User Cooperation for Traffic Offloading in Remote Hotspots

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***Abstract*—Serving mobile stations in a remote hotspot with ultra high user density in the vicinity of a densely populated area is a challenging problem in terms of user separation and necessary infrastructure. Such a scenario arises e.g. in music festivals, sport events or emergency situations. In this context, we propose to serve these mobile stations by traffic offloading combined with user cooperation. That is, the mobile stations shall form a virtual antenna array and jointly access the WLAN access points in the surrounding. We thereby propose distributed spatial multiplexing for the WLAN access at 2.4 GHz and user cooperation based on flooding at 60 GHz, all with omnidirectional antennas. With numerical simulations based on realistic channel models, we show that depending on the distance and the number of streams to transmit, high coverage can be achieved. The user cooperation at 60 GHz is very efficient, as flooding can overcome the high pathloss, and because large bandwidth can be used. However, the local users of the WLAN access points strongly suffer from the hotspot traffic. Therefore, the traffic has to be carefully distributed among different WLAN access points in order to guarantee a certain fairness among these local users.**

I. Introduction

Various approaches have been proposed how to handle the ever increasing amount of mobile data traffic [1] and number of devices to serve [2], such as network densification with traffic offloading [3], millimeter wave communication [4] or the application of massive multiple-input multiple-output (MIMO) antenna arrays [5]. However, serving users in a traffic hotspot, i.e. a very large number of users in a small area, is still a big challenge. The close vicinity of the users make them hard to differentiate in space, leading to strong interference. Furthermore, high investments into infrastructure would be necessary for sufficient coverage. In this context, we have shown in [6] how mobile stations (MSs) in such a traffic hotspot within a city, such as a busy public square or a train station, can be efficiently served. We therefore combined user cooperation with traffic offloading. That is, the MSs form a virtual antenna array [7] and jointly access the vast amount of residential WLAN access points, the so called residential backhaul access points (RBAP), in the surrounding. Hence, the traffic can be distributed over a large area without any additional infrastructure. To support distributed ownership of the RBAPs, all signal processing needs to be done on the MS side. This results in a two phase protocol with a local exchange phase between the MSs and a long-haul MIMO phase to the RBAPs. We proposed a distributed and stream wise precoding for the long-haul phase at 2.4 GHz and the local exchange based on flooding [8] at 60 GHz, all with omnidirectional antennas. We have shown, that this combination is very efficient and allows high gains compared to the reference schemes. Flooding combined with omnidirectional antennas is well suited for the data exchange, as the large pathloss at 60 GHz can be overcome by the hop by hop nature of flooding, even with omnidirectional antennas. As large bandwidths are available in the 60 GHz band, the duration of the local exchange can be significantly reduced by increasing the exchange bandwidth, and hence, the performance can be further boosted.

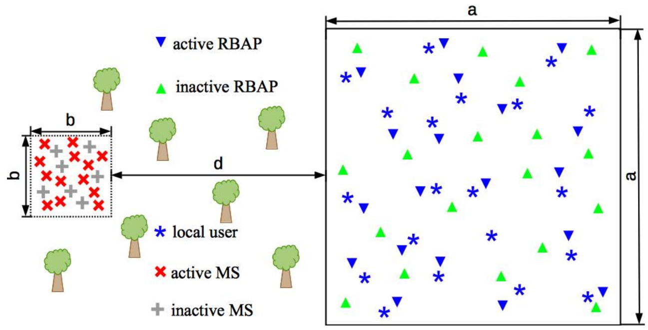

Fig. 1. System setup.

In this paper, we apply this protocol to the uplink in a setup with a remote hotspot. The setup of consideration is shown in Fig. 1. One hotspot with ultra high user density is located outside but close to a densely populated area with many RBAPs. This could e.g. be a music festival, a sports event or an emergency situation, where a crowd of people needs to get help, close to a city. We distinguish between active MSs which want to transmit data, and inactive MSs, which have no data to transmit and do not participate in the user cooperation. However, they can block the line of sight (LOS) between active users with their physical presence and thus degrade the exchange efficiency. In the city, we also consider active RBAPs and inactive RBAPs. While each active RBAP is accessed by a local user (LU), the inactive RBAPs are currently out of use or have to be shut off due to carrier sense multiple access (CSMA) collision avoidance. However, the MSs can access both types of RBAPs.

Different to [6], where the hotspot is located in the middle of a city, the distance to the RBAPs is much higher in the remote hotspot setup, leading to a strong performance drop for large distances. Therefore, the user cooperation is even more important, as with an increasing number of cooperating

Fig. 2. Proposed two phase protocol.

MSs a higher array gain can be achieved and larger distances overcome. Furthermore, a higher spatial multiplexing gain can be achieved as more streams can be transmitted. However, while a high number of transmitted streams leads to high achievable rates, the LUs strongly suffer, as for each stream one RBAP is occupied by the hotspot. Hence, to guarantee a certain fairness among the LUs, it is reasonable to trade off the performance of the hotspot versus the performance of the LUs and thus to transmit less streams but with higher transmit power per stream. In this context, based on a numerical simulation framework with realistic parameters, we investigate the performance in dependence of the distance, the number of available MSs and the number of streams to transmit and consider their impact onto the fairness aspect for the LUs. Furthermore, we also consider in-band exchange at 2.4 GHz and compare its efficiency to the exchange at 60 GHz. It is shown, that depending on the distance and the available number of users, very good coverage can be achieved. However, with increasing distance, the array gain can not compensate the high pathloss anymore. Still the performance is much better than compared to a time division multiple access scheme (TDMA).

II. User Cooperation Protocol

In order to offload the traffic to the RBAPs in the city, the MSs of the hotspot form a VAA and jointly access the RBAPs by distributed spatial multiplexing. The resulting two phase protocol with the local exchange (EX) phase and the long-haul access (AC) phase is then continuously repeated as sketched in Fig. 2.

For the protocol implementation, all nodes in the network are considered to be equipped with a single omnidirectional antenna. The RBAPs for the AC phase are chosen according to their channel strength to the participating MSs, and served by stream wise SLNR precoding [9] in the 2.4 GHz band. Note, that for each active RBAP assigned to the MSs, one LU has to be turned off during the AC phase. Additionally, all LUs in close vicinity have to be turned off as well, in order to reduce the interference for the AC signals.

In order to compute the AC signal at each MS individually, all transmit data and full instantaneous channel state information (CSI) needs to be available at all MSs. To this end, each MS in the hotspot has to share its transmit data with all other involved MSs. This exchange is done with flooding [8]. That is, one MS starts to transmit its data. Whenever another MS has received enough data to decode the message, it re-encodes the message in a different codeword and starts to support the initial MS by transmitting as well. This is done, until all MSs could decode the message. Hence, with every MS supporting the transmission, the received signal strength at the remaining MSs is increased and thus the achievable rate is increased as well. This way, bad channels can be efficiently bypassed and the performance is not anymore limited by the weakest channel

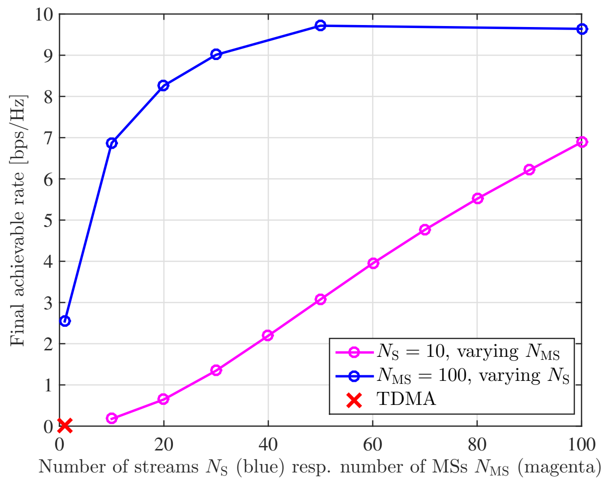

Fig. 3. Final achievable rates with 60 GHz exchange, $d = 400$ meters and fixed number of streams $N_\mathrm{S} = 10$ for varying number of MSs (magenta), fixed number of MSs $N_\mathrm{MS} = 100$ and varying number of streams (blue), and TDMA (red).

from the initial MS to all others, as it would be with a classical broadcast scheme. The exchange is either done in-band at 2.4 GHz or in the 60 GHz band. The final achievable sum rate can be denoted by

$$\bar{R}_\mathrm{MS} = \frac{R_\mathrm{MS}^\mathsf{AC}}{1 + t^\mathsf{EX}}, \tag{1}$$

where $R_\mathrm{MS}^\mathsf{AC}$ is the achievable sum rate in the AC phase, the 1 in the nominator stands for the time of the AC phase, and t^EX is the necessary time to share the data among all involved MSs. Note the importance of t^EX. While the necessary time for the AC phase is fixed, t^EX can be varied for the 60 GHz exchange by varying the exchange bandwidth and has therefore a significant influence on the performance. For the 2.4 GHz exchange, the available bandwidth is assumed to be the same as in the AC phase and hence can not be varied.

As a reference for the user cooperation scheme we use a TDMA approach. That is, one MS after the other individually communicates with one hotspot, without any cooperation.

III. Numerical Evaluations

The proposed protocol is evaluated in a setup as sketched in Fig. 1, with $a = 600$ meters and $b = 50$ meters. We conduct numerical simulations with realistic parameters, considering LOS blockage in the EX phase, block shadowing in the AC phase and realistic channel models ([4], [10]). In all simulations, the number of active and inactive RBAPs is set to 140 each, and the number of inactive MSs is equal to the number of active MSs. If we consider the EX phase at 60 GHz, the bandwidth for the exchange is assumed to be 10 times higher than for the in-band exchange and the AC phase. Depending on the available bandwidth in the 60 GHz band (i.e. depending on the other usage of the 60 GHz band in the hotspot), this factor can also be chosen higher or lower, resulting in shorter or longer t^EX. Fig. 3 shows the final achievable rates at $d = 400$ meters with 60 GHz exchange for a fixed number of streams $N_\mathrm{S} = 10$ with a varying number of MSs $N_\mathrm{MS} \in \{10, 20, \ldots, 100\}$, for a fixed number of MSs $N_\mathrm{MS} = 100$ and a varying number

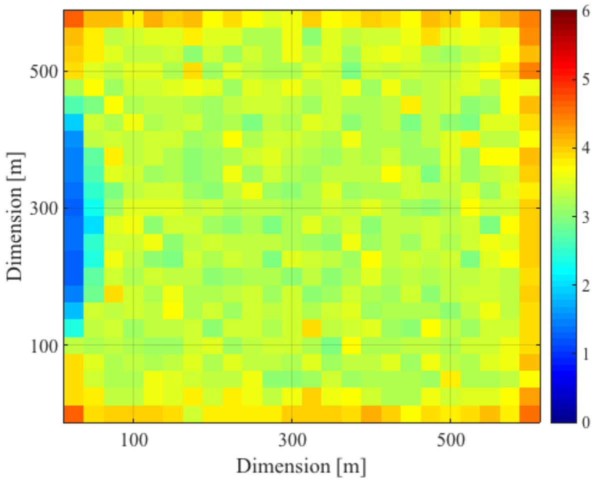

Fig. 4. Spatial rate distribution of the LUs rates [bps/Hz] with 60 GHz exchange, averaged over EX phase and AC phase for $N_{\mathrm{S}} = 10$ and $N_{\mathrm{MS}} = 100$.

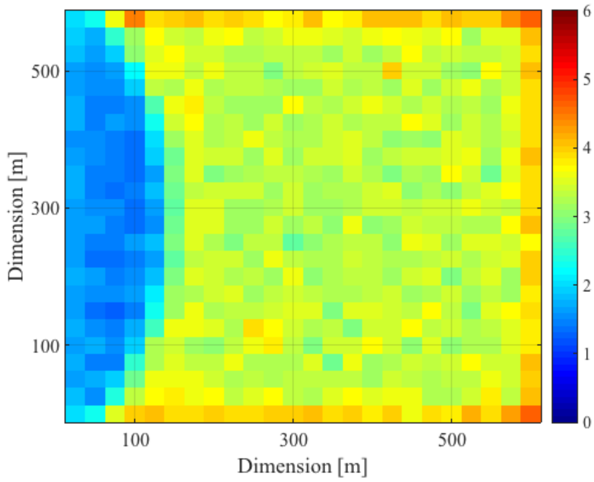

Fig. 5. Spatial rate distribution of the LUs rates [bps/Hz] with 60 GHz exchange, averaged over EX phase and AC phase for $N_{\mathrm{MS}} = 100$ and $N_{\mathrm{S}} = 50$.

of streams $N_{\mathrm{S}} \in \{1, 10, 20, 30, 50, 100\}$, and for TDMA. For the first two cases, the transmit power per stream is set to $P_{\mathrm{Tx}} = 1\mathrm{W} \cdot N_{\mathrm{MS}}/N_{\mathrm{S}}$, for TDMA to $P_{\mathrm{Tx}} = 1\mathrm{W}$. That is, if N_{S} is fixed and N_{MS} is increased (magenta curve), the available transmit power per stream is increased as well. As we are in the power limited regime due to the large distance (low signal to interference plus noise ratio), this leads to a linear increase in the achievable rate. For the case of fixed number of MSs (blue curve), the total transmit power is fixed, but the power per stream is varied. For only one stream, a large gain can be observed compared to TDMA, resulting from the huge array gain which can be achieved. Transmitting an increasing number of streams, the power per stream is decreased, but the achievable rate increases as more spatial degrees of freedom can be used. However, only up to a certain level. From $N_{\mathrm{S}} = 50$ on, the additional streams can not compensate the decreased transmit power per stream anymore. The additional RBAPs are located too far away to offer further degrees of freedom with the decreased power per stream. Hence, from an achievable rate perspective of the MSs in the hotspot, it would be reasonable to transmit 50 streams. However, this also means, that more local users (LUs) are affected compared to transmitting e.g. only 10 streams. This can be clearly seen in the following figures. Fig. 4 shows the spatial distribution of the average achievable LU rates over both, the EX and the AC phases, for $N_{\mathrm{S}} = 10$ and $N_{\mathrm{MS}} = 100$. It can be seen, that the distribution is very homogeneous except for a few LUs very close to the hotspot. There, the rate drops to approximately $1/2$ of the ordinary performance, as the corresponding RBAPs are frequently accessed by the hotspot. In Fig. 5, the same is shown for $N_{\mathrm{MS}} = 100$ and $N_{\mathrm{S}} = 50$. The effect on the LUs is much stronger, as more RBAP are occupied in each AC phase. For increasing number of MSs and streams, this effect is even stronger (shown in full paper). Hence, from a network point of view, transmitting less streams is much more efficient as the performance loss for the MSs is minor compared to the loss of the LUs. Furthermore, with the large array gain of $N_{\mathrm{S}} = 10$ and $N_{\mathrm{MS}} = 100$, it is also possible to efficiently access different RBAPs in each AC phase, in order to distribute the burden for the LUs more homogeneous. This fairness aspect will be further investigated in the full paper as well.

Fig. 6 finally shows the performance in dependence of the distance d, where we have always chosen the pairs $N_{\mathrm{S}} = 10$ and $N_{\mathrm{MS}} = 100$ and $N_{\mathrm{S}} = 50$ and $N_{\mathrm{MS}} = 100$. While for smaller distances, the performance is very good, it is strongly decreasing for increasing distance. The increased pathloss can not be compensated by the array gain anymore. However, the gain compared to the TDMA approach is still huge. In this plot, the performance of the in-band exchange is shown as well. It can be observed, that although a much lower pathloss has to be overcome in the EX phase, the performance is much worse than for 60 GHz exchange, due to the limited bandwidth. This is especially critical for small distances, where lots of data (high $R_{\mathrm{MS}}^{\mathsf{AC}}$) has to be shared and thus t^{EX} is very dominant in (1). For increasing distance d, this effect is minor, as the AC phase becomes dominant (less data to share).

IV. Discussion and Outlook

For small distances, user cooperation combined with traffic offloading is an efficient way to serve the users in a remote hotspot in the vicinity of a densely populated area. The user cooperation can be efficiently done at 60 GHz by flooding and scaling the BW appropriately. With increasing distances, the performance strongly drops, but still clearly outperforms the TDMA approach. Note, that this drastic performance drop is partially caused by the choice of the rather pessimistic channel model (Winner II, scenario C2 [10]). While we assume a rural environment between the hotspot and the city, the used channel model is suited for urban areas, with a correspondingly high pathloss exponent. However, for reasons of simplicity, we applied the same channel model between the LUs and the RBAPs and the MSs and the RBAPs.

In the full paper, we will discuss in detail the proposed protocol, the simulation framework and the performance evaluation. We will also investigate the efficiency of the EX and AC phase

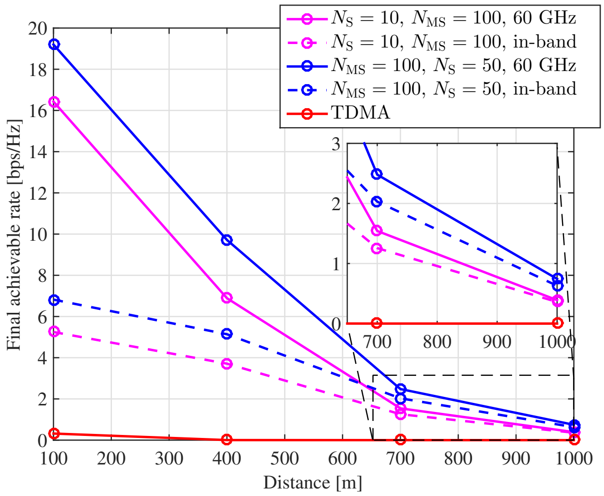

Fig. 6. Distance dependency of the final rates for in-band and 60 GHz exchange compared to TDMA.

separately and their influence on the final rate, and provide a more detailed comparison of in-band and 60 GHz exchange. Furthermore, the fairness aspect of the LUs is considered and the backhaul rates investigated, i.e. the sum of all achievable rates over all RBAPs.

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