Joint Cooperative Diversity and Scheduling in Low Mobility Wireless Networks

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***Abstract*— We consider a wireless network, which consists of several active source/destination pairs and a number of idle nodes. Multiple idle nodes volunteer as relays to facilitate the communication. All nodes have low mobility and the fading channel is essentially constant over the latency time scale of interest (block fading). Conventional adaptive scheduling techniques are either unfair or inefficient in this context. We introduce a new approach to jointly utilize adaptive scheduling and cooperative diversity in the low mobility regime. In contrast to known approaches the new scheme does not compromise the quality of service of individual source/destination links (fairness) if the number of relay nodes is sufficiently high. In a typical setup the 1%-outage aggregate throughput is improved by a factor of nine, if six source/destination pairs are considered jointly. We conclude that the joint cooperative diversity and scheduling scheme extends the benefits of adaptive scheduling to the low mobility regime.**

I. Introduction

The use of diversity in the spatial and temporal dimension to mitigate the effects of fading and therefore to increase the reliability of radio links in wireless networks is a well known technique for systems with co-located antennas (space-time coding). Recently a new form of realizing spatial diversity has been introduced in [1] and [2] called *cooperative diversity* or *user cooperation diversity*. The main idea is to use multiple nodes as a virtual macro antenna array, realizing spatial diversity in a distributed fashion. In such a network several nodes serve typically as relays for an active source/destination pair. Relays can be classified as either *decode-and-forward* (DF) or *amplify-and-forward* (AF) relays. AF relays, which are considered in this work, only retransmit an amplified version of their received signals. This leads to low-complexity relay transceivers, lower power consumption since there is no signal processing for decoding procedures. Furthermore, AF relays are transparent to adaptive modulation techniques which may be employed by the source.

In a centralized wireless access system a scheduler at the access point schedules the medium access of the wireless user nodes. A channel adaptive scheduler incorporates channel (link) state information (CSI) in this process [3]. As the achievable per-link throughput depends on the link quality, channel adaptive scheduling may improve the aggregate throughput. It thus exploits multi-user diversity [4]. Channel adaptive scheduling is particularly efficient in the high mobility regime, because the channel state varies sufficiently within the latency time scale of interest. Consequently, each node has a fair chance to see a good link in this time interval. WLANs however typically operate in the low mobility regime. In this case a channel adaptive scheduler, which optimizes the aggregate throughput, essentially would only serve the source/destination pair with best link. For quality of service (QoS) reasons, a realistic channel adaptive scheduling scheme in this case has to operate away from the aggregate throughput optimum.

If the access point has multiple co-located antennas, we can introduce time variations into a quasi-static fading environment by applying time-variant weights at the transmit antennas. This *opportunistic beamforming* scheme [5] essentially probes the weight vector space with random realizations of the antenna weights of the co-located transmit antenna array.

In [6] we propose a simple cooperative diversity scheme with AF relays. Essentially the block fading time-invariant channel is translated into a time-variant channel by introducing time-variant phase offsets at the relays. The main motivation for the present work is the observation, that this time variance could be exploited by considering several source/destination pairs jointly. We refer to our novel approach as *joint cooperative diversity and scheduling*. The scheme considerably improves the utilization of the physical resources without compromising the QoS in a block fading low mobility environment.

The remainder of the paper is organized as follows: in Section II we describe the system model and the traffic pattern. In Section III we introduce two reference schemes and define the figures of merit we use to quantify the utilization of the physical resources and the QoS (fairness). Our joint cooperative diversity and scheduling scheme is introduced in Section IV. In Section V the performance of the new scheme is evaluated and compared to the reference schemes. We conclude that joint cooperative diversity and scheduling extends the benefits of adaptive scheduling to the low mobility regime.

Notation: We shall use bold uppercase letters to denote matrices and bold lowercase letters to denote vectors. Further $(\cdot)^T$, $(\cdot)^\dagger$ stand for transpose and Hermitian transpose of a matrix, respectively. $\mathrm{diag}[a,\ldots,z]$ denotes a diagonal matrix with the elements $a,\ldots,z$ on its main diagonal, $\mathbf{I}$ is an identity matrix and $\mathbf{0}$ a matrix with all elements equal to zero. $\mathrm{E}\{\cdot\}$ is the expectation operator.

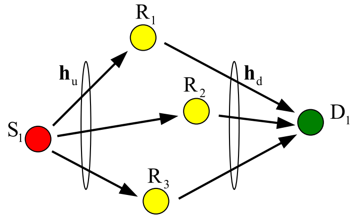


Fig. 1. 2-hop cooperative relaying network with single antenna nodes

II. System Model

In the following we derive a system model for cooperative relaying, assuming that communication takes place only over two-hop links, i.e. there is no direct connection between source and destination. Such a system is depicted in Fig. 1.

In our scenario user mobility is low and the channel coefficients are constant over the latency time scale of interest. We assume that the channel is time-invariant over at least one *transmission cycle* (block fading). As a transmission cycle we denote a period of time (i.e. a burst of symbols) in which an active source/destination pair is communicating.

We assume L amplify-and-forward relays assisting the communication link. In such a link the transmission of one data packet from the source S to the destination D occupies two time slots which both together establish one transmission cycle. In the first slot the source transmits the data packet to the relays. During the second slot the relays retransmit an amplified version of the received signals to the destination.

Usually, the data packet of the source would be received by the destination in the first time slot, too. In this paper we neglect this signal contributions to highlight only the effects of the cooperative nodes onto the throughput in such a system.

We denote the channel between the source and the relays as *uplink*, and the channel between the relays and the destination as *downlink*. The channel coefficients of the uplink are stacked in the vector $\mathbf{h}_\mathrm{u}$. The complex conjugates of the downlink channel coefficients are stacked in $\mathbf{h}_\mathrm{d}$. We consider flat fading, which usually includes path loss, shadowing and small-scale fading. For clarity of exposition we neglect the path loss. Thus, throughout this paper all channel coefficients are assumed as i.i.d. complex normal random variables $\mathcal{CN}(0,1)$.

At time instance k in the first time slot the source S sends the symbol $s^{(k)}$, with average transmitted power $\mathrm{E}\{|s^{(k)}|^2\} = P$. The received signal at all relays R_l is given by the vector $\mathbf{y}^{(k)}$ with

$$\mathbf{y}^{(k)} = \mathbf{h}_\mathrm{u} s^{(k)} + \mathbf{m}^{(k)} \tag{1}$$

where $\mathbf{m}^{(k)} \sim \mathcal{CN}(\mathbf{0}, \sigma_\mathrm{R}^2 \mathbf{I})$ contains the AWGN contributions at the relays.

Fig. 2 shows the system model of a AF relay. $\phi_{\mathrm{LO},l}$ represents the phase offset of the local oscillator (LO) at the relay R_l relative to a given reference phase. This phase offset is required in the system model, because LOs of all relays may be free running. In this case $\{\phi_{\mathrm{LO},l}\}$ are i.i.d. random variables. Only if there is a *global phase reference*, i.e. all LOs are phase synchronized, $\phi_{\mathrm{LO},l}$ is equal to zero. The factor g_l is

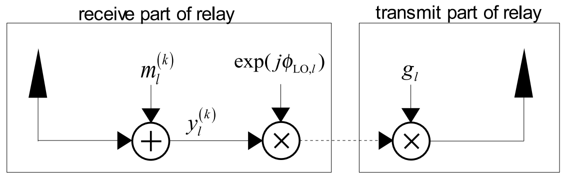


Fig. 2. System model of amplify-and-forward relay

the amplification gain at relay R_l. A popular choice of g_l (e.g. in [1]) is

$$g_l = \sqrt{\frac{P_\mathrm{R}}{P|h_{\mathrm{u},l}|^2 + \sigma_\mathrm{R}^2}}. \tag{2}$$

Each relay transmits with power P_R. We impose a total power constraint P on all relays, i.e. $P_\mathrm{R} = P/L$. With the gain matrix $\mathbf{G} = \mathrm{diag}\,[g_1, \ldots, g_L]$ and the phase reference matrix $\mathbf{\Phi} = \mathrm{diag}\left[\exp(j\phi_{\mathrm{LO},1}), \ldots, \exp(j\phi_{\mathrm{LO},L})\right]$ the received signal at the destination is given by

$$r^{(k+1)} = \mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{\Phi}\mathbf{y}^{(k)} + w^{(k+1)} \tag{3}$$

$$= \mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{\Phi}\mathbf{h}_\mathrm{u} s^{(k)} + \mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{\Phi}\mathbf{m}^{(k)} + w^{(k+1)} \tag{4}$$

where $w^{(k+1)} \sim \mathcal{CN}(0, \sigma^2)$ denotes the AWGN contribution at the destination.

The instantaneous capacity (per complex dimension) for a link described in (4) is given by

$$C_\mathrm{I} = \frac{1}{2}\log_2\left(1 + \frac{P|\mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{\Phi}\mathbf{h}_\mathrm{u}|^2}{\sigma^2 + \sigma_\mathrm{R}^2 \mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{G}^\dagger \mathbf{h}_\mathrm{d}}\right) \tag{5}$$

where σ^2 and σ_R^2 is the noise variance at the destination and the relays, respectively. The factor $1/2$ accounts for the 2 channel uses required by the relay traffic pattern.

A. Impact of local phase reference on coherent combining

If perfect up- and downlink CSI and a global phase reference are available at the relays the optimal gain coefficients g_l result in a coherent combining of the signal contributions at the destination [7].

A substantial signaling overhead is required to phase-lock all LOs of all nodes (i.e. establish a global phase reference). We consider this overhead prohibitive, i.p. if the number of relays is large. For this reason we assume in the sequel that $\{\phi_{\mathrm{LO},l}\}$ are i.i.d. random variables with uniform distribution in the interval $[0, 2\pi)$.

III. Reference Scenarios

In the following we introduce two reference scenarios as a starting point of our exposition. On the basis of this scenario characteristic performance measures are defined.

We consider a network with N_A active source/destination pairs. Fig. 3 shows a network with $N_\mathrm{A} = 2$ source/destination pairs $\mathrm{S}_1/\mathrm{D}_1$ and $\mathrm{S}_2/\mathrm{D}_2$ and their associated relaying nodes R_1 and R_2, respectively. We assume that due to transmit power constraints (power control) the source nodes are not able to transmit directly to the destination and we have to resort to a two-hop traffic pattern (source→relays; relays→destination).

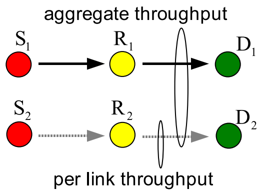


Fig. 3. Channel adaptive scheduling in static fading environment scenario

In the **reference scenario (a) "static scheduling"** the network allocates the same amount of resources (e.g. bandwidth) to each active link. This is illustrated in Fig. 5(a). Each shaded box represents an orthogonal channel. These orthogonal channels can either be separated in frequency, time, or code.

In this scenario each user experiences a well defined quality of service (QoS) over the whole transmission cylce. On the other hand the physical resource "channel" is not used optimally.

In the **reference scenario (b) "greedy adaptive scheduling"** in contrast the use of the physical resources is optimized. As indicated in Fig. 5(b) all resources are allocated to the source/destination pair with the best link. Due to the low mobility, the channel is essentially time-invariant over one transmission cycle. As a result only 1 out of N_{A} links is scheduled and the user experiences large variations in QoS (rate, delay) from transmission cycle to transmission cycle.

In this paper we use the *aggregate throughput* as a measure, how efficient the network utilizes the physical resources. The aggregate throughput is the throughput of **one** orthogonal channel (possibly averaged over the transmission cycle). Due to the block-fading channel the aggregate throughput is a random variable.

In contrast we use the *per-link throughput* as QoS measure. The per-link throughput is the throughput the user experiences in a given transmission cycle. It is again a random variable. It is is closely related to QoS parameters like data rate and delay.

In the sequel we illustrate these performance criteria for the reference scenarios. All results are based on $P/\sigma^2 = 20$dB, $\sigma^2 = \sigma_{\mathrm{R}}^2$ and the gain allocation in (2). The $N_{\mathrm{A}} = 1$ curve in Fig. 4 shows the cumulative distribution (CDF) of the throughput for scenario (a). Due to our definitions of the aggregate and the per-link throughput the corresponding distributions are identical in this scenario, because each user uses a distinct physical channel. Therefore, for scenario (a) the number of users does not affect the CDF. In contrast in scenario (b) the scheduler benefits from an increasing number of users. The solid curve in Fig. 4 shows the aggregate throughput of the greedy scheduler for $N_{\mathrm{A}} = 2$. The improved utilization of the physical resource is evident. At 10% outage probability the aggregate throughput is almost doubled.

The dashed line ("per link; $N_{\mathrm{A}} = 2$") depicts the corresponding per-link throughput. Obviously a specific link is only scheduled in a fraction of $1/N_{\mathrm{A}}$ of all transmission cycles, i.e. the probability of outage for any finite per-link outage

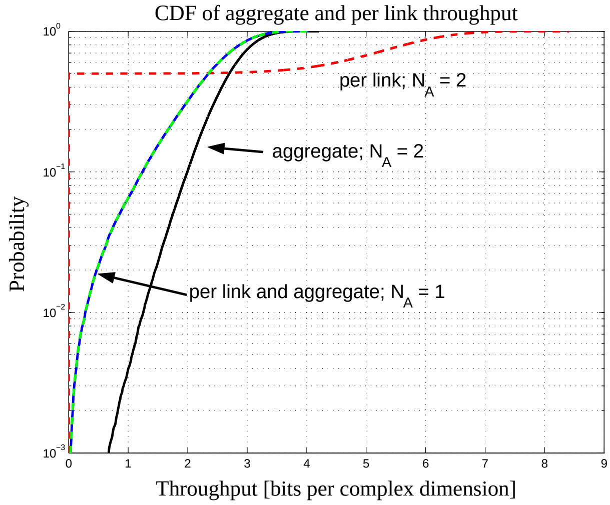


Fig. 4. CDF of the aggregate (solid lines) and the per-link throughput (dashed lines) for the static fading environment; $P/\sigma^2 = 20$dB, $\sigma^2 = \sigma_{\mathrm{R}}^2$, and $L = 1$.

throughput is lower bounded by $1 - 1/N_{\mathrm{A}}$. This is in general not acceptable and some fairness policy has to be adopted. This diminishes the channel adaptive scheduling gain and renders conventional fair channel adaptive scheduling inefficient in a quasi-static channel.

IV. Joint Cooperative Diversity and Scheduling

Our starting point is the simple cooperative diversity scheme which we proposed in [6]. It requires only very limited uplink channel state information and no downlink CSI. For clarity of exposition we briefly summarize the approach: the linear processing at the relays is time-variant, which results in a time-variant equivalent source/destination channel coefficient (i.e. a time-variant SNR at the destination). In a simple embodiment the relays use a time-invariant gain and a relay-specific time-variant phase offset (phase signature sequence). Thus, the amplification gain of relay l at time instance k is now for example given as

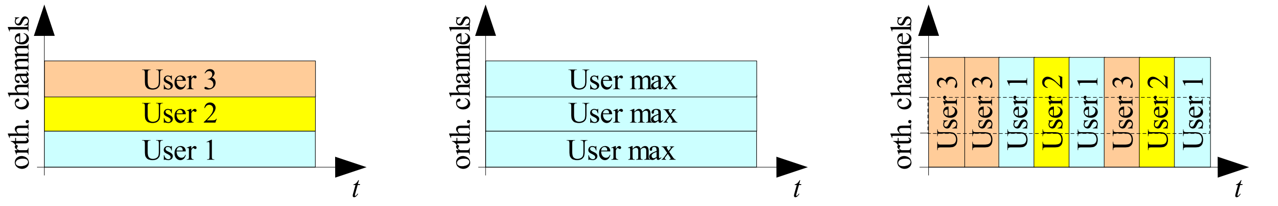
$$g_l^{(k)} = \underbrace{\sqrt{\frac{P_{\mathrm{R}}}{P|h_{\mathrm{u},l}|^2 + \sigma_{\mathrm{R}}^2}}}_{\text{time-invariant}} \cdot \underbrace{\exp\left(j\varphi_l^{(k)}\right)}_{\text{time-variant}} \tag{6}$$

where $\varphi_l^{(k)}$ denotes the relay-specific and time-dependent phase offset.

We consider all $\varphi_l^{(k)}$ as independent realizations of a random variable φ_l. If we assume an infinite number of phase realizations in each transmission cycle the capacity is the expectation of the instantaneous capacity with respect to $\{\varphi_l\}$

$$C_{\mathrm{I}} = \frac{1}{2}\,\mathrm{E}_{\{\varphi_l\}}\left\{\log_2\left(1 + \frac{P|\mathbf{h}_{\mathrm{d}}^{\dagger}\mathbf{G}^{(k)}\mathbf{\Phi}\mathbf{h}_{\mathrm{u}}|^2}{\sigma^2 + \sigma_{\mathrm{R}}^2\mathbf{h}_{\mathrm{d}}^{\dagger}\mathbf{G}^{(k)}\mathbf{G}^{(k)\dagger}\mathbf{h}_{\mathrm{d}}}\right)\right\}. \tag{7}$$

Fig. 6 shows a typical time-variant destination SNR for the link $\mathrm{S}_1/\mathrm{D}_1$. The phase signature sequence consists of 10 segments. The exploitation of this time variance (temporal



(a) static scheduling (b) greedy adaptive scheduling (c) joint cooperative diversity and scheduling

Fig. 5. Use of orthogonal channels in the network in different scheduling scenarios

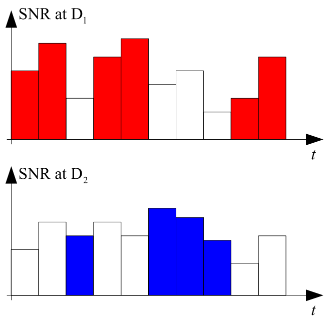


Fig. 6. Adaptive scheduling depending on the SNR at the destinations

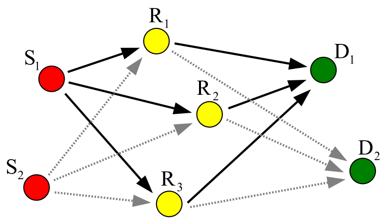


Fig. 7. Joint cooperative diversity and scheduling network scenario example

diversity) to achieve a cooperative diversity gain requires an appropriate coding scheme of the source signal. Some well suited candidates are presented in [8], [9] and [10].

The key idea of this present work is to further exploit the time-variance, which is intentionally introduced to achieve diversity by joint consideration of several source/destination pairs. For illustration we assume an idealized scheduler, which perfectly knows the time-variant destination SNRs. To optimize the aggregate throughput, this scheduler selects the best link in each time segment. This is indicated by the shaded boxes in Fig. 6. Here $\mathrm{S}_1/\mathrm{D}_1$ is scheduled in six time segments, whereas $\mathrm{S}_2/\mathrm{D}_2$ is scheduled in four. Note that in this scenario channel adaptive scheduling is reasonably fair, even if the channel itself is not time-variant. We explicitly benefit from the time-variance, which is introduced by the time-variant processing at the relays.

V. Performance Analysis

In this section we quantify the benefits of joint cooperative diversity and scheduling by some typical performance figures.

In the joint cooperative diversity and scheduling scenario the channel is time variant within one transmission cycle. Thus in each time-slot an adaptive scheduler will assign the whole bandwidth to the best source/destination pair. This is illustrated in Fig. 5(c).

The aggregate throughput in one transmission cycle is obtained by averaging the throughput in one orthogonal channel along the time axis. Note that this value is the same for all orthogonal channels, as we assume frequency flat fading. The aggregate throughput indicates how efficient the network utilizes the physical resources.

The per-link throughput is defined as the average throughput which a specific source/destination pair experiences in a given transmission cycle. In contrast to the aggregate throughput it indicates the fairness of the scheduling scheme.

With our joint cooperative diversity and scheduling scheme we want to improve the efficiency of the use of the given network resources (aggregate throughput) while guaranteeing each source/destination pair at least the same QoS as in the reference scenario (a). In this work we measure the QoS by the 1%-outage per-link throughput.

Note that all simulations results are based on the same assumptions as specified for the reference scenarios, i.e., $P/\sigma^2 = 20$dB, $\sigma^2 = \sigma_{\mathrm{R}}^2$, and $P_{\mathrm{R}} = P/L$. Further, all channel coefficients are assumed as i.i.d. complex normal random variables $\mathcal{CN}(0,1)$.

Fig. 8 shows the probability of outage of the aggregate (solid curves) and the per link throughput (dashed curves) in the joint cooperative diversity and scheduling scenario. Parameter of the curves is the number N_{A} of source/destination pairs. In this example we assume that $L = 20$ relays assist the communication. This number is kept constant for all examined N_{A}. For reference the aggregate throughput for $N_{\mathrm{A}} = 1$ without time-variant processing at the relays is shown (reference scenario (a), $L = 1$; Fig. 4). The improvement of the aggregate throughput by adaptive scheduling the source/destination pairs is clearly visible. A comparison of the $N_{\mathrm{A}} = 1$ case with the reference (a) clearly shows the diversity gain (steeper slope of the CDF), which is afforded by the time-variant relaying. Note the considerable improvement of the aggregate throughput for $N_{\mathrm{A}} > 1$.

The dashed curves in Fig. 8 show the per-link throughput. It can be seen, that the 1%-outage per-link throughput decreases with increasing number of considered source/destination pairs. Therefore, the QoS of each individual source/destination pair is affected negatively. Only for $N_{\mathrm{A}} \leq 3$ the 1%-outage per-link throughput has at least the same value as in the reference scenario (a).

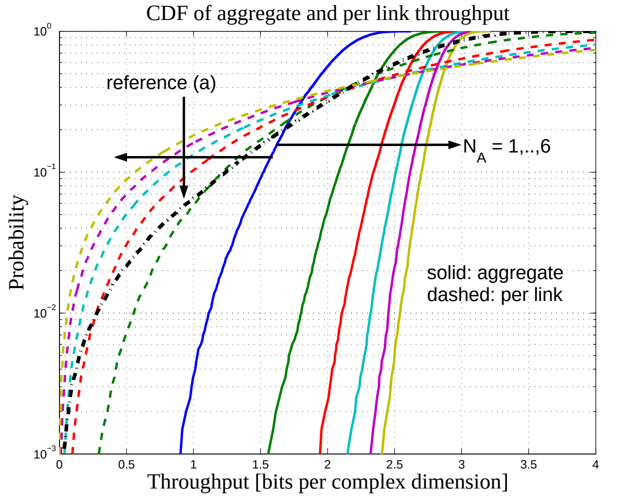


Fig. 8. CDF of the aggregate (solid lines) and the per link throughput (dashed lines) for the joint cooperative diversity and scheduling scenario; $P/\sigma^2 = 20$dB and $\sigma^2 = \sigma_{\mathrm{R}}^2$

This decrease in outage per-link throughput can be traced back to the fact that the number of relays is constant for all N_{A}. If we adapt the number of relays according to the number of source/destination pairs we are able to maintain the QoS. From simulation it can be shown that approximately $L = 10 \cdot (N_{\mathrm{A}} - 1)$ relays are required for $N_{\mathrm{A}} \geq 2$ to achieve a per-link throughput distribution which is independent of N_{A} and supports the same 1%-outage per-link throughput as in the reference scenario (a). For example, for $N_{\mathrm{A}} = 3$ the number of $L = 20$ relays is required. Thus, in the case that L is adapted, we approximately achieve the $N_{\mathrm{A}} = 3$ per-link throughput in Fig. 8 for all values of N_{A}.

In Fig. 9 we compare the 1%-outage aggregate throughput (99% coverage) of the three approaches versus the number of active source/destination pairs. Again the channel is quasi-static (block fading). It can be seen that the cooperative diversity approach [6] together with the static scheduling achieves an improvement compared to static scheduling alone if we consider $L = 20$ relays. The performance of the joint cooperative diversity and scheduling approach is shown for the case where $L = 20$ (solid curve) and for the case where L is chosen adaptively (dashed curve). It can be seen, that $L = 20$ relays are sufficient to achieve a high 1%-outage aggregate throughput, whereas it is not sufficient to maintain the QoS requirements for $N_{\mathrm{A}} > 3$. Therefore, the choice of L opens up a trade-off between QoS and the aggregate throughput in our proposed joint cooperative diversity and scheduling approach.

Finally, in Fig. 9 it can be seen that the joint cooperative diversity and scheduling approach improves the 1%-outage aggregate throughput by a factor of nine if $N_{\mathrm{A}} = 6$ source/destinations links are considered jointly.

Note that despite the block fading channel the new scheme achieves the same QoS (per-link throughput) as the static scheduler if the number of relays is sufficiently high. It is evident from Fig. 9, that the physical resource is utilized much more efficiently by the new scheme.

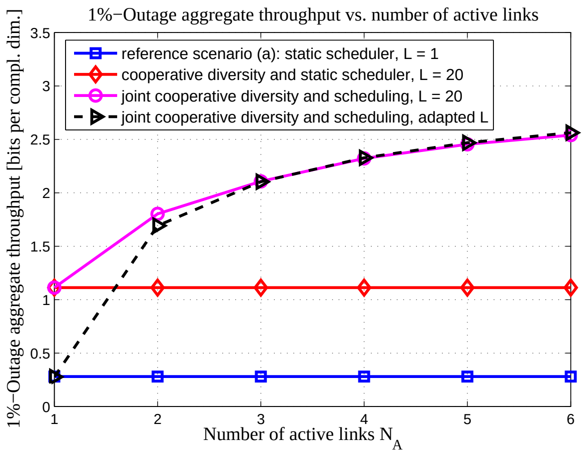


Fig. 9. 1%-Outage aggregate throughput; $P/\sigma^2 = 20$dB and $\sigma^2 = \sigma_{\mathrm{R}}^2$

VI. Conclusions

In this work we introduced a scheme for joint cooperative diversity and scheduling in low mobility wireless networks consisting of several active source/destination pairs and several idle nodes, assisting the active nodes as amplify-and-forward relays. We investigated the benefits and potential of this proposed scheme. We have shown that in contrast to a defined reference scenario this approach leads to an effective use of the given network resources and even makes a fair scheduling possible.

We conclude, that cooperative time-variant relaying promises to open up the low mobility regime to the benefits of channel adaptive scheduling.

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