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Published in:
Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP)

2011

Document Version:
Peer reviewed version (aka post-print)

Link to publication

Citation for published version (APA):
Jensen, M. A., Lau, B. K., Medbo, J., & Furuskog, J. (2011). Performance of cooperative MIMO based on measured urban channel data. In *Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP)* IEEE - Institute of Electrical and Electronics Engineers Inc.. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5782041

Total number of authors:
4

M. A. Jensen, B. K. Lau, J. Medbo, and J. Furuskog, “Performance of cooperative MIMO based on measured urban channel data,” in *Proc. 5th Europ. Conf, Antennas Propagat. (EuCAP’2011)*, Rome, Italy, Apr. 11-15, 2011.

Performance of Cooperative MIMO Based on Measured Urban Channel Data

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***Abstract*—We study the potential benefits of cooperative multiple-input multiple-output signaling from multiple coherent base stations with one or more mobile stations in an urban macrocellular environment. The analysis uses novel and fully-coherent measurements of the channel from three base stations to a single mobile station equipped with four antennas. The observed channels are used to explore the gains in capacity enabled by cooperative base station signaling for point-to-point and multi-user communications. The analysis shows that cooperative signaling using practical algorithms yields significant increases in average capacity.**

I. INTRODUCTION

While multiple-input multiple-output (MIMO) technology has demonstrated the potential for realizing significant improvements in wireless communication performance, realization of these gains depends on the communication environment [1]. For example, at the base station (BS), the elevated position and sectorized nature of the antennas leads to limited observed angular spread that makes it difficult to improve performance through spatial processing using multiple antennas. One potential solution to this problem involves using multiple BS sites working cooperatively, a solution that also potentially enables significant benefit in terms of interference control in multi-user signaling [2], [3]. The benefit of cooperative BS communication has been studied in the context of determining the channel and shadowing correlation properties for multiple BS sites and a single mobile station (MS) [4]–[7].

In this paper, we extend the prior work by reporting on the analysis of fully-coherent measurements from three BS sites to a single MS in a macrocellular environment, measurements that we believe to be the first of their kind. The observed channels are first used to explore the gains achieved with cooperative MIMO signaling to a single user [8]. This analysis shows that BS cooperation leads to an average increase in capacity of 73% over that achieved using a single BS. In places where two or more base stations contribute nearly equal signal power to the MS, this increase in capacity can exceed 90%. We then turn our attention to the performance of cooperative MIMO for multi-user communications for the downlink or broadcast channel (BC) [2] based on different practical signaling strategies over the observed channels. This analysis, which surpasses other studies on experimentally-based multi-user cooperative MIMO, shows that cooperative MIMO signaling can provide multi-user throughput gains that are significantly higher than what can be achieved using more traditional multiple-access strategies under favorable channel conditions.

II. MEASUREMENTS

Measurements were performed using three BS sites in an urban macrocell environment within Kista, Stockholm, Sweden. At each BS, a single antenna mounted a few meters above the average rooftop level of approximately 25 m transmits a linearly-polarized (45° from vertical) signal. The MS consists of two dipole and two loop antennas mounted on the top of a measurement van as a square array with an inter-element spacing of approximately 30 cm, which is 2.6 wavelengths at the excitation center frequency of 2.66 GHz. Measurement of the channel between all three BS and four MS antennas is accomplished using the Ericsson mobile channel sounder based on a prototype for LTE [9] that uses time-multiplexed orthogonal frequency division multiplexing (OFDM) symbols with 432 tones to achieve a measurement bandwidth of 19.4 MHz

The MS uses four parallel receiver chains to simultaneously downconvert the signals from the four receive antennas. Disciplined rubidium clocks at the transmitter and receiver provide a highly accurate synchronization between the BS and the MS. The system records the 4×3 MIMO channel matrix at a rate of 190 samples per second, providing high spatial resolution given the maximum van speed of 30 km/hr. All of the parameters used in the measurements are provided in Table I. Figure 1 shows the two routes along with markers indicating the distance traveled along each route and the positions of the base stations.

III. SINGLE-USER CHANNELS

To study the benefit of BS cooperation for communication with a single MS, we normalize the measured 4×3 multi-BS (MIMO) channels by the total received power of the strongest 4×1 BS-to-MS single-input multiple-output (SIMO) link at each measurement point. We then compute the capacity for

TABLE I
SPECIFICATIONS FOR THE ERICSSON CHANNEL SOUNDER

Parameter	Value
Center Frequency	2.66 GHz
Bandwidth	19.4 MHz
Frequency bins	432
Transmit power	36 dBm
Channel acquisition rate	190 channels/s
Number of BS	3
BS antenna	1 Kathrein (18 dBi 45 deg polarized)
MS antenna	2 dipoles + 2 magnetic loops

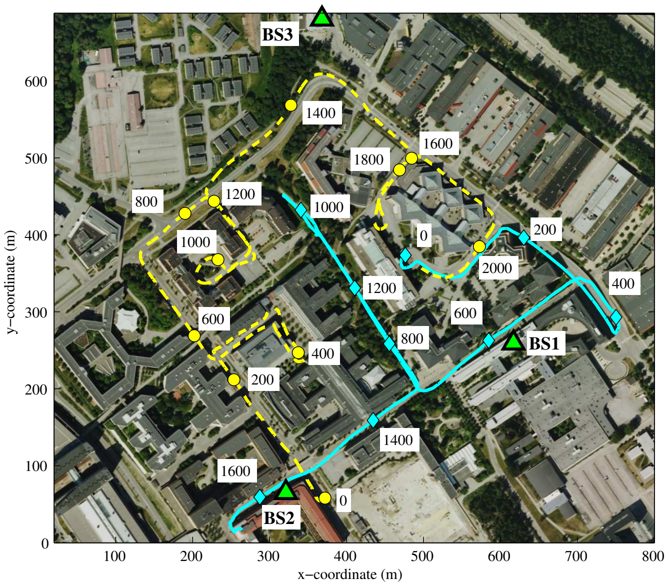

Fig. 1. Location of BSs and route 1 (- -) and route 2 (—) of MS. Distances (in meters) from starting points are indicated by ● and ♦ markers.

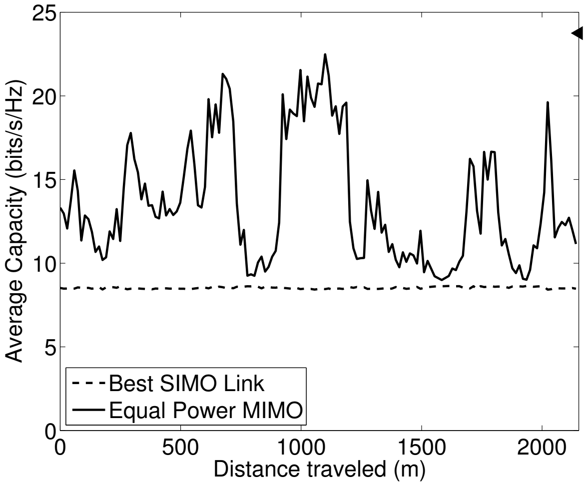

Fig. 2. Average capacity for SIMO link from the best BS and using cooperative MIMO with equal transmit power for the MS on Route 1.

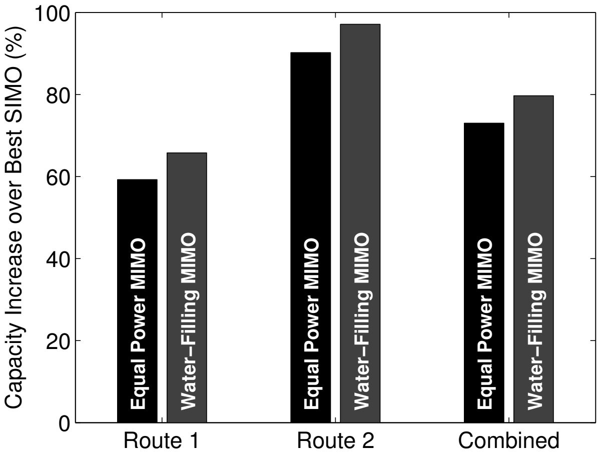

Fig. 3. Improvement in average capacity for cooperative BS signaling based on equal and water-filling transmit power relative to that of the best BS link averaged over all measurements for each route and the combined routes.

the cooperative base stations assuming a reference signal-to-noise ratio (SNR) of 20 dB and present results averaged over the frequency samples assuming that the capacity is computed with base stations transmitting equal power or assuming that power control is used to achieve the capacity of the water-filling solution.

Figure 2 plots the capacity of the best single-BS link and the multi-BS communication for Route 1 after smoothing using a moving average filter over a window of 10 wavelengths and downsampling. The capacity values in this plot are obtained assuming the base stations have equal transmit power. The average capacity achieved for channel coefficients modeled as i.i.d. zero-mean complex Gaussian random variables with 20 dB SNR is indicated by the black triangle. These results demonstrate that BS cooperation provides significant potential capacity gain, although the capacity falls short of that achievable with i.i.d. coefficients.

Next we compute the capacity obtained assuming cooperative MIMO signaling (for both equal and water-filling power allocation) from all BS sites as well as for the best BS-to-MS SIMO link averaged over all measurement points and frequencies. Figure 3 shows the percentage increase in the average capacity achieved using cooperative BS signaling relative to that achieved using the link from the best BS. These results show that BS cooperation leads to significant capacity improvements, with the capacity almost doubling for Route 2.

IV. MULTI-USER CHANNELS

For multi-user communications, we focus on two MSs on the measurement routes, which means that we use channels measured at different times to obtain the required channel data from the BSs to the spatially-displaced users. We assume that each MS only receives or transmits a single data stream.

For the BC, the cooperative BSs apply a beamformer to the signal for each MS and constrain the total transmit power P, which implies that the BSs use power control and can change their power allocation up to a total of P. The sum rate experienced for this BC can be computed using techniques in [10]. We first assume that each MS receives using only one of the vertically-polarized antennas in a multiple-input single-output (MISO) configuration. We consider three different BC MISO scenarios. (a) As a reference, each mobile user establishes a link with the BS for which the BS-to-MS gain is maximum, even if multiple MSs share the same BS. We also compute the sum rate achieved when the two MSs equally divide the communication time (time division multiple access, or TDMA), and use this rate for the reference if it exceeds that for BC MISO signaling. (b) We determine the BS-MS pairs that achieve the largest sum rate. (c) We compute the sum rate for the true cooperative BC MISO with the signaling established based on the regularized channel inversion (RCI) method [11].

We also assume a BC MIMO situation where each MS knows (through feedback) all of the transmit beamformers and can therefore construct a minimum-mean-squared error (MMSE) beamformer [11]. For this BC MIMO, we use the same scenarios as outlined above for the MISO case.

For the computations, at each measurement point we scale the channel matrices for all links by the same constant β computed from

$$\beta = \sqrt{\frac{2N_{\mathrm{B}}N_{\mathrm{r}}}{\sum_k \|\mathbf{H}_k\|_{\mathrm{F}}^2}}, \tag{1}$$

where $\mathbf{H}_k$ is the $N_{\mathrm{r}} \times N_{\mathrm{B}}$ measured channel matrix to the kth MS, N_{B} is the number of BSs, N_{r} is the number of receive antennas at each MS, and $\|\cdot\|_{\mathrm{F}}$ indicates a Frobenius norm. With this normalization and given the assumption of Gaussian noise with unit variance, the total power P represents the single-input single-output (SISO) SNR averaged over the MSs which is set to be 20 dB. Referring to Fig. 1, the first MS moves along the entirety of routes 1 and 2 while the second MS stays stationary at points that are either 700 m or 900 m from the start along route 2.

As an example, Fig. 4 plots the sum rate achieved assuming BC MISO signaling for the three topologies discussed. We first observe that the maximum gain pairing works well compared to the optimal BS-MS pairing when MS_1 is on the main roads (e.g. between displacements of 750 and 900 m) and enjoys nearly LOS propagation and therefore a dominant link with a single BS. However, when MS_1 deviates into a small "inlet" (e.g. between displacements of 250 and 550 m), the maximum gain pairing increases the multi-user interference, and therefore a different pairing that reduces interference is beneficial. We emphasize that in these interference-limited scenarios, the maximum gain pairing would suffer significant additional degradation were it not for the ability to switch to TDMA. Finally, since the link gain for two or more BSs to a single MS is similar in these regions, allowing the multiple BSs to collaborate to control interference and maximize link gains through application of the RCI beamforming weights provides sigificant additional sum rate capability.

Figure 5 shows the percentage increase in average sum rate achieved for MISO and MIMO BC signaling over all four simulations (two routes for one MS each with two locations for the second MS) relative to the sum rate achieved for the MS-BS pairing based on maximum link gain. Considering the discussion corresponding to Fig. 4, it is not surprising to see the dramatic improvement achieved by cooperative BS signaling. This plot further reveals, however, that for MIMO signaling, simply selecting the optimal pairing achieves most of the available gain. This is because the multi-antenna reception enables each MS to reduce the interference from the stream destined to the other MS, and therefore cooperative BS transmission provides only incremental additional improvement. Finally, it is important to note that while the percentage increase for MIMO BC is smaller than that for MISO BC, the average sum rate for the MS-BS pairing based on maximum link gain is substantially higher for MIMO BC than for MISO BC. The substantial performance gains observed motivate additional research aimed at making cooperative MIMO systems practical for data intensive wireless networks.

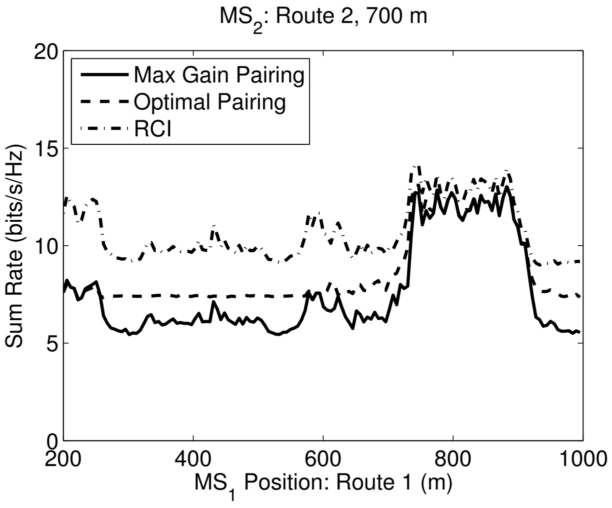

Fig. 4. Sum rates computed for different BC MISO signaling approaches when MS_1 travels along a portion of route 1 and MS_2 is at the point 700 m from the start along route 2.

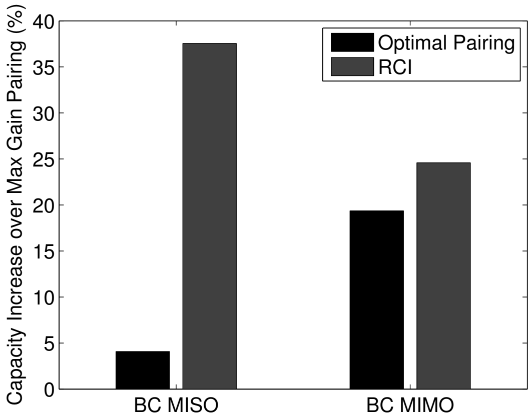

Fig. 5. Improvement in average sum rates for BC MISO and MIMO relative to the case where the signaling uses the optimal pairing between the BS and MS.

V. CONCLUSIONS

This paper uses fully-coherent measurements from three BS sites to a single MS in a macrocellular environment to explore the potential gains achievable with cooperative BS communication for single-user and multi-user scenarios. Specifically, computations with the data for point-to-point links demonstrate that the capacity increases by 73% on average and over 90% for the best route as a result of cooperative communications. Evaluation of the data with practical multi-user signaling strategies assuming two MSs shows that cooperation between the BSs can also significantly increase the multi-user sum rate. Such dramatic capacity improvement motivates further study of coherent cooperative communications for macrocellular settings.

ACKNOWLEDGMENT

This work was supported in part by Telefonaktiebolaget LM Ericssons Stiftelse för Främjande av Elektroteknisk Forskning, VINNOVA under Grant 2008-00970, and in part by the U. S. Army Research Office under the Multi-University Research Initiative (MURI) Grant # W911NF-07-1-0318.

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