OPPORTUNISTIC BEAMFORMING VS. SPACE-TIME CODING IN A QUEUED DOWNLINK

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ABSTRACT

We investigate the different usage of multiple transmit antennas in a SDMA/TDMA single-cell downlink system under random packet arrivals, correlated block-fading channels and non-perfect channel state information at the transmitter due to a feedback delay. We derive the arrival rate stability region and the adaptive scheduling policy that stabilizes any arrival rate point inside the region without knowing explicitly the arrival statistics. Then, we apply these results to the case of "opportunistic" beamforming and space-time coding. The ability of accurately predicting the channel SNR dominates the performance of opportunistic beamforming. Hence, we propose to exploit synchronous pseudo-random beamforming matrices known a priori to the receivers in order to improve the channel state information quality. Under this scheme, it appears that for given feedback delay the relative merit of opportunistic beamforming versus space-time coding strongly depends on the channel Doppler bandwidth.

1. MOTIVATION

The downlink of a single cell system is modeled as a fading Gaussian broadcast channel, whose capacity region has been completely characterized under different assumptions in several papers (e.g., [1]). In particular, it is known that, under fading ergodicity, when the base station is equipped with a single antenna and has perfect *Channel State Information* (CSI), the average throughput (long-term average sum rate) is maximized by serving the user with the largest fading coefficient at each time instant (e.g., [2]). Motivated by this result, downlink scheduling schemes such as the High-Data Rate (HDR) [3] or the 1xEV-DO [4] have been proposed. Such systems assume that all connected users have infinite backlog (i.e., all data present at the base station, no arrival processes).

When the base station is equipped with $M > 1$ antennas, the single-cell downlink falls in the class of *vector Gaussian broadcast channels*, whose capacity region with perfect CSI has been fully characterized in [5] and references therein. In particular, for a system with M transmit antennas and $K \geq M$ users, a multiplexing gain of M can be achieved, i.e., the average throughput scales as $M \log \mathsf{SNR}$ for high SNR, and M users can be served simultaneously on each slot. A low-complexity alternative usage of multiple transmit antennas for the downlink with scheduling and TDMA consists of the so called *opportunistic beamforming* proposed in [2], where the multiple antennas are used to generate a random beam inducing an artificial fading that varies slowly enough to be measured and fed back by the users but rapidly enough to make the scheduling algorithm share the channel fairly among the users. A spatial-multiplexing version of the opportunistic beamforming is proposed and analyzed in [6], where M mutually orthogonal random beams are simultaneously used to serve the best M users at each time. It is shown that for $K \gg M$ and assuming perfect SNR instantaneous feedback, the same multiplexing gain of M as for the case of perfect CSI is achievable.

In parallel with the development of opportunistic schemes, the current research and standardization trend has focused on Space-Time Coding (STC). When CSI at the transmitter is not perfect, the event that the transmitted rate falls below the instantaneous mutual information of the fading channel (*information outage* event) has positive probability. This is the event that dominates the decoding error probability for good codes in high SNR conditions [7]. In the most realistic scenario where the base station is equipped with M antennas and the mobile terminal has a single antenna, STC achieves M-fold *transmit diversity*, making block error probability decrease as $O(\mathsf{SNR}^{-M})$ for high SNR, that is, M times faster than in a single-antenna system.

Based on the optimistic assumptions of perfect SNR feedback and infinite backlog, a number of recent works showed that the transmit diversity achieved by STC is detrimental for the multiuser diversity effect connected to opportunistic beamforming/scheduling schemes [8, 9]. These results led to the naive conclusion that STC should be avoided in high data rate downlink applications. In this paper we take a deeper look into this problem by considering two fundamental aspects neglected in works such as [2, 6, 8, 9]: random packet arrivals with finite transmission buffers, and time-varying fading channels with a delay in the feedback link. Under the random packet arrival, the traditional notion of fairness is replaced by the notion of stability [10, 11]: we wish to find the transmission policy that stabilizes all users buffers, whenever the arrival rates can be stabilized, i.e., belong to the system *stability region*. The realistic assumption of feedback delay makes transmitter CSI non-perfect and hence information outage probability non-zero. Therefore there exists a non-trivial tradeoff between the transmit diversity achieved by STC and the multiuser diversity achieved by opportunistic schemes.

This research was supported by France Télécom and by the Institut Eurécom under the grant 424 87 987.

We compare STC (transmit diversity) and random beamforming with $1 \leq B \leq M$ beams. The ability of accurately predicting the channel SNR dominates the performance of opportunistic beamforming. Hence, we propose a new scheme based on pseudo-random unitary beamforming matrices known to the receivers (in analogy with random-spreading CDMA, where the downlink scrambling sequence is synchronized and known to all users in the cell). In this way, the users have only to track and predict the underlying physical channel which can be much slower than the variation of the pseudo-random beam pattern. Even under this scheme that represents a "best case" for opportunistic beamforming, it appears that for given feedback delay the relative merit of opportunistic beamforming versus STC strongly depends on the channel Doppler bandwidth. In particular, for slowly-varying channels the opportunistic beamforming with $B = M$ beams [6] achieves the best average delay, while for faster channels STC is better. In light of these results, the utility of random beamforming with $B = 1$, as in [2], is questionable.

2. SDMA/TDMA DOWNLINK SYSTEM MODEL

We consider a base station with M antennas transmitting to K user terminals each one equipped with a single antenna. Transmission is slotted and each slot comprises N channel uses (complex dimensions). The signal received at user k terminal in slot t is given by

$$\mathbf{y}_k(t) = \mathbf{X}(t)\mathbf{h}_k(t) + \mathbf{w}_k(t) \quad (1)$$

where $\mathbf{X}(t) \in \mathbb{C}^{N\times M}$ is the transmitted codeword, $\mathbf{h}_k(t) \in \mathbb{C}^{M\times 1}$ denotes the M-input 1-output channel response for the user k channel in slot t, assumed time-invariant over each slot and $\mathbf{w}_k(t) \in \mathbb{C}^{N\times 1}$ is complex circularly symmetric AWGN with components $\sim \mathcal{CN}(0,1)$. The base station has fixed transmit power γ in each slot, that is, $\mathrm{tr}(\mathbf{X}(t)\mathbf{X}(t)^H) \leq \gamma N$ for all t. Due to the noise variance normalization, γ takes on the meaning of maximum *transmit* SNR.

Coding and decoding is performed on a slot-by-slot basis. We assume that N is large enough such that good Gaussian-like codes exist whose block error probability is essentially given by the information outage probability [7].

We assume a SDMA/TDMA downlink system. Namely, at each slot, a subset of $1 \leq B \leq M$ out of K users is selected and independent information messages are sent to these users via B independently selected codewords. Information packets arrive randomly at the base station, and are stored into K queues, where queue k is associated to user k. The arrival process of queue k is denoted by $A_k(t)$, with *arrival rate* $\lambda_k \triangleq \frac{1}{N}\mathbb{E}[A_k(t)]$ in bit/channel use, and the buffer size of queue k is denoted by $S_k(t)$ expressed in bit. At the beginning of each slot, a Data Rate Control (DRC) signal $\boldsymbol{\alpha}(t) = (\boldsymbol{\alpha}_1(t), \dots, \boldsymbol{\alpha}_K(t))$ is revealed to the transmitter. The SDMA/TDMA policy is characterized by certain feasible rate functions, denoted by $p_{k,j}R_{k,j}(\boldsymbol{\alpha})$, where $R_{k,j}(\boldsymbol{\alpha})$ is a function that will be specified later, $\mathbf{p}$ is a SDMA/TDMA resource-sharing matrix, and $\boldsymbol{\alpha}$ is the current value of the DRC signal. The resource sharing matrix $\mathbf{p}$ has the following meaning: $p_{k,j} \geq 0$ is the fraction of the current slot allocated to user k on beam j or, equivalently, it is the probability with which the whole slot is allocated to user k on beam j. As it will be clear from the following treatment, these two interpretations yield the same results in terms of stability region and we may think of the second as a more practical option (only one user per beam transmits at any slot instead of partitioning the slot time into sub-slots). The set of all feasible resource-sharing matrices is

$$\mathcal{F} \triangleq \left\{ \mathbf{p} \in \mathbb{R}_+^{K\times B} : \sum_{k=1}^{K} p_{k,j} \leq 1, \ \ \forall\, j \right\} \quad (2)$$

With some abuse of notation, we denote by $\mathcal{F}$ also the set of resource-sharing feasible *functions*, i.e., the set of all functions that map the DRC signal into $\mathcal{F}$. Since the DRC signal is not ideal, there exists a non-zero probability that any specified transmission rate R cannot be supported by the channel. We assume an ARQ protocol such that an unsuccessfully decoded packet remains in the transmission buffer and is re-scheduled for transmission at a later time. We let the rate function $R_{k,j}(\boldsymbol{\alpha})$ to be the *average rate* for user k over beam j conditioned with respect to the current DRC signal $\boldsymbol{\alpha}$ and maximized over the choice of the *instantaneous* coding rate, i.e.,

$$R_{k,j}(\boldsymbol{\alpha}) = \max_{R\geq 0} \ R\left(1 - P_{\mathrm{out}}(R|\boldsymbol{\alpha})\right) \quad (3)$$

where

$$P_{\mathrm{out}}(R|\boldsymbol{\alpha}) \triangleq \Pr\left(\log_2(1+\beta_{k,j}\gamma) \leq R|\boldsymbol{\alpha}\right) \quad (4)$$

and where $\beta_{k,j}\gamma$ is the received SNR for user k associated with the signal sent on beam j. The rate $R_{k,j}(\boldsymbol{\alpha})$ is achieved on average, if user k is scheduled on beam j and allocated an instantaneous rate $R^\star$, achieving the maximum in (3), whenever the DRC signal is equal to $\boldsymbol{\alpha}$.

For a given SDMA/TDMA resource allocation policy $\mathbf{p}(t)$, the queue buffers evolve in time according to the stochastic difference equation

$$S_k(t+1) = \left[S_k(t) - N\sum_{j=1}^{B} p_{k,j}(t)R_{k,j}(\boldsymbol{\alpha}(t)) \right]_+ + A_k(t) \quad (5)$$

for all $k = 1, \dots, K$, where $[\cdot]_+ \triangleq \max\{\cdot, 0\}$. In order to define stability, we follow [10] and define the buffer overflow function $g_k(S) = \limsup_{t\to\infty} \frac{1}{t}\sum_{\tau=1}^{t} 1\{S_k(\tau) > S\}$. We say that the system is stable if $\lim_{S\to\infty} g_k(S) = 0$ for all k. We define the system stability region Ω as the set of all arrival rates K-tuples $\boldsymbol{\lambda} \in \mathbb{R}_+^K$ such that there exists a resource-sharing policy for which the system is stable. Clearly, for the system defined above the main goal of a SDMA/TDMA policy is to stabilize the system whenever $\boldsymbol{\lambda} \in \Omega$.

3. MAIN RESULTS

The stability theory of [10] can be easily extended to our setting, where the role of the power allocation in [10] is played by the resource-sharing allocation $p_{k,j}$ and the role of the channel state in [10] is played by the DRC signal $\boldsymbol{\alpha}(t)$. A slight modification of the proofs in [10] is required to take

into account the fact that here we have B beams, each of which can be shared by several users. However, this modification is rather trivial and the details can be found in [12]. Under the following assumptions:
i) $\{A_k(t) : k = 1, \ldots, K\}$ is a set of jointly stationary ergodic Markov arrival processes with rates $\boldsymbol{\lambda} = (\lambda_1, \ldots, \lambda_K)$ and $\mathbb{E}[A_k^2(t)] < \infty$;
ii) $\boldsymbol{\alpha}(t)$ is a jointly stationary ergodic Markov K-dimensional DRC process independent of the arrival processes;
iii) $\{\boldsymbol{\alpha}(1), \ldots, \boldsymbol{\alpha}(t-1)\} \to \boldsymbol{\alpha}(t) \to \{\beta_{k,j}(t) : k = 1, \ldots, K,\ j = 1, \ldots, B\}$ is a Markov chain; we have the following result.

Theorem 1 [stability region]. Under assumptions i), ii) and iii), the stability region of the SDMA/TDMA downlink system defined above is given by

$$\Omega = \mathbf{coh} \sum_{\mathbf{p} \in \mathcal{F}} \left\{ \boldsymbol{\lambda} \in \mathbb{R}_+^K \ : \ \lambda_k \leq \sum_{j=1}^{B} \mathbb{E}\left[p_{k,j}(\boldsymbol{\alpha}) R_{k,j}(\boldsymbol{\alpha})\right], \ \forall\ k \right\} \tag{6}$$

where **coh** means "closure of the convex hull". □

For any $\boldsymbol{\lambda} \in \Omega$ there exists a memoryless stationary policy $\mathbf{p}$ (i.e., a function of the instantaneous DRC signal $\boldsymbol{\alpha}$ at time t only) that stabilizes all queues. However, for any given $\boldsymbol{\lambda}$ the stabilizing policy is, in general, a function of $\boldsymbol{\lambda}$ and of the statistics of $\boldsymbol{\alpha}$. An *adaptive policy* is a function $\mathbf{p}$ of the instantaneous buffer sizes $\{S_k(t)\}$ and of the DRC signal $\boldsymbol{\alpha}(t)$ such that, even not knowing the arrival rates, it stabilizes the queues whenever $\boldsymbol{\lambda} \in \Omega$ [10, 11]. This is given by the next result.

Theorem 2 [max-stability adaptive policy]. Under the same assumptions of Theorem 1, the SDMA/TDMA adaptive resource-sharing policy given by

$$\widehat{\mathbf{p}} = \arg\max_{\mathbf{p} \in \mathcal{F}} \sum_{k=1}^{K} \theta_k S_k \sum_{j=1}^{B} p_{k,j} R_{k,j}(\boldsymbol{\alpha}) \tag{7}$$

for any strictly positive weights $\theta_k > 0$, stabilizes the system for all $\boldsymbol{\lambda} \in \Omega$. □

The solution of (7) is readily given explicitly by

$$\widehat{p}_{k,j}(S_1, \ldots, S_k; \boldsymbol{\alpha}) = \left\{ \begin{array}{ll} 1 & k = \arg\max_{k'} \theta_{k'} S_{k'} R_{k',j}(\boldsymbol{\alpha}) \\ 0 & k \neq \arg\max_{k'} \theta_{k'} S_{k'} R_{k',j}(\boldsymbol{\alpha}) \end{array} \right. \tag{8}$$

The max-stability adaptive policy allocates on each beam j in slot t the user maximizing the product $\theta_{k'} S_{k'}(t) R_{k',j}(\boldsymbol{\alpha}(t))$. The parameters θ_k can be used in order to provide different quality-of-service to the users, as they have an influence on the average individual delays [10].

4. APPLICATION TO PRACTICAL SCHEMES

In this section we apply the max-stability policy to STC and opportunistic beamforming. We assume that the channel vectors $\mathbf{h}_k(t)$ are mutually statistically independent for different index k and i.i.d. for different antennas. $\mathbf{h}_k(t)$ is constant over each slot of N channel uses, and changes from slot to slot according to a stationary ergodic L-order Gauss Markov process, given by $\mathbf{h}_k(t) = -\sum_{\ell=1}^{L} A_\ell \mathbf{h}_k(t-\ell) + \boldsymbol{\nu}_k(t)$ where $\boldsymbol{\nu}_k(t) \sim \mathcal{CN}(0, \sigma^2 \mathbf{I})$ is an i.i.d. process. Then, we let $\boldsymbol{\alpha}(t)$ be a function of the MMSE predictor $\mathbf{g}_k(t)$ of $\mathbf{h}_k(t)$ given a delayed noiseless observation $\mathbf{h}_k(t-d), \ldots, \mathbf{h}_k(t-d-L+1)$, where d denotes the feedback delay measured in slots. This model is made in order to meet the assumptions ii) and iii) of Section 3. We compare the following system choices.

Space Time Coding (STC). In this case, $\mathbf{X}(t) \in \mathbb{C}^{N \times M}$ denotes the transmitted space-time codeword, assumed to be drawn from a Gaussian i.i.d. ensemble. The system can not exploit spatial multiplexing since the user terminals have only one antenna. Hence, STC yields only M-fold transmit diversity. The instantaneous channel gain of user k is given by $\beta_k(t) = \frac{1}{M}|\mathbf{h}_k(t)|^2$. Each user feeds back its DRC $\alpha_k(t) = \frac{1}{M}|\mathbf{g}_k(t)|^2$ such that the total number of feedbacks is K (suitably quantized) real values. All the results of Section 3 apply with $B = 1$, since a single user is served on each slot.

Opportunistic beamforming. We consider opportunistic beamforming using $B \leq M$ mutually orthogonal beams. In [6] $B = M$ while in [2] $B = 1$ with $M > 1$ antennas. It is clear that the quality of the DRC signal depends critically on the ability of predicting the physical channels $\mathbf{h}_k(t)$. Then, we propose a modification of [2, 6]: as in usual random-spreading CDMA, each user in the system is synchronized with a common random number generator that generates the random beamforming matrices. Hence, the matrices can be considered a priori known. Moreover, since they are unitary, they have no impact on the estimation of the underlying physical channel that can be achieved with usual pilot-aided schemes and linear prediction. In this way, the speed of variation of the random beams is independent of the ability of estimating the channels, that depends uniquely on the Doppler bandwidth. Therefore, we let the random beams change independently at each slot. We have $\mathbf{X}(t) = \sum_{j=1}^{B} \mathbf{s}_j(t) \boldsymbol{\phi}_j^T(t)$, where $\mathbf{s}_j(t) \in \mathbb{C}^{N \times 1}$ is the signal associated to beam j, $\boldsymbol{\phi}_j(t) \in \mathbb{C}^{M \times 1}$ is the beamforming vector for beam j in slot t, and it is assumed that $\boldsymbol{\phi}_j^H(t) \boldsymbol{\phi}_m(t) = \delta_{j,m}$. User k "sees" SINR for the signal in beam j equal to

$$\mathsf{SINR}_{k,j}(t) = \frac{|\boldsymbol{\phi}_j^T(t) \mathbf{h}_k(t)|^2}{B/\gamma + \sum_{m \neq j} |\boldsymbol{\phi}_m^T(t) \mathbf{h}_k(t)|^2} \tag{9}$$

for $j = 1, \ldots, B$. The instantaneous channel gain is given by $\beta_{k,j}(t) = \mathsf{SINR}_{k,j}(t)/\gamma$. The outage rate (3) conditioned on the prediction $\mathbf{g}_k(t)$ of the channel can be computed by numerical integration (details are given in [12]). As a matter of fact, each user feeds back B outage rates for each of the beams such that the total number of feedbacks is KB (suitably quantized) real values.

5. NUMERICAL RESULTS AND CONCLUSIONS

Simulation setting. We considered mutually independent arrival processes such that $A_k(t) = \sum_{j=1}^{M_k(t)} b_{k,j}(t)$, where $M_k(t)$ is an i.i.d. Poisson distributed sequence that counts the number of packets arrived to the k-th buffer at the beginning of slot t and $b_{k,j}(t)$ are i.i.d. exponentially distributed random variables expressing the number of bits per packet. We take $\mathbb{E}[b_{k,j}(t)] = N$ ($N = 2000$ in our simulations), so that λ_k coincides with the average number of packets arrived in a slot (N channel uses). We consider a Gauss-Markov process of order $L = 5$ where the coefficients are chosen to approximate Jake's Doppler model [13]. Inspired by the HDR system [3], we let $T_{slot} = 1.67$ msec and the feedback delay $d = 2$ slot. The average SNR is set $\gamma = 10$ dB. For opportunistic beamforming, we generate a new set of random beams every slot.

Maximum sum rate. First, we evaluate the maximum sum rate of STC and opportunistic beamforming. Since the maximum sum-rate is given by the intersection point between the boundary of the stability region and the symmetric arrival vector $\lambda_1 = \cdots = \lambda_K$, this allows us to know exactly the total arrival rate where the buffers diverge under the symmetric arrival condition by using the max-stability adaptive policy.

Fig. 1, 2 shows the maximum sum-rate vs. the number of users for mobile speed $v = 0$ km/h (ideal DRC) and $v = 25, 60$ km/h (non-ideal DRC) by using STC, opportunistic beamforming respectively. For the case of STC, the maximal sum-rate is given by

$$\mathbb{E}_{\boldsymbol{\alpha}}\left[\max_{k=1,\ldots,K} R_{out,k}(\alpha_k)\right] \overset{(a)}{=} \mathbb{E}_{\boldsymbol{\alpha}}\left[R_{out}(\max_{k=1,\ldots,K} \alpha_k)\right] \quad (10)$$

$$= \int_0^\infty R_{out}(x) K \cdot \left(\frac{(\frac{M}{1-\sigma_e^2})^M e^{-\frac{Mx}{1-\sigma_e^2}} x^{M-1}}{(M-1)!} \right) \cdot \left(1 - e^{-\frac{Mx}{1-\sigma_e^2}} \sum_{k=0}^{M-1} \frac{\left(\frac{Mx}{1-\sigma_e^2}\right)^k}{k!} \right)^{K-1} dx$$

where σ_e^2 denotes the channel prediction error and (a) follows from the fact that $R_{out}(x)$ is a monotonic increasing function of x. For the case of opportunistic beamforming with B beams, the maximum sum-rate is given by

$$\mathbb{E}_{\boldsymbol{\alpha}}\left[\sum_{m=1}^{B} \max_{k=1,\ldots,K} R_{\text{out},k,m}(\boldsymbol{\alpha}_k)\right]$$

and can be evaluated only by Monte-Carlo simulation for the non-ideal DRC case. Notice that in Fig. 2 we let $B = M$. The performance with $M = 1$ in both figures is the same and represents also the performance of the opportunistic single-beamforming with $M > 1$.

In Fig.1, we observe that there is a non-trivial tradeoff between transmit diversity and multiuser diversity under the imperfect DRC. The number of users after which transmit diversity becomes harmful depends heavily on the DRC quality, $K = 2$ for ideal DRC, and $K = 5, 28$ for non-ideal DRC with $v = 25, 60$ km/h, respectively. In Fig. 2, we observe large gain with $M = 2, 4$ beams especially for $K \geq 10, 15$ for the perfect DRC case. Unfortunately, this multiplexing gain decreases dramatically as the quality of the DRC signal gets worse. For poor DRC quality with $v = 60$ km/h, multiple beams are harmful independently of the number of users in the system.

Average delay performance. We evaluated the average delay of STC and opportunistic beamforming as a function of the mobile speed in km/h by letting the total arrival rate to 2.5 bit/channel use. By Little's theorem, the average delay is given by $\overline{D} = \frac{1}{NK}\sum_{k=1}^{K} \overline{S}_k/\lambda_k$ measured in slot where $\overline{S}_k$ denotes the k user's time-averaged buffer size in bit. We consider the symmetric arrival case. Figs. 3,4,5 shows the average delay for a system with 50 users with STC, random beamforming with $B = 1$ and random beamforming with $B = M$, respectively. Clearly, the case $M = 1$ is the same in all three figures and it is introduced for the sake of comparison with a standard single-antenna system.

For a very slowly-varying channel (close to $v = 0$ km/h) the STC system becomes non-ergodic and there is a positive probability of buffer overflow. This probability is reduced by increasing transmit diversity, thanks to the so called "channel-hardening effect" [9]: ergodicity is recovered in the spatial domain by increasing the number of transmit antennas.

As seen from Fig. 4 and 5, opportunistic random beamforming decreases the average delay by making the channel vary almost i.i.d.. When the channel is slow (up to 40km/h), opportunistic beamforming with M beams achieves the smallest delay. As v increases (i.e., the quality of DRC becomes worse), STC outperforms the random beamforming schemes due to its better outage rate. Interestingly, the opportunistic beamforming systems become unstable (the average delay diverges) with $M = 2, 4$ and v larger than 60 km/h.

These results show that the ranking of STC and opportunistic beamforming is not clear and depends critically on the ability of feeding back accurate SNR measurements or predictions. Generally speaking, it appears that the opportunistic single beamforming is not very attractive because its performance is dominated by either STC for large Doppler bandwidth or the opportunistic M-beamforming for small Doppler bandwidth.

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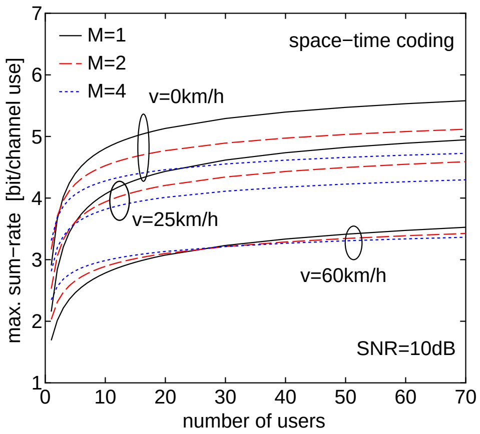

Fig. 1. max. sum-rate vs. number of users (STC)

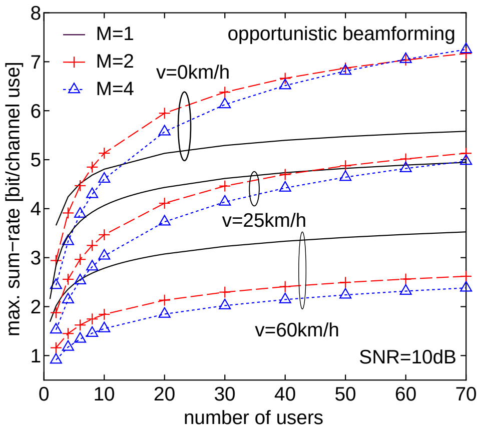

Fig. 2. max sum-rate vs. number of users (beamforming)

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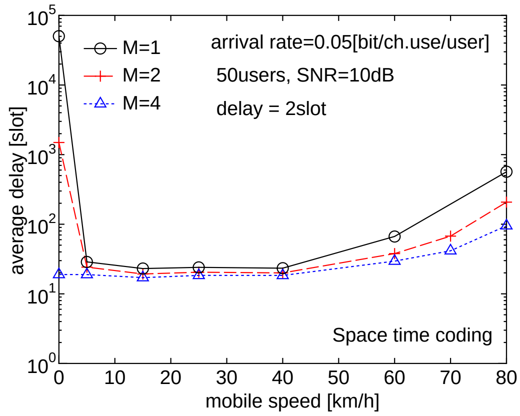

Fig. 3. average delay vs. speed (STC)

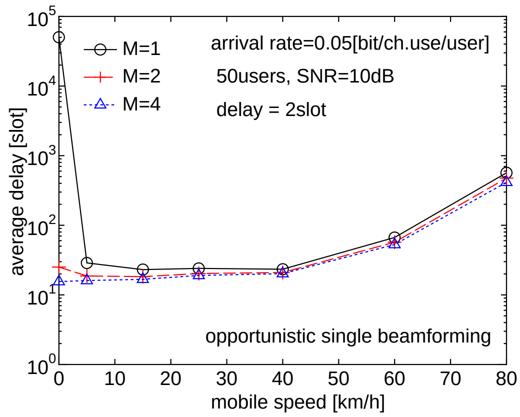

Fig. 4. average delay vs. speed ($B = 1$ beamforming)

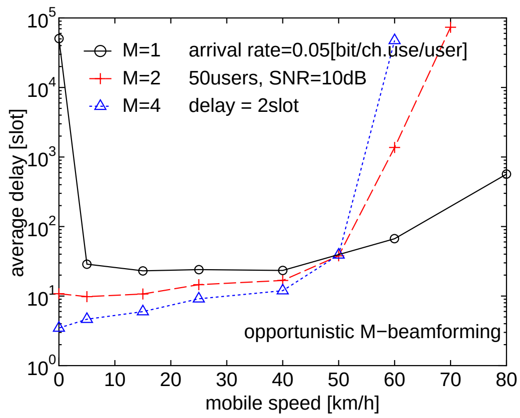

Fig. 5. average delay vs. speed ($B = M$ beamforming)