Mobile Wireless Access via MIMO Relays

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***Abstract*—While a network with stationary nodes can provide large capacity in many current wireless systems, a network with mobile users suffers from severe performance degradation. This happens due to quick channel variation and its resulting protocol overheads that are especially large for multiuser multiple-input multiple-output (MIMO) systems. In this paper, we propose a relay-assisted multiuser MIMO downlink system to support highly mobile wireless access. Through a theoretical throughput analysis that explicitly considers the protocol overheads, we show that the MIMO relay significantly enhances the sum throughput of the system. While the introduced hardware complexity improves the throughput in low and moderate SNR regime, the throughput is improved by relay scheduling for spatial reuse in high SNR regime. We also discuss the practicality of this approach, characterizing challenging open problems in practice. Applications such as mobile video delivery can benefit from the enhanced system performance by our proposed architecture.**

I. Introduction

It is believed that next generation wireless networks will adopt multiple-input multiple-output (MIMO) technology to have higher speed and larger capacity than its predecessors. Through signal processing over multiple radio chains, MIMO opens a new dimension–*spatial domain*–in addition to the traditional temporal, spectral resources, greatly enhancing the system capacity. As a result, data delivery such as high definition video streaming over wireless is being discussed even for a cellular like highly loaded system.

Considering different hardware complexities of user equipment and a base station (BS), multiuser MIMO is regarded as one of the core technologies for downlink (a BS to user link) in most wireless standardization activities [1], [2]. Multiuser MIMO is especially helpful to improve the sum throughput of the system when there exists asymmetry between the numbers of transmit and receive antennas [3].

Despite its potential, there is a critical drawback that multiuser MIMO for downlink requires channel state information (CSI) with high accuracy. This leads physical and medium access control (MAC) layer protocols to consume a part of given resources as *protocol overheads*. The minimum protocol overhead is a pilot signal from the transmitter for each transmit antenna and optional CSI feedback from the receivers, the amount of which scales with the number of antennas and

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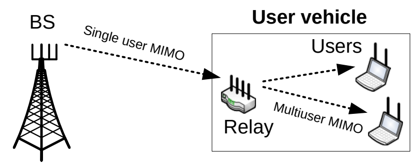

Fig. 1. The proposed relay-assisted MIMO network.

users. Consequently, it is widely accepted that the system performance enhanced by multiuser MIMO would be limited only to a network with stationary users and having more antennas at user equipment is believed to be essential to support high mobility.

To support mobile wireless access even with a small number of user antennas, we propose a relay-assisted MIMO downlink illustrated in Fig. 1. In our system, a BS has multiple antennas, and users have fewer antennas than BS's. A MIMO relay, which has at least as many antennas as the BS's, is installed in a user vehicle to compensate the performance loss from the high mobility. Consequently, while stationary users are directly served by the BS without any relay, the mobile users take advantage of the relays in the vehicle. The downlink for the mobile users is thus composed of two hops: BS-relay and relay-user links. The relay decodes the signal from the BS, encodes it again and forwards to the users. The physical volume of the vehicle provides large space for mounting as many antennas as the BS at the relay.

Explicitly taking the protocol overheads into account, the proposed system significantly enhances the sum throughput of the users, enabling applications such as mobile video delivery. The improvement, when the BS and relay have four antennas and the user has one antenna, is at most 2.7 times of the base-line system, which is multiuser MIMO downlink with zero-forcing beamforming where the users are directly served by the BS. With two additional antennas at the relay, the throughput even improves to at most 6.5 times of the base-line system.

While this gain brought by additional hardware mostly benefits low SNR users, we found that the throughput of high SNR users can be improved by exploiting the asymmetric characteristics of BS-relay and relay-user links. The gain for high SNR users is 170% in addition to the gain from the hardware. The asymmetry allows the BS to serve relays without the interruption by relay-user link transmission, enabling spatial reuse between the relays. This is possible because of high channel gain between the relay and users and the stationarity of the relay-user link. To make this system work, however, user and relay scheduling and relay power control should be addressed. We characterize these issues as well.

The rest of this paper is structured as follows. First we give two sets of overview on related work in Section II and on MIMO systems in Section III, respectively. In Section IV, our system model and assumptions are explained. Section V provides the theoretic throughput gain of the proposed system and its analysis, identifying the leverages to enhance it. Section VI summarizes the open challenges to achieve theoretic gains in practice and the broader impact of this study. This paper finally concludes in Section VII.

II. Related Work

From the information theoretical aspect, MIMO relays have been extensively studied so far. In order to characterize the capacity of such a network setup, cooperative schemes where a BS and relay send signals at the same time are widely considered [4]. The cooperation is mostly considered to improve transmission rates. The capacity characterization of the relay network is available in one bit error precision [5], and the exact capacity region is unknown as of today.

As another branch of research, MIMO relays are considered as a means to extend the coverage of transmission in the view of a network, providing two hop relaying. Recent efforts on this are made in standards activities such as IEEE 802.16j [6]. This leverage is also considered in [7], [8] when a set of single antenna users can cooperate in a distributed manner.

The physical layer techniques for two hop MIMO relaying are discussed in [9], [10], focusing more on throughput performance. The authors [9] show that decoding-and-forwarding relay outperforms amplifying-and-forwarding and hybrid relays when MIMO relays employ one of single user MIMO schemes with CSI at the transmitter for free. Amplifying-and-forwarding MIMO relays are optimized via geometric programming in [10], utilizing multi-antenna capability of the relay to concurrently serve users by multiuser MIMO, which closely resembles our architecture.

In contrast, we assume the decoding-and-forwarding MIMO that is mobile with the users. This architecture is mentioned in IEEE 802.16j [6]. However, our work distinguishes itself from the previous work in two viewpoints. First, the performance of the MIMO relay is analyzed with an explicit protocol overhead model for single and multiuser MIMO. Second, through the analysis, we have found that the time-sharing for two hop relaying can be minimized by scheduling the relays for spatial reuse.

III. MIMO System Overview

In this section, we first present a brief overview on how MIMO is able to provide parallel spatial streams from a transmitter to a receiver by making use of postprocessing at the receiver. Then, multiuser MIMO downlink is introduced by identifying that preprocessing may substitute for the post-processing. Other types of multiuser MIMO technologies can be found in [3]. Here a spatial stream refers to a stream of data delivered in the spatial domain created by signal processing across multiple radio chains.

*1) **Single User MIMO**:* MIMO communication creates multiple spatial streams, thanks to multi-path fading as well as the receive postprocessing across multiple radio chains. The signals experience different multi-paths caused by rich scattering between a transmitter and receiver. As a result, the receiver can take multiple *different* observations on mixed signals using multiple antennas, which leads to multiple linear equations that can be solved in various ways. This MIMO communication between one transmitter and receiver is called *single user MIMO*.

In single user MIMO, the creation of spatial streams relies on the postprocessing at the receiver while the preprocessing at the transmitter improves the quality of spatial streams. As they are combined over the air, the signals do interfere with each other. The MIMO receiver performs signal processing (postprocessing) based on current channel state to eliminate the interference, thus providing parallel spatial streams. Accompanied with the postprocessing, the transmitter is allowed to preprocess transmit signals for signal quality improvement at the receiver, if CSI is either perfectly or partially available at the transmitter.

*2) **Multiuser MIMO Downlink**:* If transmitters have more antennas than receivers in a network, which may be typical in future network deployment, the number of spatial streams is limited to the number of receive antennas if single user MIMO is applied. This is because the receivers cannot obtain a sufficient number of observations on the mixed signals.

By having more than one receiver, multiuser MIMO downlink overcomes this limit. With the aid of *accurate CSI*, the transmitter in the multiuser MIMO downlink precancels the interference between spatial streams before the transmission. By this precancelation, spatial streams are created without any postprocessing at the receivers. Essentially, the preprocessing substitutes for the postprocessing in single user MIMO.

However, it is expensive to have the CSI on multiple receiver links at the transmitter for the precancelation. In single user MIMO, the receiver removes the interference between spatial streams by using the CSI that can be accurately estimated by pilot signals from the transmitter. In the multiuser MIMO downlink, however, the CSI available at the receiver should be fed back to the transmitter through extra signaling.[1] Not only does this require additional signaling overheads, but it also lowers the accuracy of the information due to digital quantization [11]. This fact motivates us to take into account the protocol overheads in evaluating system throughput.

*3) **Diversity and Spatial Multiplexing**:* In both single user and multiuser MIMO, multiple spatial streams can be used to deliver redundant information, making transmission more

[1] In time division duplex systems, channel state of the forwarding link may be the same as the state of the reverse link with accurate channel calibration hardware, but this is not true in general.

reliable, or to carry different sets of information, achieving a higher transmission rate. These two strategies are respectively referred to as MIMO diversity and spatial multiplexing [12]. In this paper, we confine our interests to spatial multiplexing while the benefits in terms of transmission reliability can be achieved by the same approach.

IV. System Model

We propose a relay-assisted MIMO downlink for mobile users as shown in Fig. 1. A BS has many antennas, a relay has at least as many antennas as the BS, and users have fewer antennas than them. The relay is installed at the user vehicle, thus having high mobility as the users do. We assume that the wireless communication in this system is scheduled and coordinated in time and spatial domains within a narrow bandwidth.

• *Channel characteristics:* Interestingly, the BS-relay and relay-user links have radically different characteristics. The channel response of the BS-relay link significantly varies over time while that of the relay-user link is stationary. In addition, because of their proximity, the channel gain of the relay-user link is very high, compared to the BS-relay link.

For the purpose of throughput analysis, it is assumed that the signal attenuates in distance by free space path-loss model with exponent 3.[2] For a given received SNR from the BS to users, the distance between the BS and the users is computed by the free space model. The relay is placed 1m apart from the users on the line between the BS and users. For fast fading, Rayleigh fading model is used with block fading law. The channel varies due to fast fading independently, discretely at the beginning of each mini-slot (will be defined shortly).

• *MIMO schemes:* We adopt zero-forcing receiver and zero-forcing beamforming [13] for the BS-relay link and relay-user links, respectively. In the standards activities [1], [2], these two are being considered due to their simplicity in implementation. Note that unlike the relay-user link, we do not apply any preprocessing on the BS-relay link in order to avoid the need for the CSI feedback overheads. For comparison, we consider the base-line system where the BS directly serves the users via multiuser MIMO downlink with zero-forcing beamforming.

• *Frame format:* It is assumed that the transmission from the BS to the users through the relay follows the frame format as shown in Fig. 2. According to individual mobility, each user and relay have different time duration of which a channel response lasts flat. The difference depends on a coherence time of each link. This time duration is termed a mini-slot. In general, the duration for the BS-relay mini-slot is longer than that of the relay-user's since the relay and users move together.

Each mini-slot is used in part to exchange necessary information, which corresponds to pilots and feedback, and the rest of it is used for actual data transmission. For the BS-relay mini-slot, there are only pilots without feedback,

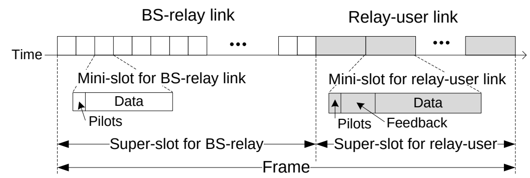

Fig. 2. Mini-slots, super-slots and frame for transmission. Due to vehicle's mobility, mini-slot for the BS-relay link is shorter than the relay-user's.

thus performing open-loop transmission. For the mini-slot of the relay-user link, however, both pilots and feedback exist since the zero-forcing beamforming relies on the CSI at the transmitter.

Data is forwarded through the BS-relay link using a BS-relay super-slot, which is composed of multiple mini-slots. The forwarded data is delivered to the users by using the relay-user super-slot, which is a multiple of a relay-user mini-slot. The relay-user super-slot immediately follows the BS-relay's, forming a frame. Note that the transmission efficiency is maximized when the throughput during the BS-relay super-slot is the same as the throughput by the relay-user.

The duration of different time slots and frames is all described in a symbol unit, and it is fixed throughout this paper. As a result, throughput is also measured in bits per symbol, which is given by Shannon's equation: $\log(1+\mathsf{SNR})$. A symbol thus represents the practical limitation on time sampling rate and frequency band allocation of the system. Most of all, the overheads are modeled in a concise way when the symbol unit is employed.

• *Overhead model:* The authors in [14] showed that the training overheads (pilots) can be minimally reduced down to one symbol per transmit antenna. For feedback, it is assumed that the system adopts the random vector quantization and one symbol is sufficient to feed back the index of one quantized channel vector. This is reasonable since the number of feedback bits, which are required to keep the CSI accuracy sufficient, exponentially increases as the throughput per symbol also exponentially increases [15]. It is assumed the adaptive modulation for feedback bits results in one symbol for a channel vector index.[3]

Denote the number of antennas at the BS by N_{bs}, at the relay by N_{rn} and at the user k by N_k. Also denote the protocol overheads of single user MIMO with zero-forcing receiver by V_{su} and the overheads of the multiuser MIMO downlink with the zero-forcing beamforming by V_{mu}. Two quantities per mini-slot are then easily computed by

$$V_{su} = N_{bs} \quad \text{and} \quad V_{mu} = N_{bs} + \sum_{k \in \mathcal{K}} N_{rn} N_k, \qquad (1)$$

where $\mathcal{K}$ is a set of selected users. It is assumed $|\mathcal{K}| = N_{bs}$. Since the sufficient number of feedback bits (e.g., $1.3(N_{bs} - 1)\log_2 \mathsf{SNR}$ bits in [15]), results in highly accurate CSI at the

[2]A path-loss exponent does not affect the tendency of the curves in the figure in Section V. In fact, the gain goes higher when the exponent gets larger.

[3]The amount of feedback overheads by the assumption, however, is the minimal in a sense that the practical protocols tend to apply no adaptive modulation to control and management signals.

transmitter, and thus, in what follows, it is assumed that the quantization loss is negligible.

V. Theoretical Throughput Gains

To see the theoretical gain of having mobile MIMO relays, the throughput of systems with minimum overheads is investigated in this section.

A. Throughput Calculation

• *Individual mini-slot throughput:* Given a channel matrix at ith BS-relay mini-slot, which is denoted by $\mathbf{H}_i$, zero-forcing receiver used in the mini-slot gives the instant throughput [16]

$$R_{br,i} = L_{br} \sum_{k\in\mathcal{K}} \log\left(1 + \frac{\mathsf{SNR}_{br}}{|\mathcal{K}|[(\mathbf{H}_i^{\dagger})^{*}\mathbf{H}_i^{\dagger}]_{kk}^{-1}}\right) \qquad (2)$$

bits per symbol, where $\mathbf{H}_i^{\dagger}$ is the pseudoinverse of $\mathbf{H}_i$, the superscript $*$ is the complex conjugate operation. $[\mathbf{A}]_{kk}^{-1}$ is a k-th diagonal element of the inverse of matrix $\mathbf{A}$. SNR_{br} is the received SNR at the relay in a linear scale. L_{br} is the time proportion for pure data transmission, which is given by $L_{br} := (T_{br} - V_{su})/T_{br}$ where T_{br} is the mini-slot duration for the BS-relay link in symbols and V_{su} is defined in Eq. (1).

Now consider the relay-user mini-slot throughput. The instant throughput of zero-forcing beamforming with limited feedback is easily derived as done in [15]. Denote the channel vector from the BS to user k in jth mini-slot by $\mathbf{h}_{k,j}$ and its quantized version through feedback by $\hat{\mathbf{h}}_{k,j}$. For the preprocessing, the BS composes channel matrix $\hat{\mathbf{H}}_j = [\mathbf{h}_{k_1,j}, \mathbf{h}_{k_2,j}, \cdots, \mathbf{h}_{k_{|\mathcal{K}|},j}]$ and computes the preprocessing matrix by $\mathbf{G}_j = \hat{\mathbf{H}}_j^{\dagger} = [\mathbf{g}_{k_1,j}, \mathbf{g}_{k_2,j}, \cdots, \mathbf{g}_{k_{|\mathcal{K}|},j}]$. Then, the throughput of the relay-user mini-slot is given by

$$R_{ru,j} = L_{ru} \sum_{k\in\mathcal{K}} \log\left(1 + \frac{\mathsf{SNR}_{ru}|\mathbf{h}_{k,j}^{*}\mathbf{g}_{k,j}|^2}{|\mathcal{K}| + \mathsf{SNR}_{ru}\sum_{p\neq k}|\mathbf{h}_{k,j}^{*}\mathbf{g}_{p,j}|^2}\right) \quad (3)$$

bits per symbol, where L_{ru} is a time proportion for the relay-user link which is defined as $L_{ru} := (T_{ru} - V_{mu})/T_{ru}$ where T_{ru} is mini-slot duration for the relay-user link. SNR_{ru} is the received SNR at the users, and due to the proximity between relay and users, $\mathsf{SNR}_{ru} \gg \mathsf{SNR}_{br}$.

• *Sum throughput (frame throughput):* Denote the mean throughput of ith BS-relay mini-slot by $R_{br} := \mathbb{E}_{\mathbf{H}_{br,i}}[R_{br,i}]$ and the throughput of jth relay-user mini-slot by $R_{ru} := \mathbb{E}_{\mathbf{H}_{ru,j}}[R_{ru,j}]$.

Let us also denote the number of BS-relay mini-slots by n and the number of relay-user mini-slots by m, which altogether form a frame. The scheduler in our system determines these parameters to maximize the instant throughput from the BS to the users through the relays. Given $\{\mathbf{H}_{br,i}\}_{i=1}^{n}$ and $\{\mathbf{H}_{ru,j}\}_{j=1}^{m}$, the instant throughput of our proposed system is denoted and computed by $R_{prop} = \frac{1}{n+m}\min\{\sum_{i=1}^{n} R_{br,i}, \sum_{j=1}^{m} R_{ru}\}$. Since $R_{br,i}$ and $R_{ru,j}$ are iid for i and j, by the law of large number, $\mathbb{E}[R_{prop}] \rightarrow \frac{1}{n+m}\min\{n\cdot R_{br}, m\cdot R_{ru}\}$ as n and m grow. The upperbound is easily found by allowing fractional values for n and m as

$$R_{prop}^{\max} := \frac{R_{br}\cdot R_{ru}}{R_{br} + R_{ru}} \geq \mathbb{E}[R_{prop}], \qquad (4)$$

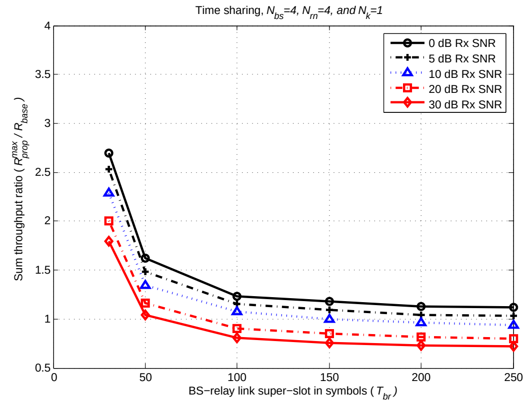

Fig. 3. Sum throughput ratio with time-sharing (N_{bs}=N_{rn}=4,N_k=1).

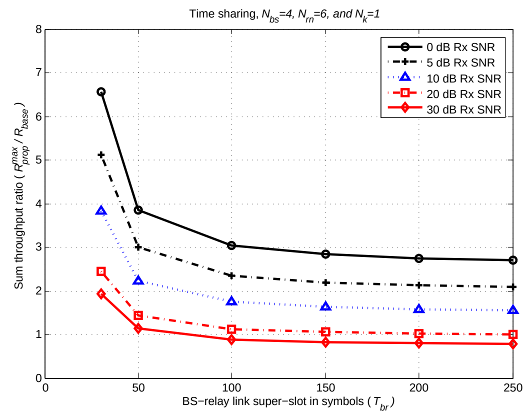

Fig. 4. Sum throughput ratio with time-sharing (N_{bs}=4,N_{rn}=6,N_k=1).

where the equality holds when $n = R_{ru}$ and $m = R_{br}$. By assuming a perfect scheduler for m and n, the upperbound is studied as the sum throughput of our system.

For comparison, the sum throughput of the multiuser MIMO downlink with zero-forcing beamforming is considered without a relay and termed a base-line system.[4] The sum throughput of the base-line system is thus computed by by Eq. (3) with SNR_{bu} which is the received SNR from the BS directly to users. We denote the expectation of the throughput of the base-line system by R_{base}.

B. Numerical Results and Analysis

In Figs. 3, 6, 4 and 7, the sum throughput ratios of the proposed relay system over the base-line system are depicted, which is computed by $R_{prop}^{\max}/R_{base}$, with respect to different received SNRs. The x-axes of the figures represent the duration of a BS-relay mini-slot, which also represents user mobility: a small mini-slot corresponds to the users with high mobility and vice versa.

• *Relay gains:* In Fig. 3, the throughput ratios are depicted when $N_{bs} = 4$, $N_{rn} = 4$ and $N_k = 1$ for $k \in \mathcal{K}$ and

[4]We use this systems as a base-line because multiuser MIMO downlink with zero-forcing beamforming achieves higher throughput than single user MIMO capacity due to the minimum overheads and small number of user antennas in our system configuration.

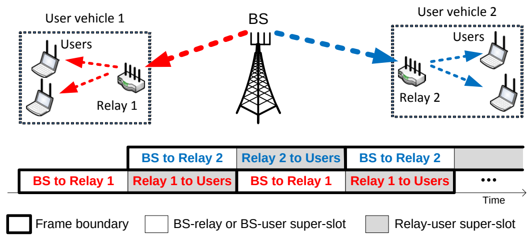

Fig. 5. One example of super-slot schedules for spatial reuse.

$|\mathcal{K}| = N_{bs}$. The propose system achieves at most 270% throughput of the base-line system when the user mobility is high. However, the throughput gain exponentially decreases as the user mobility reduces. With stationary users experiencing high SNR, the throughput is even worse than the base-line system. Since the proportion of the overheads to the BS-relay mini-slot duration for our system is less than that of base-line system ($V_{su} < V_{mu}$), our system achieves a large throughput gain with high mobility. As mobility decreases, however, the proportion of the overheads becomes negligible ($L_{br} \approx T_{br}$), and the penalty of time-sharing between the BS-relay and relay-user links is notable especially for the users with high SNR. A sophisticated adaptive scheme that chooses either relaying or direct service to users is thus needed.

- *Gains with a relay with more antennas:* With the aid of additional antennas *at the relay*, the throughput gains are enormous: Fig. 4 shows that having two more antennas at the relay provide at most 650% of the throughput enhancement. This is even with the increase of the feedback overheads in the relay-user mini-slots. Those antennas add two degrees of freedom in the spatial domain of both BS-relay and relay-user links, substantially improving the quality of MIMO signal processing on both links. Huge gain is in part because of the sub-optimality of the zero-forcing method [13]. The gains, however, become negligible and even worse than the base-line system as the SNR goes high. The time-sharing penalty for high SNR users is still expensive even with more antennas at the relay.
- *Spatial reuse gains:* The MIMO relay gains so far come from the additional hardware complexity in the system. The time-sharing, however, penalizes the users with high SNR even with the added complexity, making the relay attractive only when the users experience low or moderate SNRs. We found that the proposed system can be further improved by appropriate *user and relay scheduling* and *relay power control* for spatial reuse. The improvement is especially significant for high SNR users, which complements the gains by the added hardware complexity.

Suppose that two mobile relays with users are in one cell as shown in Fig. 5. Once the transmission to Relay 1 by the BS is over, the BS may immediately serve Relay 2 while Relay 1 is forwarding data with reduced power without generating interference to Relay 2. Even with reduced power, the relay may forward data to users in a short time period, thanks to high channel gain and stationarity of a relay-user link: *while high channel gain allows the relay to transmit in a high rate, the stationarity reduces the protocol overheads.* Therefore, our system where transmission goes through two hops becomes virtually equivalent to the base-line system *without the feedback overhead*. One example of the scheduled super-slots is depicted in Fig. 5.

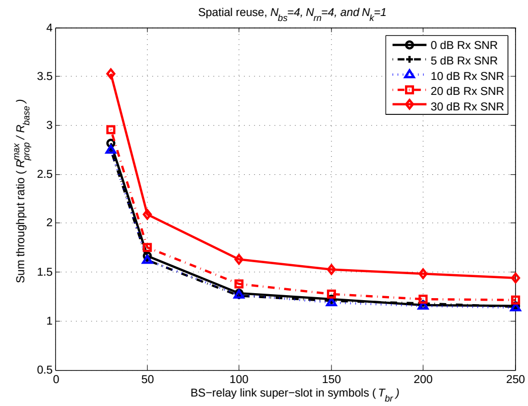

Fig. 6. Sum throughput ratio with spatial reuse (N_{bs}=N_{rn}=4,N_k=1).

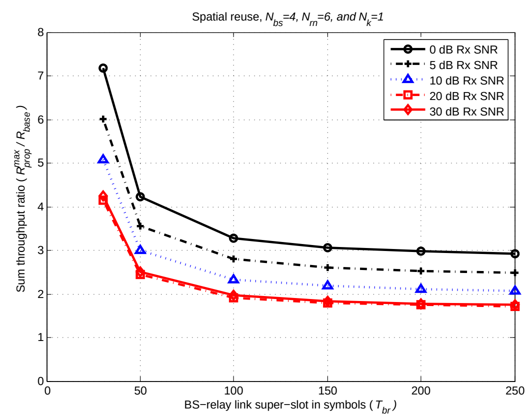

Fig. 7. Sum throughput ratio with spatial reuse (N_{bs}=4,N_{rn}=6,N_k=1).

Fig. 6 depicts the throughput ratios when spatial reuse in serving relays is perfectly done. Spatial reuse results that the frame is composed of a single BS-relay super-slot even in the proposed system. Compared to Fig. 3, the sum throughput gains in Fig. 6 are improved by at most 170% for the 30 dB SNR users in addition to the gains by having the relays. The sum throughput when 2 additional antennas are installed at the relay is shown in Fig. 7. It is observed that the further improvement of the throughput by spatial reuse is 220% for the users with 30 dB SNR. Note that the gain in a real system could be more significant since the minimum overheads are considered in this analysis.

VI. Achieving Gains in Practice

This section discusses the practicality of the MIMO relays at the user vehicles and the issues in achieving the throughput gains observed in the previous section.

*1) **Additional Antennas**:* An alternative solution to enhance the throughput of highly mobile users is to have as many user antennas as those at the BS. Because of the form-factor limitation in practice, installation of many antennas at the user equipment is not likely to yield a rich scattering that is essential for the MIMO operation. Meanwhile, the physical volume of the vehicle can be maximally utilized to install antennas and thus have a desirable MIMO channel. This fact makes the proposed system attractive in practice.

*2) **User and Relay Scheduling**:* User and relay scheduling is defined in this paper as selecting relays or users for current and future super-slots in order to maximize user utilities. In this paper, we have investigated sum throughput as user utilities. The challenge is that the proposed system should consider super-slots in future as well: it is required to make sure that the BS is constantly serving users or relays so that the loss from the time sharing for the BS-relay and relay-user links is minimized. In other words, the scheduler should provide spatial reuse for the relay-user links.

This scheduler is also responsible for determining n and m, adjusting the throughput of BS-relay and relay-user links. The parameter m may be controlled by the relay, but the centralized decision making may be a better approach due to the available information at the BS such as statistics on signal strengths of users and relays, etc. Two parameters also determine the busy period of the receiving relay since the relay is supposed to serve the users after its reception from the BS. In the BS's view, this unavailability complicates the scheduling as well.

*3) **Relay Power Control**:* Beside the scheduling of the relays that are apart from each other, our system can leverage transmit power control for spatial reuse. Thanks to the high channel gain between the relay and users, the relay may achieve a sufficient transmission rate to serve the users with low transmit power. Moreover, even when the rate is limited by the low transmit power, using multiple mini-slots for the relay-user super-slot can achieve both the completion of its forwarding and the minimization of interference to others.

Power control is closely related to scheduling in two viewpoints: first, the level of transmit power allowed for the relay is determined by the wireless channel between the currently scheduled relay and those that will be scheduled in the next frame. Second, the power level determines the number of mini-slots needed for the relay-user super-slot. As a consequence, the relay is not available to receive data from the BS during the relay-user super-slot. The scheduler should be aware of this unavailability and its duration.

*4) **Cooperative MIMO**:* It is interesting that, if placing a relay may induce too much cost for users, the same approach can be taken without the relay as well. Instead of being aided by the relay, individual users may exchange their received signals to decode the spatial streams in a cooperative manner, which is called a *virtual MIMO* [8] or *cooperative MIMO* [7]. Thanks to the high channel gain and stationarity, the users may cooperate locally, not interfering the transmission by the BS. Only a small change to the user and relay scheduling described in Section VI-2 would be needed. Alternatively, user equipment with different wireless access capability (e.g., a mobile phone with WLAN capability) may use other access method for the cooperation, exploiting the channel stationarity. In this case, a convergence layer between two different wireless access protocols should be newly added for the cooperation.

VII. Conclusion

In this paper, we have discussed a relay-assisted MIMO system and identified the potential that can enable high throughput mobile wireless access, which is multiple times of the system without a relay. While the gain by hardware upgrade is mainly for low and moderate SNR users, we have found that the system can be further improved by scheduling the mobile relays for spatial reuse. This scheduling is essential since it mainly improves high SNR users, complementing the MIMO relay gains in all range of SNRs. We have also discussed a few challenging open problems to be addressed for the spatial reuse, which is our current focus of research. Applications such as intensive video streaming to mobile users can benefit from the proposed system.

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