Resource Allocation for QF VMIMO Receive Cooperation in Urban Traffic Hotspots

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***Abstract*—User cooperation enabled traffic offloading has been shown to be a promising concept to serve a large number of mobile stations in the uplink of an urban traffic hotspot scenario. Multiple mobile stations form a virtual antenna array and jointly access the nearby WLAN access points, achieving large gains compared to non-cooperating schemes. In this paper we consider the corresponding downlink, where the non-cooperating WLAN access points individually transmit their signals to the mobile stations in the hotspot. In order to decode these signals, each mobile station then quantizes its received signal and broadcasts it to the other cooperating mobile stations. The channel access times allocated to the cooperating mobile stations in the broadcasting phase thereby strongly impact the quantization rates and eventually the system performance. Hence, these resources have to be assigned carefully, leading to a non-convex optimization problem. In this context, we propose an efficient resource allocation scheme which yields promising results at low computational complexity. Applying this scheme we then evaluate the downlink of user cooperation enable traffic offloading in an urban traffic hotspot scenario.**

I. Introduction

Serving mobile stations (MSs) in an area with ultra high user density, such as a busy public square or a sports stadium, is a challenging problem. While next generation wireless communication proposals such as massive multiple-input multiple-output (MIMO) and millimeter wave (mmW) communication promise high gains, they also require huge investments into the infrastructure. Furthermore, the performance of massive MIMO systems is limited by the potentially correlated scattering [1] and in mmW communication, the high number of necessary RF chains is a limiting factor [2].

In [3] we have shown that combining user cooperation with traffic offloading is a promising concept for the uplink in such a scenario. By forming a virtual transmit antenna array, multiple MSs jointly transmit to multiple typically privately owned WLAN access points in the surroundings (further called residential backhaul access points (RBAPs)). Considering a hybrid protocol implementation with the RBAP access at 2.4 GHz and the local exchange with message flooding [4] at 60 GHz, we demonstrate large gains compared to non-cooperative approaches employing a complex numerical simulation setup with realistic parameters and channel models in [3].

In the present paper, we consider the corresponding downlink, where the non-cooperating RBAPs simultaneously but independently transmit to the cooperating MSs. In order to achieve spatial multiplexing and decode the messages, the MSs quantize their received signals and broadcast them among each other. The broadcasting rate and the channel access time of the mobile stations in the broadcasting phase thereby determine their quantization rate, which eventually impacts the final decoding rate. Furthermore, the total duration of the broadcasting phase strongly affects the system throughput.

To optimize the performance, the resources in the broadcasting phase have to be assigned carefully. Related resource allocation problems were discussed in the context of cloud radio access networks (CRANs), e.g., in [5] and [6]. Different to the problem at hand where each MS has an individual broadcasting rate constraint, a sum rate constraint is considered on the second hop. A similar setup leading to the same optimization problem is considered in [7], where the impact of the resource allocation on the system performance is investigated. While it is shown that it would be best if only a subset of the MSs forward their quantized observation, no algorithm to specify the optimal number of MSs nor their channel access time is provided.

To this end, we propose a novel resource allocation scheme in this paper. At low computational complexity, it identifies the MSs which should forward their observations and determines their channel access time. We then employ the proposed scheme in a numerical performance evaluation of the user cooperation enabled traffic offloading downlink in the simulation setup of [3] and evaluate its performance. It is shown that the proposed resource allocation yields promising results compared to a multi-start gradient search at a fraction of the computational complexity. Substantial gains can be achieved compared to non-cooperating schemes.

II. System Setup

The considered setup is identical to the one introduced in [3] and is shown in Fig. 1. It represents an urban traffic hotspot with ultra high user density surrounded by buildings with many RBAPs. The traffic hotspot, modeled by a square of side length b, contains N_{MS} users which want to offload their traffic (active MSs) and $\bar{N}_{\mathrm{MS}}$ idle users (inactive MSs). The idle users do not want to offload their traffic, but potentially disturb the data exchange among the active users, e.g., by line of sight (LOS) blockage. In the area around the traffic hotspot we consider a large number of RBAPs. We distinguish between N_{AP} active RBAPs which are currently communicating with a local user (LU) and $\bar{N}_{\mathrm{AP}}$ inactive RBAPs which are in idle

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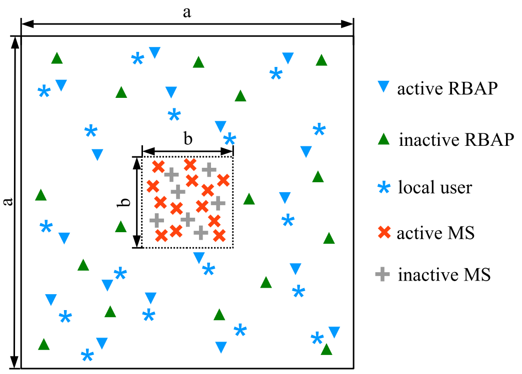

Fig. 1. Urban hotspot scenario.

mode, but principally available for the MSs in the hotspot. All nodes are considered to be equipped with a single omnidirectional antenna and to be half-duplex.

III. User Cooperation Enable Traffic Offloading in Urban Hotspots: Downlink

Analogously to the uplink presented in [3], the downlink of user cooperation enabled traffic offloading consists of a long-haul MIMO access phase (AC), where the MSs are served by the RBAPs, and a local exchange phase (EX), where the MSs exchange their received signals in order to decode. Both phases are considered to be synchronized among all involved nodes. For the offloading, the MSs in the hotspot can incorporate active as well as inactive RBAPs. If an active RBAP is incorporated, the corresponding LU is not served during the AC phase. The details of the RBAP assignment and the required medium access control protocol setup, as well as the performance of the LUs are discussed in [3] and not further considered in this paper.

Not all active MSs in the cluster have to be served simultaneously. To decrease the coordination among the MSs and potentially also improving the performance, sub-clusters of M of the N_{MS} active MSs are considered. Multiple such sub-clusters can then be served sequentially[1].

A. QF VMIMO Receive Cooperation

In the AC phase each MS is independently served by one RBAP. For reasons of simplicity, all LUs are considered to be in downlink mode as well. Hence, the MSs receive a superposition of all M RBAP signals for the MSs plus the signals intended for the remaining LUs. For frequency flat fading channels, the received signal of MS l is thus given as

$$y_l = \sum_{m=1}^{M} h_{lm} s_{\text{MS},m} + \sum_{j \in \mathcal{J}} f_{lj} s_{\text{LU},j} + n_l, \tag{1}$$

with h_{lm} the channel between RBAP m and MS l, $\mathcal{J}$ the set of currently served LUs and f_{lj} the channel from the RBAP serving LU j to MS l. The transmit symbols are assumed to be $s_{\text{MS},m} \sim \mathcal{CN}(0, P_{\text{MS}})$ for the MSs and $s_{\text{LU},j} \sim \mathcal{CN}(0, P_{\text{LU}})$ for the LUs. $n \sim \mathcal{CN}(0, \sigma_n^2)$ denotes additive white Gaussian noise. The variance of the received signal is thus given as

$$\sigma_{y_l}^2 = \underbrace{P_{\text{MS}} \cdot \sum_{m=1}^{M} |h_{lm}|^2}_{\lambda_l} + \underbrace{P_{\text{LU}} \cdot \sum_{j \in \mathcal{J}} |f_{lj}|^2 + \sigma_n^2}_{\sigma_{i_l}^2}, \tag{2}$$

with signal power λ_l and interference plus noise power $\sigma_{i_l}^2$.

The MSs then quantize their analog received signal and forward it to each other in the EX phase, such that each MS can decode the signals on its own. As all MSs are half-duplex nodes, only one MS can forward its quantized observation at a time. The time assigned to MS l is thereby denoted by τ_l. For the clarity of exposition we normalize without loss of generality all time intervals to the duration of 1 channel use of the AC phase. Hence, for the broadcasting rate R_l of MS l (i.e. in the time which one channel use takes in the AC phase MS l can transmit R_l bits of information to all other involved MSs at negligible probability of error), the *effective quantization rate* of MS l is given as $Q_l = \tau_l \cdot R_l$.

Considering a vector quantizer at the MSs, the quantization noise is additive and Gaussian distributed [8], with zero mean and variance

$$\sigma_{q_l}^2 = \frac{\sigma_{y_l}^2}{2^{Q_l} - 1} = \frac{\sigma_{y_l}^2}{2^{\tau_l R_l} - 1}. \tag{3}$$

After all observations are exchanged, each MS can decode the messages for the MSs in the hotspot. The *achievable decoding rate* is thereby given as

$$R^{\text{QF}} = \log_2 \det \left(\mathbf{I} + (\mathbf{D}_i + \mathbf{D}_q)^{-1} \mathbf{\Lambda}_s \right), \tag{4}$$

with $\mathbf{I}$ the identity matrix, the signal covariance matrix $\mathbf{\Lambda}_s = P_{\text{MS}} \cdot \mathbf{H}\mathbf{H}^{\text{H}}$, where $\mathbf{H} \in \mathbb{C}^{M \times M}$ denotes the channel between the RBAPs and the MSs with the elements h_{lm}, $\mathbf{D}_i = \text{diag}\left(\sigma_{i_1}^2, \ldots, \sigma_{i_M}^2\right)$ the interference plus noise covariance matrix and $\mathbf{D}_q = \text{diag}\left(\sigma_{q_1}^2, \ldots, \sigma_{q_M}^2\right)$ the quantization noise covariance matrix.

The total duration of the EX phase is given as $\tau_{\text{tot}} = \sum_{m=1}^{M} \tau_m$. Hence, the throughput of the protocol can be stated as

$$R_{\text{MS}} = \frac{1}{1 + \tau_{\text{tot}}} \cdot R^{\text{QF}}. \tag{5}$$

Thereby, τ_{tot} has two opposing effects. A larger τ_{tot} leads to higher quantization rates, increasing the decoding rate R^{QF} (if the τ_l are reasonably assigned to the MSs), but at the same time decreases the factor in front of R^{QF} in Eq. (5). Hence, the channel access times of the MSs (τ_l) have to be assigned carefully in order to optimize the system throughput, leading to a non-convex optimization problem as discussed in the next section.

Note: In Eq. (4), we considered all observations to be quantized, although each MS would have its own observation without quantization noise. That is, we consider a lower bound on the achievable sum rate, which is the same for all MSs, simplifying the rate allocation for the RBAPs (not considered in this paper).

[1]To further improve the performance, the sub-clusters could also be served simultaneously with a certain spatial reuse, leading to large gains in the uplink [3]. However, the spatial reuse is not further considered in this paper, as we focus on the performance of the quantize and forward resource allocation.

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IV. Resource Allocation

The same resource allocation problem is considered in [7], where multiple non-cooperating sources transmit over multiple quantize-and-forward relays to a final destination which jointly decodes the source data streams based on the quantized observations. As discussed in [7], the maximization of the throughput in Eq. (5) leads to a non-convex optimization problem to which no closed form solution can be found. Hence, either a computationally expensive optimization algorithm is applied such as a multi-start gradient search (still not guaranteed to find the optimal solution), or a suboptimal but low complexity solution is considered. To this end, in [7] simple relay selection schemes are investigated and compared to multi-start gradient search and to equal resource allocation for all relays. For fixed τ_{tot} it is shown that large gains in the decoding rate can be achieved by only considering an optimized subset of the relays and assigning equal resources to them. Further optimizing the channel access times only leads to minor additional gains. However, to achieve these gains with relay selection, it is crucial to know the optimal number of relays in the subset and the total resources to allocate in the EX phase (i.e. τ_{tot}). If these numbers are not known in advance, it is computationally very demanding to find them. Hence, a low complexity resource allocation algorithm which inherently determines the optimized subset of MSs to forward their observation and the corresponding channel access times would be helpful to optimize the performance of user cooperation enabled traffic offloading in the downlink. Such an algorithm is presented in the following.

A. Cascade Algorithm

In order to identify the MSs to consider, we propose to add one MS after the other to the subset of MSs forwarding their observation, as long as the throughput R_{MS} in Eq. (5) can be increased. The MSs are thereby considered in descending order of relevance to the rate R^{QF}. We measure the relevance of MS l in terms of the partial derivative of R^{QF} with respect to the time τ_l allocated to MS l at the point $\tau_1 = \tau_2 = \cdots = \tau_M = 0$, given as

$$\frac{\partial R^{\text{QF}}}{\partial \tau_l}\bigg|_{\tau_m=0\ \forall\ m\in\{1,\dots,M\}} = \frac{\text{SNR}_l}{1+\text{SNR}_l}\cdot R_l. \tag{6}$$

Recall that R_l is the broadcasting rate of MS l (see Sec. III-A). We propose to allocate to MS l the time

$$\tau_l = \log_2(1+\text{SNR}_l)/R_l, \tag{7}$$

such that the effective quantization rate is $Q_l = \log_2(1 + \text{SNR}_l)$. Here, $\text{SNR}_l = \lambda_l/(\sigma_{i_l}^2)$ denotes the signal to noise ratio (SNR) of MS l, with λ_l the signal power and $\sigma_{i_l}^2$ the interference plus noise power (see Eq. (2)). For each potential MS to be added, the throughput in Eq. (5) is evaluated. Once it decreases compared to the previous subset of MSs or if all MSs are considered already, the resource allocation is stopped. That is, the proposed algorithm determines the subset of MSs, the τ_l to assign to them and thus τ_{tot} inherently.

This procedure is motivated as follows. The MSs are chosen in order of the strongest increase in R^{QF} if no MS is considered yet. Although this criteria only guarantees optimality for the choice of the first MS (as for all succeeding MSs the partial derivatives change), the succeeding MSs are still a reasonable choice. From Eq. (6) we see that they have a strong broadcasting rate R_l and can thus provide large quantization rates Q_l while requiring only limited resources τ_l. Furthermore, permanently adapting the selection criterion would strongly increase the computational complexity.

Serving the MSs with $\tau_l = \log_2(1 + \text{SNR}_l)/R_l$ leads to the effective quantization rate $Q_l = \log_2(1 + \text{SNR}_l)$. That is, MSs with high information content (i.e. high SNR_l) get more resources and quantize their observation with a higher rate, as they potentially contribute more to the decoding rate. Furthermore, as the MSs with high R_l are considered first (as discussed above) no resources are wasted. MSs with low SNR but high R_l contribute only little information but also do not waste much resources as τ_l gets small, and nodes with low SNR and low R_l are chosen at the end and thus do not harm the strong MSs. The quantization noise variance resulting from this choice of τ_l is given as

$$\sigma_{q_l}^2 = \frac{\sigma_{i_l}^2(\lambda_l+\sigma_{i_l}^2)}{\lambda_l}, \tag{8}$$

which simplifies to $\sigma_{q_l}^2 \approx \sigma_{i_l}^2$ at high SNR. That is, the nodes just get as much resources as necessary to achieve an effective SNR of $\lambda_l/(\sigma_{q_l}^2 + \sigma_{i_l}^2) \approx 0.5 \cdot \text{SNR}_l$. Once all relays are considered this leads to

$$\begin{aligned} R^{\text{QF}} &\approx \log_2\left(\det\left(\mathbf{I}+\frac{1}{2}\cdot\mathbf{D}_i^{-1}\mathbf{\Lambda}_s\right)\right) && (9)\\ &\approx \log_2\left(\left(\frac{1}{2}\right)^M\cdot\det\left(\mathbf{I}+\mathbf{D}_i^{-1}\mathbf{\Lambda}_s\right)\right) && (10)\\ &= \log_2\left(\det\left(\mathbf{I}+\mathbf{D}_i^{-1}\mathbf{\Lambda}_s\right)\right) - M && (11)\end{aligned}$$

at high SNR. Hence, independent of R_l, there is at least a *quantization noise penalty* of M bit in the throughput due to the choice of τ_l in Eq. (7). Nevertheless, without iterative optimization, the proposed τ_l are a reasonable choice for practical wireless systems, as large gains can be achieved with only limited complexity (see Sec. V-C).

Compared to a gradient search, the implementation of the algorithm can be done very efficiently by computing $\mathbf{D}_q$ once for all $\tau_l = \log_2(1 + \text{SNR}_l)/R_l$ and then setting $\mathbf{A} = (\mathbf{D}_i + \mathbf{D}_q)^{-1}\mathbf{\Lambda}_s$. In each iteration of adding a new MS, the rows in $\mathbf{A}$ corresponding to non-considered MSs can be set to the all-zero-vector (as $\sigma_{q_l}^2 \to \infty$). Hence, computing the inverse is only necessary once in the beginning, whereas it is necessary in each step of the gradient search. Furthermore, at most M iterations of updating the throughput are necessary with the cascade algorithm, leading to a much lower computational complexity, especially for large M.

V. Performance Evaluation

In the following, we are going to discuss the numerical evaluation of the proposed protocol.

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A. *Protocol Implementation*

Analogously to [3], the data exchange among the MSs is considered to be done in the 60 GHz band by message flooding [4]. By using flooding in the EX phase, the problem of the high path loss with a single omnidirectional antenna at 60 GHz can be circumvented and the message is spread fast among the MSs. The broadcasting rate R_l of MS l is then determined by the achievable rate with which the weakest of all involved MSs can be reached.

The AC phase is considered to be done in the 2.4 GHz band. The RBAPs are assigned according to their channel strength. For the comparison to the uplink of the protocol, we consider the implementation in [3] with stream-wise maximization of the signal-to-leakage-plus-noise-ratio [9] to separate the streams from the hotspot to the RBAPs.

B. *Simulation Framework*

For the performance evaluation, we are going to use the same setup and parameters as introduced in [3]. The width of the setup in Fig. 1 is set to $a = 600$ meters and the width of the hotspot to $b = 50$ meters. $N_{\text{AP}} = \bar{N}_{\text{AP}} = 140$ active and inactive RBAPs as well as $N_{\text{MS}} = \bar{N}_{\text{MS}} = 256$ active and inactive users are randomly distributed in the respective area.

For the 60 GHz channel between the MSs in the hotspot, the path loss and shadowing is drawn from the log-distance path loss model of [10]. For each link we determine whether it is LOS or not. To this end, each user in the hotspot (active and inactive) is modeled as a circle with a diameter of 0.6 meters. Whenever the connection between the centers of two users is blocked by another user, the link is considered non-LOS (NLOS), otherwise LOS. For the LOS channels, Ricean fading is assumed with a K factor which is log-normal distributed with mean $\mu = 7$ and standard deviation $\sigma = 3$, accounting for the strong LOS link [11]. For the NLOS channels, Rayleigh fading is assumed. All other channels in the network are considered to be NLOS with path loss and shadowing coefficients drawn according to the WINNER II scenario C2 channel model [11]. More details on the simulation framework can be found in [3].

The transmit power of the RBAPs are set to $P_{\text{MS}} = 0.1$ W for the communication to the MSs in the hotspot and to $P_{\text{LU}} = 0.01$ W for the communication with the LUs. The transmit power of the MSs in the hotspot is set to $P_{\text{EX}} = 0.1$ W. The bandwidth at 2.4 GHz is assumed to be 20 MHz and the corresponding receiver noise variance $\sigma_n^2 = 10^{-12}$ W. The bandwidth for the local exchange phase (EX) at 60 GHz is set to $\beta \cdot 20$ MHz, with the bandwidth scaling factor β. The corresponding noise variance is then $\beta \cdot \sigma_n^2$ W.

C. *Performance Evaluation and Discussion*

In the first simulations we consider $\beta = 10$ and evaluate the performance of the cascade resource allocation as a function of the maximum number of MSs that can cooperate. To this end, we define a cluster of M out of the N_{MS} MSs in the hotspot by picking the first MS randomly and then assigning the $M-1$ nearest neighbors to it. Specifically, we consider the cluster sizes $M \in \{1, 2, 4, 8, 16, 32, 64, 128, 256\}$, and compare the results to a multi-start gradient search.

TABLE I
AVERAGE NUMBER OF CONSIDERED MSS.

M	2	4	8	16	32	64	128	256
Cascade	1.97	3.8	6.6	9.2	10.7	11.6	11.9	12.2
Gradient	1.98	3.7	6.3	9.6	12.3	15.2	17.9	19.8

TABLE II
TOTAL EXCHANGE TIME τ_{tot}.

M	2	4	8	16	32	64	128	256
Cascade	0.15	0.42	0.99	1.67	2.31	2.85	3.43	4.00
Gradient	0.22	0.52	1.05	1.79	2.59	3.54	4.59	5.56

At first, we investigate the average number of MSs selected to forward their observation, shown in Tab. I. It can be seen that for both resource allocation schemes, the gap between the number of selected MSs and the cluster size M is strongly increasing with increasing cluster size. At large cluster sizes only a small subset of the nodes is forwarding its information. This mainly comes from the fact that for increasing cluster size the achievable broadcasting rates are strongly decreasing, as more MSs need to be reached and larger distances have to be overcome. Hence, less information can be exchanged in the same time and it is not worth to consider more MSs to forward as the increase in the decoding rate can not compensate the longer duration of the EX phase.

The average number of MSs selected by the cascade algorithm is clearly below the corresponding number for the gradient search for large cluster sizes. This comes from the strict relation of τ_l and R_l in Eq. (7). For the decreasing R_l at large M, the assigned resources τ_l are potentially too large, leading to a lower number of considered MSs. Analogously to the number of considered MSs, τ_{tot} only increases slowly with increasing cluster size as can be seen in Tab. II.

The number of considered MSs also strongly impacts the average decoding rate R^{QF} as shown in Fig. 2. As only a limited number of additional MSs forward their quantized observations at large cluster size, the achievable decoding rate starts to saturate. Due to the suboptimal number of active MSs and the channel access time assigned to them, a large gap

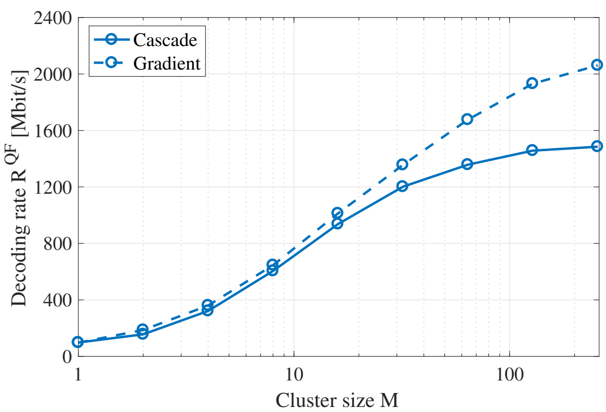

Fig. 2. Average achievable decoding rate R^{QF}.

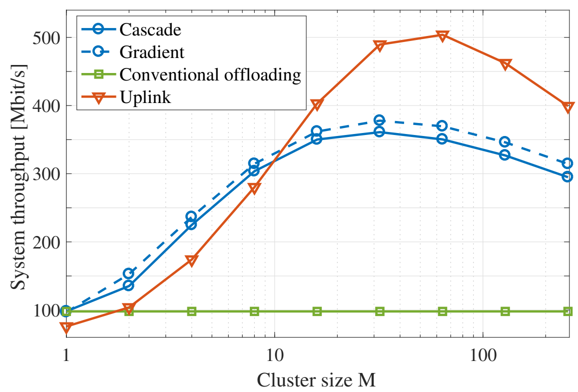

Fig. 3. Average system throughput R_{MS}.

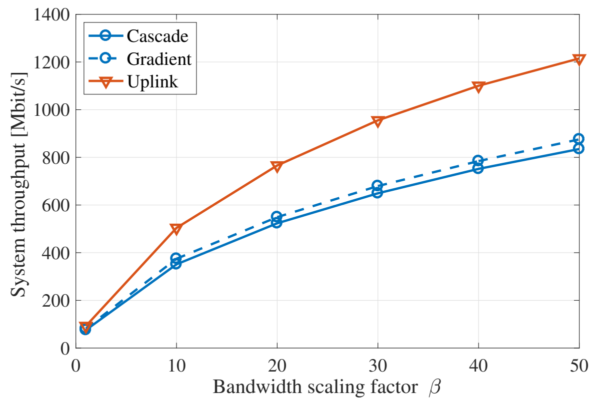

Fig. 4. Bandwidth scaling for $M = 64$.

between the achievable decoding rate of the gradient search and the cascade algorithm can be observed. Nevertheless, considering the resulting throughput R_{MS}, the lower resulting τ_{tot} of the cascade resource allocation partially compensate the loss in R^{QF} as can be seen in Fig. 3. Although a mostly suboptimal subset of MSs is considered, the performance of the cascade resource allocation is getting close to the gradient search at much lower complexity. As already observed for the uplink in [3], the best performance is achieved if multiple sub-clusters are served sequentially (peak at $M = 32$). That is, a higher throughput can be attained at lower system complexity (coordination and medium access control).

Fig. 3 also shows the performance of the uplink in comparison to the downlink. As can be seen, the downlink outperforms the uplink for a low cluster size M. This comes from the fact that at low cluster size many LUs are still communicating with their RBAPs. As these LUs are potentially close to the RBAPs assigned to the hotspot, their interference is strong in the uplink. In the downlink in contrast, the active RBAPs transmitting to their LUs are farther away from the MSs in the hotspot. Hence, the interference is lower. Furthermore, a large portion of the MSs forward their observation (c.f. Tab. I), leading to a high spatial multiplexing gain. At increasing M however, more and more LUs are turned off in the uplink, leading to a lower interference at the RBAPs assigned to the hotspot. In this regime, the uplink clearly outperforms the downlink due to the strong impact of the quantization noise and the limited number of MSs which forward their information. Still, compared to a conventional offloading scheme where the MSs are served sequentially, huge gains can be achieved in the downlink, already for a limited cluster size.

With increasing bandwidth in the EX phase higher broadcasting rates can be achieved. This leads to a strongly increased system throughput as shown in Fig. 4 for $M = 64$. The cascade algorithm closely follows the performance of the gradient search even for a very large bandwidth. That is, for practical operating regimes, the cascade resource allocation is a reasonable trade-off between performance and computational complexity. Compared to the achievable throughput in the uplink [3], again a substantial performance difference can be observed.

VI. Conclusions

In this paper, we presented the downlink protocol of user cooperation enabled traffic offloading and evaluated its performance using a novel resource allocation algorithm for the comprised quantize and forward step. Despite its simplicity, the proposed algorithm leads to very promising results at low computational complexity. Large gains can be achieved by the user cooperation protocol in the downlink compared to a conventional offloading scheme. Due to the strong impact of the quantization noise however, the performance in the downlink severely suffers compared to the uplink at large cluster size. At low cluster size however, the downlink outperforms the uplink.

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