User Cooperation Enabled Traffic Offloading in Urban Hotspots

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***Abstract*—In this paper, we propose to serve the mobile stations in an urban traffic hotspot by combining user cooperation with traffic offloading to the vast amount of residential WLAN access points. Different to existing virtual MIMO approaches, we include local users, which are assigned to the access points and compete for the physical resources. Furthermore, all signal processing shall be done on the mobile station side. This makes the protocol fully transparent for the access points and allows it to be overlaid on the existing infrastructure and protocols. We thereby discuss the necessary coordination with the local users and suggest a hybrid protocol implementation with distributed spatial multiplexing for the WLAN access at 2.4 GHz and a local exchange with message flooding at 60 GHz, all with single omnidirectional antennas. Using a numerical simulation framework with realistic parameters and channel models, the protocol is thoroughly evaluated, considering multiple clusters and spatial reuse. It is thereby shown that the 60 GHz exchange is very efficient even with omnidirectional antennas. For a moderate cluster size of 16 nodes per cluster, a 10 fold increase in the sum rate is achieved. By scaling the bandwidth for the user cooperation this gain can be further scaled.**

I. Introduction

Future wireless communications networks face high demands regarding the number of devices to serve, as well as the amount of mobile data traffic to handle [1]. Especially in areas with high user density, such as city centers, new concepts and technologies are necessary to meet these demands. Various proposals have been made for 5G, the next generation of wireless networks, such as massive multiple-input multiple-output (MIMO) systems [2], millimeter wave (mmW) communication [3], or network densification with heterogeneous networks (HetNets) and traffic offloading to wireless local area networks (WLANs) [4].

However, serving the users in a traffic hotspot, i.e. in an area with ultra high user density, such as busy public squares or train stations, still remains a problem. The performance of massive MIMO is limited by the potentially correlated scattering in such a dense environment [4]. In mmW communication, the high number of RF chains necessary for the large antenna arrays is a limiting factor, as they are very power consuming [5]. Furthermore, for both approaches, huge investments into infrastructure (more antennas/ access points) would be necessary to serve the large amount of users. Traffic offloading to existing WLAN access points (residential backhaul access points (RBAPs)) scales poorly in the number of mobile stations (MSs), as the MSs have to be served sequentially in time by a single RBAP (or by a few RBAPs if the hotspot size allows for spatial reuse).

A possible way to handle the problem is to combine user cooperation with traffic offloading. That is, the MSs form a virtual MIMO (VMIMO) array and then simultaneously access a large number RBAPs in the surroundings. This way, multiple MSs can be separated by spatial multiplexing without additional infrastructure. Cooperative communication schemes and virtual MIMO have been widely studied in literature. Based on a Wyner model, [6] investigates conferencing MSs on orthogonal channels to enhance multi-cell processing for the uplink of cellular networks. In [7], a three-stage relaying framework is proposed with a VMIMO link between two clusters of nodes, and optimized in terms of power allocation with the objective of minimizing the outage probability at the destination. In [8], cooperating clusters are optimized under energy, delay and data rate constraints. All these approaches promise high gains in network capacity, as cooperative (virtual) MIMO enables spatial multiplexing and the associated array gain increases the radio range.

For these reasons, we propose to serve the MSs in an urban traffic hotspot by *user cooperation combined with traffic offloading*. Different to previous approaches (e.g. [6]–[8]) we (i) take into consideration local users (LUs), which are assigned to the individual RBAPs, and the mutual interference between the LUs and offloaded traffic and (ii) require that all signal processing shall be done on the MS side, such that the RBAPs do not have to distinguish between offloaded traffic and LUs. This allows distributed ownership of the RBAPs as no cooperation among them is necessary and makes the protocol fully transparent for the RBAPs. Hence, the protocol can be overlaid on the existing infrastructure, without any central processing. These constraints mandate a careful design of both, the local exchange and the access phase, which are typical for VMIMO.

In this context, we discuss user cooperation combined with traffic offloading in terms of the required cooperation and coordination, and provide a rigorous feasibility study for the uplink, based on user cooperation (local exchange phase) with flooding [9] at 60 GHz and RBAP access at 2.4 GHz (access phase), all with single omnidirectional antennas. The proposed setup is then thoroughly evaluated using a numerical simulation framework with realistic parameters and channel models. Special emphasis is placed on the trade-off between the local exchange phase and the access phase. Fig. 1a) shows a typical scenario with a hotspot of MSs in an environment of less densely spaced RBAPs. In Fig. 1b) we evaluate the

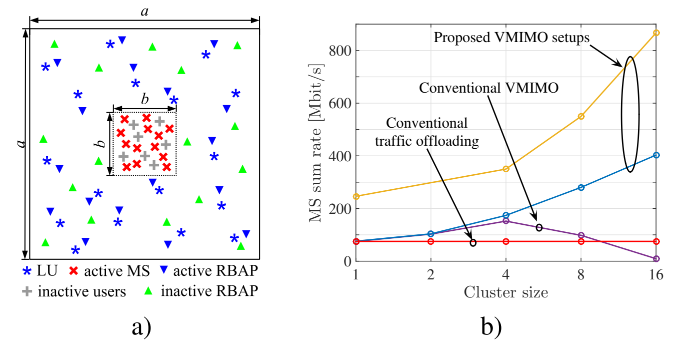

Fig. 1. a) Typical scenario with a hotspot of MSs surrounded by less densely spaced RBAPs. b) Comparison of MS sum rate for conventional traffic offloading (red), conventional VMIMO (purple) and two proposed VMIMO setups (blue, yellow).

average backhaul access rate made available to the MS hotspot by the RBAPs (MS sum rate). The x-axis shows the number of MSs that cooperate in order to form a VMIMO cluster. In the conventional offloading case (time division multiple access) the active MSs are sequentially served by their strongest RBAP (the x-axis is meaningless in this case). With conventional VMIMO (explained below) the sum rate is almost doubled for cluster size 4 but the inefficiency of the local exchange phase diminished the gain for larger cluster size. In contrast, our proposed setups (details further below) benefit from an increasing cluster size. For a moderate cluster size of 16 we achieve a 5 to 10 fold increase of the MS sum rate compared to conventional offloading.

The remainder of the paper is arranged as follows. In Section II, the system setup is described. The Sections III and IV discuss the protocol for single and multiple clusters. Section V shows the feasibility study including the proposed implementation, the simulation framework and numerical results. Section VI then concludes the paper.

II. System Setup

The setup of consideration is shown in Fig. 1a). It contains one hotspot with ultra high density of users and many RBAPs around it. This setup could e.g. model a city center with a very busy public square where people meet ad hoc. In the hotspot, we distinguish between users who want to transmit data, the active MSs, and inactive users who currently don't want to transmit data. However, the inactive users might disturb the data exchange among the active MSs due to line-of-sight (LOS) blockage. The number of active MSs is denoted by N_{MS} and the number of inactive users by $\bar{N}_{\mathrm{MS}}$. Around this hotspot, many RBAPs are considered, uniformly distributed over the remaining area. Again, we distinguish between active RBAPs and inactive RBAPs. Each active RBAP is communicating with a LU in close vicinity. The inactive RBAPs are currently not in use or idle for interference mitigation. The number of active RBAPs is denoted by N_{AP}, the number of inactive RBAPs by $\bar{N}_{\mathrm{AP}}$ and the number of LUs by $N_{\mathrm{LU}} = N_{\mathrm{AP}}$.

III. User Cooperation for Ultra Dense Environments

In order to serve the MSs in an area with ultra high user density, the MSs shall form a virtual MIMO array to jointly access the vast amount of RBAPs in the surrounding. Hence, the traffic of the hotspot is distributed over a larger area without additional infrastructure. To support distributed ownership, the wireless system has to be designed such that it minimizes the coordination between these RBAPs. Thus, all signal processing shall be done on the MS side and the RBAPs accessed by distributed spatial multiplexing. This makes the protocol fully transparent for the RBAPs and the hotspot simply appears like a virtual LU. This results in a two state protocol with an exchange phase (EX) and an access phase (AC) as shown in Fig. 2. In the EX phase, the involved MSs share their transmit data with all other MSs in the hotspot. Once all MSs received the data, each can individually compute its precoded uplink signal, and then they jointly access the assigned RBAPs (AC). This procedure is continuously repeated.

Fig. 2. Temporal illustration of the proposed two phase protocol.

While in the uplink precoding is necessary to separate the streams, in the downlink the RBAPs simply transmit their individual streams and the MSs do joint decoding. To this end, they need to quantize their received signal and share it with all involved MSs. In this paper we focus on the uplink with the distributed spatial multiplexing and the coordination with the LUs.

A. RBAP Assignment and Medium Access Control

The RBAPs for the AC phase can be chosen out of all available RBAPs (active and inactive), as for the AC phase, their mutual influence does not matter. The choice of the RBAPs has to be coordinated among the MSs in the hotspot, e.g. according to their channel strength. However, as LUs are assigned to the active RBAPs, the transmission of the hotspot and the LUs has to be coordinated carefully.

In the optimal case, the virtual MIMO scheme can be simply overlaid on the existing infrastructure and protocols without any further coordination. Both, the LUs and the hotspot apply carrier sense multiple access collision avoidance (CSMA/CA) for the RBAP access, while the RBAPs can not distinguish between their packets. However, this approach is only feasible for a small number of MSs, as all RBAPs need to be available simultaneously for the hotspot in order to transmit all streams. The higher the number of MSs (and thus the number of involved RBAPs), the lower is the probability that this is the case, as the LUs might access the idle RBAPs.

To mitigate this problem, a deterministic approach can be applied. That is, all RBAPs are accessed individually by the hotspot for the protocol setup. If a collision with LUs occurs, the access is simply repeated until the RBAP can be connected. The hotspot then transmits a time-table to each of them which defines fixed time slots for the LUs and the hotspot. This time-table is forwarded from the RBAPs to all assigned LUs. Once all involved nodes know the time-table, the protocol can be applied without further coordination.

While setting up the protocol and coordinating the transmission with the involved LUs, as well as channel state information (CSI) acquisition and cluster formation (see below) are crucial elements of the proposed scheme to work efficiently, we do not further focus on these parts in this paper, but rather investigate the performance once the protocol is set up.

B. The Two Phase Protocol

a) The AC phase: In the following, we consider a single cluster c with a subset of M out of N_{MS} MSs applying the protocol. Multiple such clusters could be served sequentially. During the AC phase the received signal of an RBAP l can be written as

$$y_l = \bar{\mathbf{h}}_{l,c}\mathbf{Q}_c\mathbf{s}_{\mathrm{MS},c} + \sum_{j\in\mathcal{J}} f_{l,j}s_{\mathrm{LU},j} + n, \tag{1}$$

where $\bar{\mathbf{h}}_{l,c} \in \mathbb{C}^{1\times M}$ is the channel vector from the MSs in the cluster c to RBAP l, $\mathbf{Q}_c \in \mathbb{C}^{M\times M}$ is the precoding matrix for the spatial multiplexing, $\mathbf{s}_{\mathrm{MS},c} \in \mathbb{C}^{M\times 1}$ is the transmit signal vector of the MSs in the hotspot c, $\mathcal{J}$ is the set of currently transmitting LUs, $f_{l,j}$ the channel from LU j to RBAP l, $s_{\mathrm{LU},j} \in \mathbb{C}$ the transmit symbol of LU j and $n \in \mathbb{C}$ is circularly complex additive white Gaussian noise with zero mean and variance σ_n^2. Depending on the assignment of the RBAP, the desired signal is either one of the LU signals or one stream of $\mathbf{s}_{\mathrm{MS},c}$. The achievable rate of the MSs in the hotspot in the AC phase is then the sum over the rates of all transmitted streams, and is denoted by $R^{\mathsf{AC}}_{\mathrm{MS},c}$ (in bit/s). That is, $R^{\mathsf{AC}}_{\mathrm{MS},c} \cdot t^{\mathsf{AC}}_c$ bits are transmitted in an AC phase of duration t^{AC}_c. The achievable rate of the LUs during the AC phase is the sum over the individual rates of all LUs in $\mathcal{J}$ and is denoted by $R^{\mathsf{AC}}_{\mathrm{LU},c}$.

The separation of the multiple streams of the hotspot is achieved by stream wise distributed precoding at each MS individually. To this end, depending on the precoding algorithm, instantaneous CSI at the transmitter (CSIT) to specific RBAPs has to be available.

b) The EX phase: In order to be able to compute the AC signal individually at each MS, all transmit data needs to be available at all cooperating MSs. Hence, to achieve maximal fairness, each MS has to share $R^{\mathsf{AC}}_{\mathrm{MS},c} \cdot t^{\mathsf{AC}}_c/M$ bits per AC phase with all other involved MSs in the EX phase. The time it takes until this exchange is completed for all MSs is denoted by $t^{\mathsf{EX}}_{\mathrm{tot}}$. The achievable rate of the LUs during the EX phase is the sum over the individual rates of all LUs and is denoted by $R^{\mathsf{EX}}_{\mathrm{LU},c}$.

c) Protocol Performance: Combining the EX and AC phase if only cluster c is considered, the final achievable sum rate of the MSs is given as

$$R_{\mathrm{MS}} = \frac{R^{\mathsf{AC}}_{\mathrm{MS},c} \cdot t^{\mathsf{AC}}_c}{t^{\mathsf{AC}}_c + t^{\mathsf{EX}}_{\mathrm{tot}}} = \frac{R^{\mathsf{AC}}_{\mathrm{MS},c}}{1+\xi}, \tag{2}$$

where $\xi = t^{\mathsf{EX}}_{\mathrm{tot}}/t^{\mathsf{AC}}_c$. The achievable rate of the LUs averaged over the EX and AC phase is then

$$R_{\mathrm{LU}} = \frac{R^{\mathsf{AC}}_{\mathrm{LU},c} \cdot t^{\mathsf{AC}}_c + R^{\mathsf{EX}}_{\mathrm{LU},c} \cdot t^{\mathsf{EX}}_{\mathrm{tot}}}{t^{\mathsf{AC}}_c + t^{\mathsf{EX}}_{\mathrm{tot}}} = \frac{R^{\mathsf{AC}}_{\mathrm{LU},c} + R^{\mathsf{EX}}_{\mathrm{LU},c} \cdot \xi}{1+\xi}, \tag{3}$$

and the backhaul access rate (i.e. the sum rate of all RBAPs) averaged over the EX and AC phase is

$$R_{\mathrm{b}} = R_{\mathrm{MS}} + R_{\mathrm{LU}}. \tag{4}$$

By varying the performance of the EX phase (e.g. by varying the transmit power in the EX phase and the exchange bandwidth), $t^{\mathsf{EX}}_{\mathrm{tot}}$ can be varied. Hence the rates for the MSs can be traded off versus the performance of the LUs.

IV. Multiple Clusters and Spatial Reuse

Instead of applying this two state protocol to a single cluster, the hotspot can be split up into multiple small clusters each operating individually. Smaller clusters are more efficient in the exchange (as less nodes have to be reached) and also require less CSIT. By applying a spatial reuse in the EX and/or AC phase, multiple clusters can exchange or access simultaneously, and hence further increase the efficiency of the protocol. To this end, we introduce the number of clusters N_{C} and the reuse factors for the EX (r^{EX}) and the AC (r^{AC}) phase, where one out of r^{EX} respectively r^{AC} clusters is active simultaneously. In this paper, we focus on $N_{\mathrm{C}} = 16$ clusters only with M MSs per cluster, and consider various reuse factors.

The achievable rate of cluster c in the AC phase is still denoted by $R^{\mathsf{AC}}_{\mathrm{MS},c}$. Again, each MS in cluster c shares $R^{\mathsf{AC}}_{\mathrm{MS},c} \cdot t^{\mathsf{AC}}_c/M$ bits per AC phase with each other MS in the cluster. The necessary time thereof is denoted by t^{EX}_c. For reasons of simplicity, we assume that t^{AC}_c is the same for all clusters in the performance evaluation. Furthermore, we assume that all simultaneously active clusters need to be done with their data exchange before the next set of clusters can start an EX or AC phase. That is, the exchange time of the set of concurrently exchanging clusters $\mathcal{C}_i$ is given by

$$t^{\mathsf{EX}}_{\max,i} = \max_{c\in\mathcal{C}_i}(t^{\mathsf{EX}}_c). \tag{5}$$

The total exchange time of all clusters is then given as

$$t^{\mathsf{EX}}_{\mathrm{tot}} = \sum_{i=1}^{r^{\mathsf{EX}}} t^{\mathsf{EX}}_{\max,i}, \tag{6}$$

and thus, the MS sum rate follows as

$$R_{\mathrm{MS}} = \frac{\sum_{c=1}^{N_{\mathrm{C}}} R^{\mathsf{AC}}_{\mathrm{MS},c} t^{\mathsf{AC}}_c}{r^{\mathsf{AC}} t^{\mathsf{AC}}_c + t^{\mathsf{EX}}_{\mathrm{tot}}} = \frac{\sum_{c=1}^{N_{\mathrm{C}}} R^{\mathsf{AC}}_{\mathrm{MS},c}}{r^{\mathsf{AC}} + \xi}. \tag{7}$$

While splitting up the hotspot into small clusters and applying a spatial reuse can improve the performance in the EX phase, it also means that less MSs are available per cluster for the distributed beamforming in the AC phase, leading to smaller array and multiplexing gains. Furthermore, the clusters need to coordinate the reuse pattern and their RBAP choices.

V. Feasibility Study

In this section, we provide a feasibility study of the discussed protocol. We propose an example implementation, provide a simulation framework based on realistic parameters and channel models and discuss the results of the numerical evaluation. This feasibility study should give an insight into the possible performance gains and point out the main potential and challenges of the procedure.

A. Protocol Implementation

The protocol implementation is based on the AC phase in the 2.4 GHz ISM band, and the EX phase in the 60 GHz license free band. While the low frequency in the AC phase allows to spread the hotspot traffic over a large area, large bandwidth is available in the 60 GHz band, allowing for an efficient EX phase. In order to keep the complexity and the power consumption of the devices low, all nodes are considered to be equipped with a single omnidirectional antenna.

a) EX phase: To distribute the information in the EX phase the flooding protocol of [9] is considered. In flooding, the message spreads out like a wave from the initializing MS to all receiving MSs. That is, the initializing MS starts to transmit its message while all other MSs are in receiving mode. As soon as a receiving MS can decode the message, it becomes a relay. To this end, it re-encodes the message using a different codebook and supports the initializing MS by transmitting its codeword as well. This is done, until all MSs could decode the message. As all MSs use a different codebook, the signal contributions add up in power at the receiving MSs. This results in an instantaneous achievable rate for MS k at time instant τ of

$$R_{k,\tau} = \log_2\left(1 + \frac{\sum_{k' \in \mathcal{K}_\tau} P_{\text{EX}} g_{k,k'} g_{k,k'}^*}{\sigma_n^2 + \sum_{\tilde{k} \in \tilde{\mathcal{K}}_\tau} P_{\text{EX}} g_{k,\tilde{k}} g_{k,\tilde{k}}^*}\right), \quad (8)$$

with $\mathcal{K}_\tau$ the set of transmitting MSs in the cluster of MS k at time instant τ, $\tilde{\mathcal{K}}_\tau$ the set of all other transmitting MSs in the hotspot at time instant τ, $g_{k,k'}$ the channel from MS k' to MS k (assumed to be constant over the whole EX phase) and P_{EX} the transmit power per MS. For each MS becoming a relay, the instantaneous achievable rate for the receiving MSs is increased, if the interfering MSs are spatially separated enough (which is achieved by sufficient spatial reuse).

By using flooding in the EX phase, we can circumvent the problem of the high path loss with a single omnidirectional antenna at 60 GHz. In a hotspot with ultra high user density, the nodes are very close. Hence, as the message is flooded through the clusters from node to node, only small distances have to be overcome for which high rates can be achieved. That is, the weak channels can be bypassed by relays, and the message can be distributed very efficiently to a large number of MSs without routing or beam forming.

As a reference for flooding, a simple broadcast scheme is considered as well, where a MS sharing its data is not supported by other MSs. Hence, the performance is limited by the weakest channel to all involved MSs. This is considered the conventional VMIMO scheme.

b) AC phase: The RBAPs for the AC phase are assigned according to their channel strength. That is, for cluster c we choose the M RBAPs with the highest

$$p_{l,c} = \bar{\mathbf{h}}_{l,c} \bar{\mathbf{h}}_{l,c}^{\mathsf{H}}, \quad (9)$$

where $(\cdot)^{\mathsf{H}}$ denotes the Hermitian transpose. If a reuse $r^{\mathsf{AC}} < N_{\text{C}}$ is applied, we use a simple fairness algorithm, which assigns the RBAPs to the clusters in a round robin fashion according to their channel strengths (9), until all clusters have their required number of RBAPs.

For the spatial multiplexing, we maximize the signal-to-leakage-plus-noise ratio for each stream according to [10]. To this end, all RBAPs currently in use which are not served by this stream are considered for the leakage calculation. Hence, if $\tilde{\mathbf{H}}_{l,c}$ denotes the channel from the MSs in cluster c to all RBAPs except RBAP l, the precoding vector for this stream m can be found as

$$\mathbf{q}_{m,c} \propto \text{max. eigenvector}\left(\left(\sigma_n^2 \mathbf{I} + \tilde{\mathbf{H}}_{l,c}^{\mathsf{H}} \tilde{\mathbf{H}}_{l,c}\right)^{-1} \bar{\mathbf{h}}_{l,c}^{\mathsf{H}} \bar{\mathbf{h}}_{l,c}\right), \quad (10)$$

with $\mathbf{I}$ the identity matrix and $\mathbf{q}_{m,c}\mathbf{q}_{m,c}^{\mathsf{H}} = P_{\text{AC}}$, the transmit power available per stream. That is, the MSs need to know the channel vectors to the assigned RBAPs and the covariance matrices of the channel to all other RBAPs. The precoding matrix is then given by

$$\mathbf{Q}_c = [\mathbf{q}_{1,c}, \ldots, \mathbf{q}_{M,c}]. \quad (11)$$

A similar approach is considered in [11], where we provide some numerical results for the AC phase in a remote hotspot.

B. Simulation Framework

The performance evaluation is done with numerical simulations in a setup as sketched in Fig. 1a). The width of the setup is thereby set to $a = 600$ meters and the width of the hotspot to $b = 50$ meters. $N_{\text{AP}} = 140$ active and $\bar{N}_{\text{AP}} = 140$ inactive RBAPs are randomly distributed in the respective area, whereby a minimal distance of $d_{\text{min,AP}} = 40$ meters between all active RBAPs and between all inactive RBAPs has to be fulfilled. This minimal distance should reflect the necessary separation between simultaneously working RBAPs due to CSMA/CA. The LUs are randomly placed around their assigned RBAPs within a distance $10 \leq d_{\text{min,LU}} \leq 20$ meters. The active and inactive users are randomly placed within the hotspot area with a minimal distance of 1 meter to each other. Variable numbers of active and inactive users are evaluated, but they are always chosen to be equal, $N_{\text{MS}} = \bar{N}_{\text{MS}}$. The minimal distance between any RBAP and MSs in the hotspot is set to 10 meters.

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 [3], which is based on real world measurements in New York. For each link we determine whether it is LOS or not. To this end, each user in the hotspot 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. 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 [12]. All antenna heights are set to 1.5 meters, and the transmit frequency is set to 2.4 GHz. For the MSs in the hotspot, block shadowing to the RBAPs is assumed. That is, the hotspot is split up into equally distributed squares of 10 meters width. All MSs in one

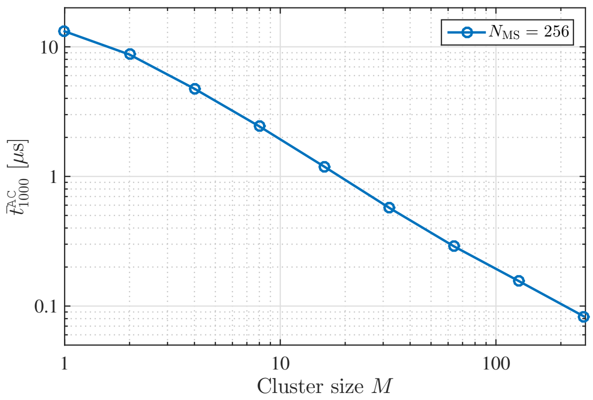

Fig. 3. Performance in the AC phase for fixed number of MSs (256) and varying cluster size considering LUs assigned to the RBAPs. Lower number of MSs lead to almost the same curves, as the performance does not strongly depend on the node density.

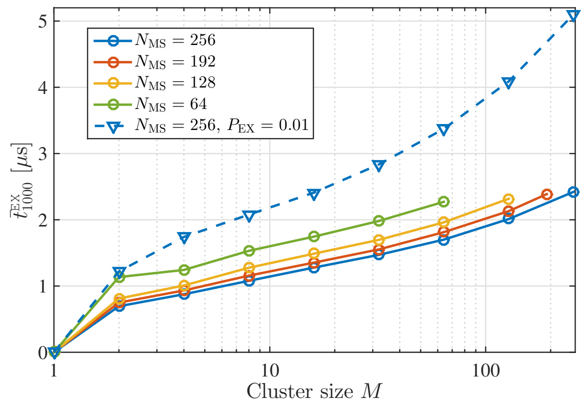

Fig. 4. Performance in the EX phase considering fixed number of MSs and varying cluster size, for transmit power 0.1 W and 0.01 W for comparison.

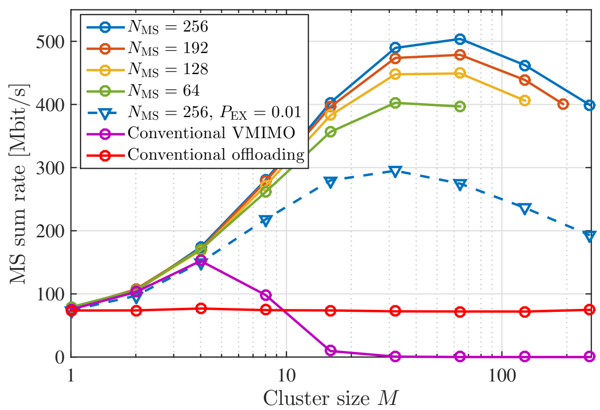

Fig. 5. Final achievable sum rate $\bar{R}_{MS}$ considering fixed number of MSs and varying cluster size, for transmit power 0.1 W and 0.01 W, and conventional offloading as well as conventional VMIMO for $N_{MS} = 256$ as reference.

square then observe the same shadowing to a specific RBAP. In all simulations, we assume that full CSIT to the assigned RBAPs as well as the channel covariance to all other RBAPs is available at all MSs.

The transmit power of the LUs is set to $P_{LU} = 0.01$ W. The transmit power of the MSs in the hotspot is set to $P_{AC} = 0.1$ W in the AC phase and to $P_{EX} = 0.1$ W and $P_{EX} = 0.01$ W for comparison in the EX phase. 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 exchange 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.

The performance evaluation is done considering the achievable sum rate of the MSs, the backhaul rates as well as the LU rates, averaged over 1000 Monte Carlo simulations ($\bar{R}_{MS}$, $\bar{R}_b$, $\bar{R}_{LU}$). In order to directly compare the performance of the EX and the AC phase, we also consider the average time to transmit 1000 bits in the AC phase, $\bar{t}^{AC}_{1000}$, and the average time to exchange 1000 bits in the EX phase, $\bar{t}^{EX}_{1000}$. The smaller they are, the more efficient is the protocol. By applying Jensen's inequality, it is straight forward to show that a lower bound on the MS sum rate can then be found by $\bar{R}_{MS} \geq 1000/(\bar{t}^{AC}_{1000} + \bar{t}^{EX}_{1000})$.

C. Performance Evaluation and Discussion

In the first simulations, a single cluster with M out of the N_{MS} MSs is considered, i.e. only a subset of the available MSs cooperates. The clusters are formed by picking the first MS randomly and then assigning the $M-1$ nearest neighbors to it. This setup is evaluated for $N_{MS} \in \{64, 128, 192, 256\}$ with clusters sizes $M \in \{1, 2, 4, 8, 16, 32, 64, 128, 192, 256\}$ (up to the maximal possible number $M \leq N_{MS}$). Fig. 3 shows $\bar{t}^{AC}_{1000}$ for $N_{MS} = 256$. All other N_{MS} are not shown, as the curves are almost the same. As expected, $\bar{t}^{AC}_{1000}$ decreases with increasing number of nodes in the cluster, as more RBAPs can be accessed at once. In Fig. 4, the corresponding $\bar{t}^{EX}_{1000}$ is shown, considering $\beta = 10$ and $P_{EX} = 0.1$ W. Two observations can be made. The first is, that lower $\bar{t}^{EX}_{1000}$ are achieved for higher N_{MS}, as the distance between the MSs is decreased. The second is, that in contrast to $\bar{t}^{AC}_{1000}$, with fewer MSs in a cluster, smaller $\bar{t}^{EX}_{1000}$ can be achieved. Also shown in this figure is the performance for $P_{EX} = 0.01$ W with $N_{MS} = 256$ MSs, where the exchange efficiency clearly suffers. The lower transmit power decreases the achievable rates between the nodes and reduces the diversity in the flooding, leading to higher $\bar{t}^{EX}_{1000}$.

Combining the AC and the EX phase, an optimal cluster size can be found in terms of the MS sum rate. This is shown in Fig. 5. The maximal achievable rate is not achieved at the maximal M. Hence, we do better if we only consider a subset of the nodes in the hotspot at once. Furthermore, already with relatively few nodes ($M = 16$) very good performance can be achieved. This significantly reduces the complexity, as less CSIT and less coordination is necessary. Fig. 5 also shows the performance of the conventional VMIMO for $N_{MS} = 256$. As the performance of the broadcast exchange in a cluster depends on the weakest channel, the performance gets very poor, as the number of nodes per cluster and with it the distances to overcome increases. This impressively shows how efficiently flooding can deal with the problem of the high path loss with a single omnidirectional antenna at 60 GHz. Comparing $P_{EX} = 0.1$ W with $P_{EX} = 0.01$, a significant performance drop can be observed, analogously to the performance drop in the EX phase. However, while the MS sum rate decreases,

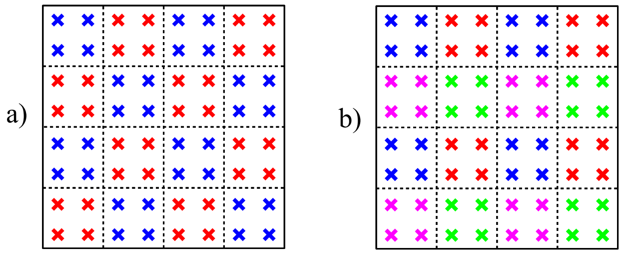

Fig. 6. 16 uniformly arranged clusters with: a) reuse pattern for reuse factor 2, b) reuse pattern for reuse factor 4.

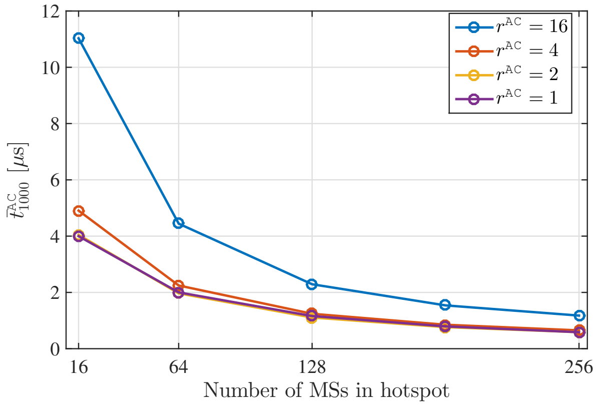

Fig. 7. Performance in the AC phase for fixed number of clusters and varying number of MSs, considering different reuse factors. The yellow curve is hidden behind the purple curve.

also the energy consumption is decreased. Compared to a conventional traffic offloading approach, where one MS after the other accesses an RBAP, large gains can be obtained.

By comparing Fig. 3 and Fig. 4, it can be seen that the EX phase is the bottleneck for large M. The efficiency in the exchange can e.g. be improved by increasing β or applying a spatial reuse. In the following, the latter case is investigated, where we consider $N_{\mathrm{C}} = 16$ uniformly placed clusters (c.f. Fig. 6), with $M \in \{1, 4, 8, 12, 16\}$ randomly placed MSs per cluster (i.e. $N_{\mathrm{MS}} = \{16, 64, 128, 256\}$), and different reuse factors $r^{\mathrm{EX}}, r^{\mathrm{AC}} \in \{1, 2, 4, 16\}$, with reuse patters as shown in Fig. 6. Note that $M = 1$ corresponds to a conventional offloading scheme with spatial reuse (no EX phase).

The performance in the AC phase is shown in Fig. 7. By decreasing the reuse factor from 16 down to 2 (i.e. more clusters active simultaneously), the performance is strongly increased, even though the clusters interfere with each other in the RBAP access. For a reuse factor of 1, no further gain can be achieved, as the interference between the clusters can not be compensated anymore by the additional RBAPs accessed.

In the EX phase, $\beta = 10$ and $P_{\mathrm{EX}} = 0.1$ W is considered. The resulting performance is shown in Fig. 8, where also the performance of $P_{\mathrm{EX}} = 0.01$ W for a reuse of 2 is shown for comparison. The efficiency in the EX phase can be strongly increased by applying a reuse factor of 4. Due to the spatial separation and the likely LOS blockage, there is a strong interference separation between simultaneously active clusters. For a reuse of 2 the efficiency slightly drops again, and for reuse 1 (i.e. all clusters are exchanging simultaneously), the

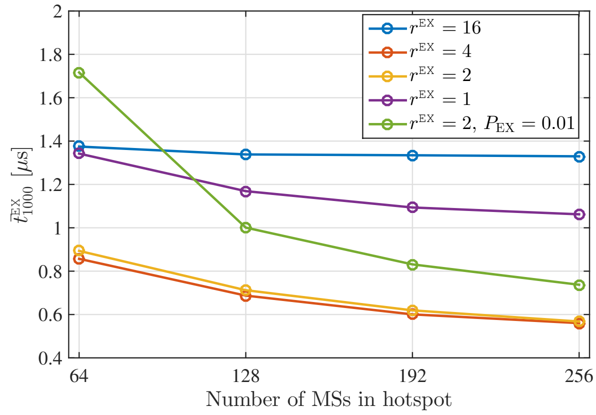

Fig. 8. Performance in the EX phase for fixed number of clusters and varying number of MSs, considering different reuse factors and $P_{\mathrm{EX}} = 0.1$ W and $P_{\mathrm{EX}} = 0.01$ W.

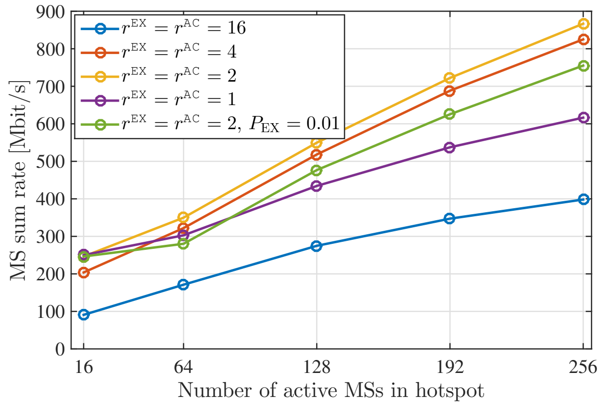

Fig. 9. Final achievable sum rate $\bar{R}_{\mathrm{MS}}$, for fixed number of clusters and varying number of MSs, considering different reuse factors and $P_{\mathrm{EX}} = 0.1$ W and $P_{\mathrm{EX}} = 0.01$ W.

performance strongly suffers, as the mutual interference is too strong.

The resulting MS sum rate is shown in Fig. 9, where always the same reuse factor is considered for both phases. The best results can be achieved for a reuse factor of 2. The AC as well as the EX phase become much more efficient due to the spatial reuse and scale beneficially with the number of nodes. While already for $M = 1$ with spatial reuse a large gain compared to conventional offloading can be achieved, increasing the cluster size and therefore applying VMIMO, strongly increases the gain, even with lower transmit power in the exchange phase ($P_{\mathrm{EX}} = 0.01$ W).

Tab. I shows the average backhaul rates $\bar{R}_{\mathrm{b}}$. It can be seen, that they do not drastically change, as the loss of the LUs is compensated by the MSs. Only the multiple cluster scheme with spatial reuse 2 notably suffers, as many LUs have to be

TABLE I
BACKHAUL RATES [GBIT/S], I.E. AVERAGE SUM RATES OF ALL RBAPS ($N_{\mathrm{MS}} = 256$).

Scheme	Without hotspot	Conventional offloading	$N_{\mathrm{C}} = 1$ $M = 64$	$N_{\mathrm{C}} = 16$ $r{=}2$, $M{=}16$
$\bar{R}_{\mathrm{b}}$	9.81	9.71	9.94	8.55

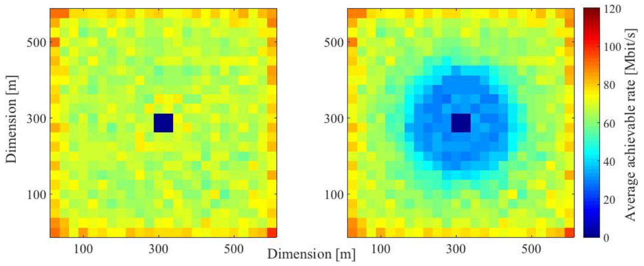

Fig. 10. LU rates during EX phase (left) and averaged over EX and AC phase (right) for 16 clusters with 16 nodes each and spatial reuse 2.

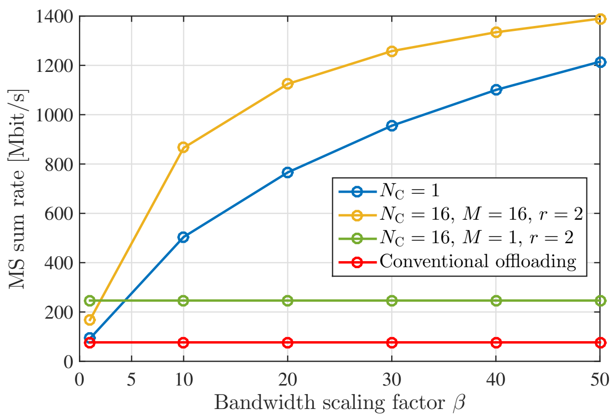

Fig. 11. Achievable rates for 256 MSs and varying β. $M = 16$ for $N_C = 16$ and $M = 64$ for $N_C = 1$.

turned off frequently. By looking at the spatial distribution of the average achievable rates of the LUs, the drawback for the LUs becomes clearly visible. The left side of Fig. 10 shows the spatial distribution of the LU rates during the EX phase of any of the user cooperation schemes. Similar average LU rates are achieved independent of the location, except for edge effects. The dark blue square in the middle is the hotspot, where no RBAPs and LUs are located. Comparing these rates to the rates on the right side of Fig. 10, where the average LU rates over both phases are shown for $N_C = 16$ with $r = 2$ and $M = 16$, it can be seen that the LUs around the hotspot suffer strongly, due to the frequent RBAP access of the hotspot.

Fig. 11 in the end shows the achievable rates for different exchange bandwidths, $\beta \in \{1, 10, 20, 30, 40, 50\}$. The results are shown for $N_{MS} = 256$ and considering a single cluster with $M = 64$, as well as 16 clusters with $M = 16$ and spatial reuse 2. Increasing the bandwidth strongly decreases the time needed for the EX phases, leading to much higher achievable rates in the end. However, the bandwidth can not be scaled arbitrarily. First of all, even in the 60 GHz band, the bandwidth might be limited. Furthermore, for a constant transmit power, the achievable rates saturate, as we reach the power limited regime.

VI. Conclusions and Outlook

In this paper, we discussed a transparent user cooperation protocol which can be overlaid on existing infrastructure. It allows to efficiently serve the MSs in an urban traffic hotspot by traffic offloading to the vast amount of WLAN access points in the surrounding. We discussed the necessary coordination among the MSs and the local users assigned to the access points, and proposed a system implementation with user cooperation at 60 GHz with flooding, and WLAN access at 2.4 GHz with SLNR precoding. With a numerical simulation framework considering realistic channel models and local users assigned to the WLAN access points, it has been shown that 60 GHz communication combined with flooding is very efficient for the user cooperation, even with a single omnidirectional antenna per node. With 10 times more bandwidth in the user cooperation phase than in the access phase, a 5 fold increase in the MS sum rate compared to conventional offloading can be achieved already with only 16 out of 256 MSs cooperating, requiring only limited channel state information and coordination among the nodes. By splitting up the hotspot into 16 clusters with 16 nodes each and applying a spatial reuse in 1 out of 2 clusters even a gain of roughly 10 compared to conventional offloading can be achieved and a more than 3 fold increase compared to 16 clusters with only 1 MS per cluster, underlining the potential of the user cooperation. While the performance of the conventional offloading does not scale with the number of users, the achievable sum rate can be increased for the virtual MIMO scheme by increasing the number of nodes per cluster. By scaling the bandwidth for the user cooperation up to 50 times the bandwidth for the access phase, the gain can be even further increased. Hence, it is a promising approach to serve the MSs in an urban traffic hotspot. By optimizing the clustering and the number of nodes per cluster further improvements are expected.

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