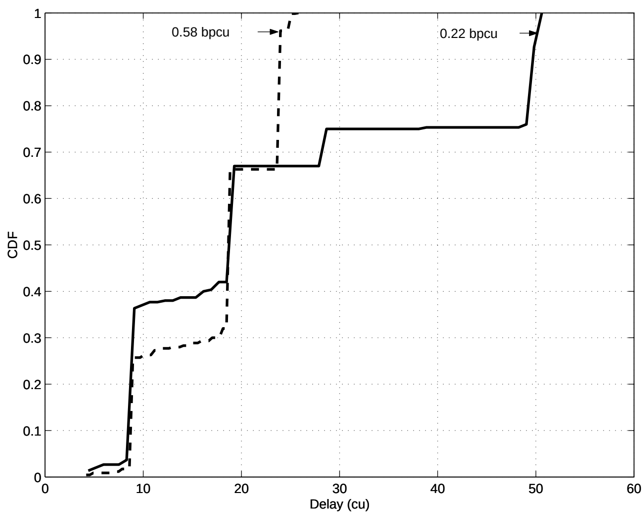

Figure 3: Empirical CDF of delay between consecutive channel uses ("cu") for two service-classes using the delay-differentiated scheduler with 10 relays and with four MIMO antennas in source and destination nodes.

Figure 3 depicts the performance of a delay-differentiated scheduler with two service classes in a randomized network with four antennas in each source and destination node and with 10 relay nodes. The first class is delay-intolerant with maximum service delay set to 25 channel uses. The second class tolerates at most 50 channel uses between consecutive scheduling instants. Fig. 3 shows an empirical cumulative density function for users in both delay classes and the resulting capacities, in terms of bits-per-channel-use (bpcu). The total capacity is 0.8 bpcu. The delay intolerant users are scheduled more frequently and they attain 0.58 bpcu, whereas the delay tolerant users attain 0.22 bpcu. Comparing this to the corresponding results from Fig. 2, we notice that the performance is almost identical with that of the assignment algorithm and only about 8 % less than the max-capacity scheduler.

5. CONCLUSION

In this paper we have considered the combined use of delay-differentiated channel-aware schedulers and MIMO relay networks. The pseudo-random relays randomize the effective MIMO channel seen by the destination node and enables efficient multiuser scheduling. While channel "hardening" with a large number of MIMO antennas reduces scheduling gains (compared to round-robin) it, on the other hand, enables efficient delay-differentiation.

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