User Cooperation for Traffic Offloading in Remote Hotspots

Tim Rüegg, Armin Wittneben
Swiss Federal Institute of Technology (ETH) Zurich,
Communication Technology Laboratory, CH-8092 Zurich, Switzerland
Email: rueegg@nari.ee.ethz.ch, wittneben@nari.ee.ethz.ch

***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. at music festivals, sport events or in emergency situations. In this context, we propose to serve the mobile stations in such a remote hotspot by user cooperation combined with traffic offloading. That is, the mobile stations shall form a virtual MIMO array and jointly access the WLAN access points in the surrounding. Based on numerical simulations with realistic parameters, the performance of the user cooperation scheme is evaluated and its interdependency with the local users assigned to the WLAN access points is investigated. It is thereby shown, that the performance of the local users strongly suffers from the hotspot traffic. Hence, two different schemes trading off the performance of the local users versus the performance of the mobile stations in the hotspot are proposed and evaluated.**

I. Introduction

Various approaches have been proposed how to handle the ever increasing amount of mobile data traffic and number of devices to serve [1], such as network densification with traffic offloading [2], millimeter wave communication [3] or the application of massive multiple-input multiple-output (MIMO) antenna arrays [4]. 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 lack of sufficient physical resources makes them hard to separate. Furthermore, high investments into infrastructure would be necessary for sufficient coverage.

In this context, we show in [5] how mobile stations (MSs) in such a traffic hotspot within a city can be efficiently served without any additional infrastructure. We therefore combine user cooperation with traffic offloading to the vast amount of residential WLAN access points (further called residential backhaul access points (RBAP)) in the surrounding. This results in a two phase protocol with a local exchange phase between the MSs and a long-haul virtual MIMO phase to the RBAPs. We propose distributed spatial multiplexing for the long-haul phase at 2.4 GHz and the local exchange based on flooding [6] at 60 GHz, all with omnidirectional antennas. This combination is very efficient and allows high gains compared to the reference schemes, as the large path loss of a single omnidirectional antenna at 60 GHz can be efficiently overcome by the hop by hop nature of flooding. Due to the large amount of available bandwidth in the 60 GHz band, the local exchange phase can be boosted by scaling the used bandwidth for the user cooperation.

A setup not addressed in [5] is the remote hotspot. That is, an area with ultra high user density 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. On the one hand, this scenario is interesting out of a practical perspective, as the coverage of cellular networks normally does not support big crowds of people in such areas. With virtual MIMO large distances can be overcome due to the high array gain and multiple streams can be transmitted simultaneously. Hence, traffic offloading to the RBAPs in the close vicinity is a reasonable approach. On the other hand, this scenario is also interesting out of a theoretical perspective. In contrast to [5], where the local exchange phase was limiting the performance, in the remote hotspot scenario the long-haul phase becomes the bottleneck due to the large distances and the correspondingly high path loss. This also affects the local users (LUs) which are assigned to the RBAPs. They suffer strongly from the frequent RBAP access by the MSs in the hotspot.

In this context, we investigate the performance of user cooperation combined with traffic offloading for the remote hotspot scenario, based on a numerical simulation study with realistic parameters. As for this scenario, the long-haul MIMO phase is the bottleneck, the focus of the paper is on this part of the protocol. Furthermore only the UL is considered. We evaluate the performance of the proposed protocol with increasing distance and investigate its interdependency with the LU performance and the backhaul rate of the system. To relieve the burden of the LUs, two different approaches are proposed. We thereby show how the MS performance can be traded off with the LU performance.

II. System Setup

The setup of consideration is shown in Fig. 1. One hotspot with ultra high user density is located in the vicinity of a densely populated area with many RBAPs. The area between the hotspot and the city is assumed to be a rural environment with trees or even a plain field. The number of MSs in the hotspot is denoted by N_{MS}. In the city, we consider active RBAPs and inactive RBAPs. While each active RBAP is accessed by a LU, the inactive RBAPs are currently out of use or idle for interference mitigation. The number of active RBAPs is denoted by N_{AP} and the number of inactive RBAPs by $\bar{N}_{\mathrm{AP}}$. The MSs can access both types of RBAPs. The goal is then to serve the MSs in the hotspot with a rate as high as

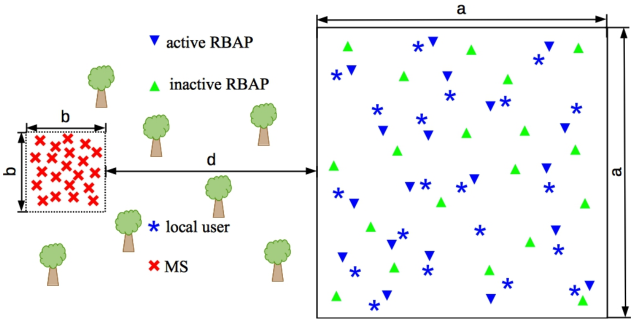

Fig. 1. System setup.

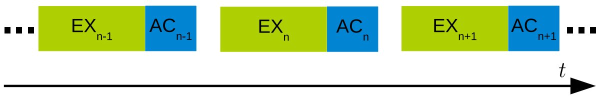

Fig. 2. Sequence of the proposed two phase protocol.

possible without corrupting the LUs and the backhaul rates of the whole network too much. All nodes are considered to be equipped with a single omnidirectional antenna. Note, that in this paper only the uplink of the MSs in the hotspot and of the LUs is considered.

III. User Cooperation Protocol

In order to serve the MSs in a remote hotspot where no communication infrastructure is available, we propose that the traffic of the MSs is offloaded to the RBAPs in the close city. Analogously to [5], the MSs shall form a virtual antenna array (VAA) [7] and then jointly access the RBAPs in the city by distributed spatial multiplexing. In order to keep the coordination among the RBAPs at a minimum, they are assumed to be unable to cooperate. That is, all signal processing has to be done at the MS side. Hence, the resulting protocol consists of two phases: a local short range exchange phase (EX) and a long-haul MIMO access phase (AC). These two phases are then continuously repeated as sketched in Fig. 2. In the following, we will roughly discuss the two phases of the protocol and their implementation in the simulation study. A detailed description can be found in [5].

By forming a VAA in the AC phase, larger distances can be overcome due to the array gain, and spatial multiplexing can be achieved. The RBAPs for the traffic offloading can be chosen out of all, active as well as inactive RBAPs. Note however, that to each active RBAP a LU is assigned, communicating in the same frequency band as the MSs. To mitigate interference, the LUs of the assigned RBAPs, as well as the LUs within a certain *dead-zone distance* to these RBAPs are turned off.

Instead of transmitting the maximal possible number of streams N_{MS} from the hotspot, the available transmit power can be focused on a lower number of streams N_{s}. The receive signal of an RBAP l can then be written as

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

with $\bar{\mathbf{h}}_l \in \mathbb{C}^{1\times N_{\mathrm{MS}}}$, the channel vector from the cooperating MSs to RBAP l, $\mathbf{Q} \in \mathbb{C}^{N_{\mathrm{MS}}\times N_{\mathrm{s}}}$ the precoding matrix and $\mathbf{s}_{\mathrm{MS}} \in \mathbb{C}^{N_{\mathrm{s}}\times 1}$ the signal vector of the MSs. The set $\mathcal{J}$ contains all LUs which are currently transmitting, $f_{l,j} \in \mathbb{C}$ denotes the channel from LU j to RBAP l, $s_{\mathrm{LU},j} \in \mathbb{C}$ the signal of LU j and $n \in \mathbb{C}$ finally is circularly complex additive white Gaussian noise with zero mean and variance σ_n^2. Depending on the RBAP, either the signal of the hotspot is the desired one, or the signal of a LU. The achievable rate of the MSs in the hotspot during the AC phase is then the sum over the achievable rates of all N_{s} transmitted streams, denoted by $R_{\mathrm{MS}}^{\mathsf{AC}}$ (in bit/s). That is, $R_{\mathrm{MS}}^{\mathsf{AC}} \cdot t^{\mathsf{AC}}$ bits are transmitted during one AC phase of duration t^{AC}.

The assignment of the RBAPs is done according to their channel strength

$$p_{l,c} = \bar{\mathbf{h}}_l \bar{\mathbf{h}}_l^{\mathsf{H}}, \tag{2}$$

whereby the strongest N_{s} RBAPs are chosen. For the distributed spatial multiplexing, the precoding matrix is computed at each MS individually. To separate the streams, we maximize the signal-to-leakage-plus-noise-ratio (SLNR) for each stream separately according to [8], whereby only the RBAPs assigned to the hotspot are considered for the leakage calculation. We omit to do power loading and thus assign equal power to each stream. For the precoding, instantaneous channel state information (CSI) is required, which is assumed to be available. Furthermore, the MSs have to be synchronized and their transmission coordinated with the RBAPs and LUs. However, these important aspects are not topic of this paper and will be addressed in future work.

In order to compute the AC signal at each MS individually, all transmit data needs to be available at all MSs. To this end, each MS in the hotspot shares $R_{\mathrm{MS}}^{\mathsf{AC}} \cdot t^{\mathsf{AC}}/N_{\mathrm{MS}}$ bits with all other involved MSs. This exchange can be done by any means, e.g. in-band, out-of-band or even using a different physical layer such as ultra wide band (UWB) communication. As this paper focuses on the AC phase, we do not further specify the implementation of the EX phase, but assume certain values based on [5] for the evaluation of the protocol. The time it takes until all transmit data is exchanged is denoted by t^{EX}. The final achievable sum rate of the protocol for the given setup can then be denoted by

$$\bar{R}_{\mathrm{MS}} = \frac{R_{\mathrm{MS}}^{\mathsf{AC}} \cdot t^{\mathsf{AC}}}{t^{\mathsf{AC}} + t^{\mathsf{EX}}} = \frac{R_{\mathrm{MS}}^{\mathsf{AC}}}{1+\xi}, \tag{3}$$

where $\xi = t^{\mathsf{EX}}/t^{\mathsf{AC}}$ denotes the ratio between the duration of the EX phase and the AC phase. 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.

IV. Local User Performance Enhancement

In the previously described original protocol, the LUs of an RBAP assigned to the hotspot have to be turned off during the AC phase in order to mitigate interference. The same is true for LUs within a certain *dead-zone distance*. However, this causes a severe performance drop for the affected LUs (c.f. Fig. 6, further discussed in Section V-A). Therefore, we propose two schemes in this section in order to enhance the performance of these LUs, namely a round-robin based allocation of the RBAPs and an approach based on successive interference cancellation (SIC).

A. Fractional Reuse Allocation

In the fractional reuse allocation scheme (FRAS), the idea is that an active RBAP can only be accessed by the hotspot in one of δ AC phases. Additionally, the *dead-zone distance* is set to 0. This way, the LUs have to be turned off less frequently. However, more interference is present in the network as in the original scheme (no *dead-zone*), degrading the performance of the MSs in the hotspot. Furthermore, the MSs in the hotspot have to access RBAPs further apart. The RBAP assignment works still the same way, with the little difference that the N_s strongest RBAPs are chosen, of which no active RBAP has been used in the last $\delta - 1$ AC phases.

B. SIC Decoding

In the SIC scheme (SICS) no LU is turned off. Instead, an RBAP which is assigned to the MSs in the hotspot first decodes the signal of its local user under the interference of the hotspot signal (and all other LU signals), then subtracts this signal, and decodes the hotspot signal without interference from the corresponding LU. This way, the interference for the hotspot signal is reduced while no LU has to be turned off. However, only the interference from the own LU is mitigated. All interference from other LUs which would normally be turned off as they are within the *dead-zone*, is still present and degrades the MS performance. Different to FRAS, always the best RBAPs can be accessed.

Although this SIC approach is of high complexity in a practical implementation, there are suboptimal implementations available, making it very interesting to investigate.

V. Numerical Evaluations

The performance evaluation of the proposed schemes is done in a setup as sketched in Fig. 1 with parameters similar to [5]. The width of the hotspot is thereby chosen as $b = 50$ meters, the width of the city as $a = 600$ meters and the distance d is varied in the simulations, $d \in \{100, 400, 700, 1000\}$ meters. The number of active and inactive RBAPs is set to $N_\mathrm{AP} = \bar{N}_\mathrm{AP} = 140$. These RBAPs are randomly placed within the corresponding area with a minimal distance of $d_\mathrm{min,AP} = 40$ meters between all active RBAPs and between all inactive RBAPs. The LUs are randomly place around their corresponding RBAPs within a distance of $10 \leq d_\mathrm{min,LU} \leq 20$ meters. The *dead-zone distance* is set to 20 meters for the original protocol. In the hotspot, we consider $N_\mathrm{MS} = 100$ MSs. All channels are assumed to be Rayleigh fading with path loss and shadowing drawn according to the WINNER II channel model scenario C2 [9]. Thereby, all connections are assumed to be no-line-of-sight (NLOS), the terminal heights are set to 1.5 meters and the transmit frequency to 2.4 GHz. For the MSs in the hotspot, block shadowing is considered with a block size of 10 meters. That is, all MSs within such a block observe the same shadowing to a specific RBAP. During the AC phase, the sum transmit power of the hotspot is set to $P_\mathrm{MS}^\mathsf{AC} = N_\mathrm{MS} \cdot 1$ W in order to overcome large distances. The transmit power of

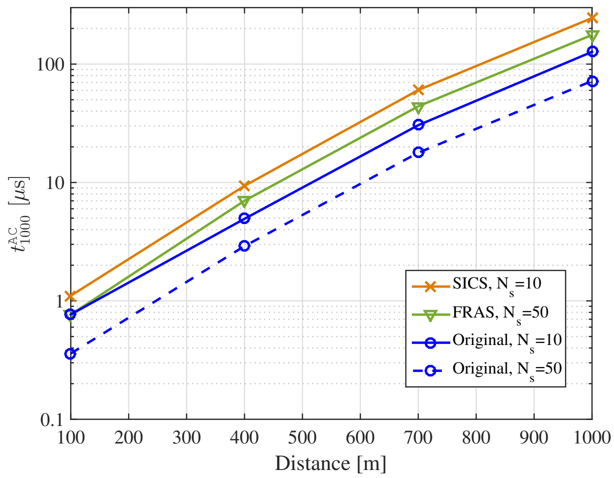

Fig. 3. Performance in the AC phase: Distance dependency of t_{1000}^AC for $N_\mathrm{MS} = 100$.

the LUs is assumed to be $P_\mathrm{LU} = 0.01$ W. The bandwidth is considered to be 20 MHz, with the corresponding noise variance $\sigma_n^2 = 10^{-12}$ W.

The evaluation of the performance is done by means of the achievable spectral efficiency multiplied with the operational bandwidth, i.e. by the total possible achievable data rate. As figures of merit we use the time to transmit 1000 bits t_{1000}^AC for the AC phase and the time to exchange these 1000 bits t_{1000}^EX in the EX phase. t_{1000}^EX is thereby not evaluated and assumed to be $t_{1000}^\mathsf{EX} = 2.3\ \mu s$. This is a reasonable value for $N_\mathrm{MS} = 100$, which can be achieved e.g. with flooding at 60 GHz. Further details on this specific implementation of the EX phase can be found in [5]. These numbers allow to directly compare the efficiencies of the two phases. The smaller they are, the higher is the efficiency. The final achievable rate can then be determined by $\bar{R}_\mathrm{MS} = 1000/(t_{1000}^\mathsf{AC} + t_{1000}^\mathsf{EX})$.

A. Simulation Results

The following simulations have been performed for $N_\mathrm{MS} = 100$ and different number of streams. The results for t_{1000}^AC are shown in Fig. 3 for $N_\mathrm{s} = 50$ and $N_\mathrm{s} = 10$ streams. This figure also shows t_{1000}^AC for the two LU performance enhancement schemes which will be discussed later. It can be observed that for all distances $N_\mathrm{s} = 50$ performs better than $N_\mathrm{s} = 10$, although the transmit power per stream is lower (due to the fixed transmit power). That is, by increasing the number of streams, a better performance can be achieved, 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 additionally assigned RBAPs are located too far away to offer further degrees of freedom with the decreased power per stream. Hence, the results are shown for $N_\mathrm{s} = 50$ with the maximum achievable rate and for $N_\mathrm{s} = 10$ as a reference accessing less RBAPs (and requiring less CSI). While for $d = 100$ meters still very low t_{1000}^AC can be achieved, it strongly increases with increasing distance, as the path loss becomes very severe. Compared to the considered performance in the EX phase ($t_{1000}^\mathsf{EX} = 2.3\ \mu s$), which is constant for all number of streams and distances, it is now clearly visible, that for large distances the AC phase is the bottleneck for this setup (in contrast to [5], where the EX phase is the bottleneck).

This has a strong impact on the performance of the LUs, as can be seen in Fig. 6. It shows the spatial distribution of the LU rates within the city for the different distances, averaged over the EX and AC phase. While for $d = 100$ meters, the performance drop is not very severe yet (low t_{1000}^{AC} compared to t_{1000}^{EX}), the LUs strongly suffer for larger distances, as their RBAPs are accessed very frequently (t_{1000}^{AC} much higher than t_{1000}^{EX}). The larger the distance, the more the LUs suffer. Transmitting only 10 streams would decrease the number of affected LUs, but the basic problem remains the same.

To relieve the burden of the LUs, FRAS and SICS have been introduced in Section IV. The results of their performance in the AC phase is also shown in Fig. 3. FRAS has thereby been simulated with $N_{\mathrm{s}} = 50$ streams and $\delta = 3$, and SICS with $N_{\mathrm{s}} = 10$ streams. The different number of streams is due to the fact, that we have chosen the solution for each scheme which performs better. As can be seen, FRAS performs much better in the AC phase, especially for large distances. While for FRAS, the LUs of the assigned active RBAPs are turned off, in SICS no LU is turned off. Only the interference from the own LU can be cancelled and the interference from all other LUs is still present. As the signal power of the MSs is very weak compared to the interference power, this has a strong impact on the achievable rates. Therefore, the performance in the AC phase is degraded compared to FRAS, although FRAS can not always use the best RBAPs (active RBAPs can only be used in one of δ AC phases). This is also the reason why SICS with only 10 streams performs better than SICS with 50 streams. Due to the lower transmit power per stream but with the same amount of interference in the network, the achievable rate drops for 50 streams.

Compared to the original scheme, both LU performance enhancement approaches suffer from the increased interference in the AC phase. However, the loss in the performance for the MSs in the hotspot is compensated by the increase in performance for the LUs. Fig. 7 shows the spatial distribution of the LU rates for different distances for FRAS. Although still a degradation of the LU performance can be observed (as still some LUs have to be turned off in each AC phase), it is much smaller than in the original scheme. However, the area in which the LUs suffer is increased, as FRAS resorts on more RBAPs over the δ AC phases. For SICS, nearly no performance drop can be observed anymore. Only a very slight degradation for $d = 100$ meters is visible, where the MS signal is still strong. For larger distances, the AC signal is very weak compared to the LU signals and the noise. Hence, the performance drop of the LUs with SIC is very small.

Combining t_{1000}^{AC} with t_{1000}^{EX} leads to the final achievable rates shown in Fig. 4 which also shows the performance of TDMA. As t_{1000}^{EX} is constant for all number of streams and all schemes (except TDMA), the original scheme with $N_{\mathrm{s}} = 50$ outperforms all others in terms of achievable rate for the MSs in the hotspot (as already seen in Fig. 3). For all schemes, the performance strongly decreases with distance. Compared

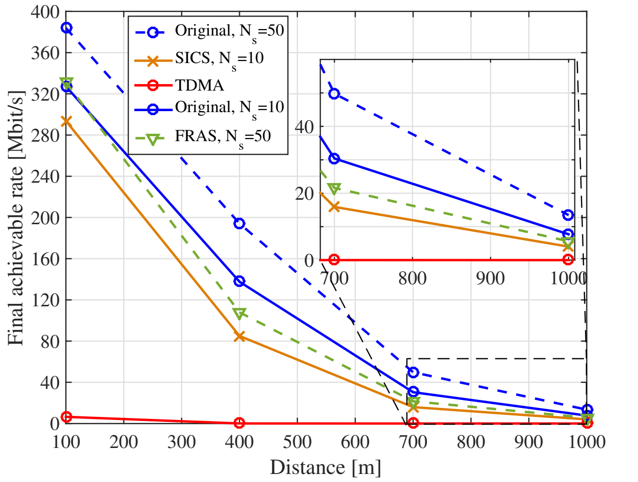

Fig. 4. Distance dependency of the final achievable rates for $N_{\mathrm{MS}} = 100$.

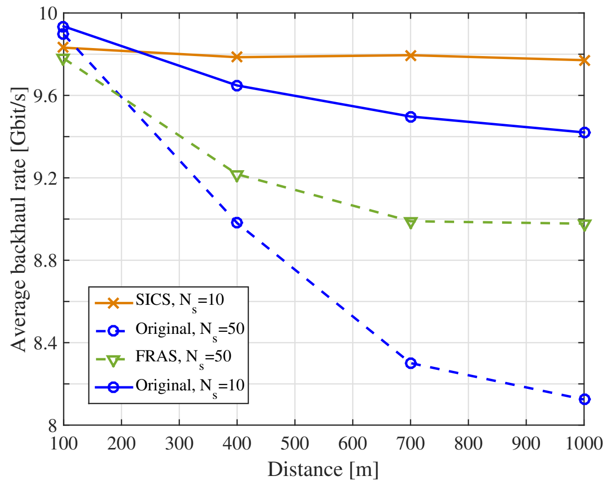

Fig. 5. Distance dependency of the backhaul rates for $N_{\mathrm{MS}} = 100$ nodes.

to the TDMA scheme, the gain is huge, as with TDMA only one stream is transmitted, lower power is available and no array gain can be achieved.

Fig. 5 compares the average backhaul rates, i.e. the sum rate of all RBAPs in the system averaged over the EX and AC phases. It shows that with increasing distance, the backhaul rate of the original scheme with $N_{\mathrm{s}} = 50$ suffers the most. In this scheme, many LUs are turned off frequently. As the MSs in the hotspot can only achieve very low rates compared to the LUs (especially at large distances), this leads to a strong drop of the backhaul rates. Consequently, FRAS has the second strongest drop over distance. For the original scheme with $N_{\mathrm{s}} = 10$, the drop in the backhaul rates is much lower, as less LUs have to be turned off. For SICS finally, nearly no drop can be observed, as no LUs have to be turned off and their rates do not significantly drop.

VI. Conclusions

User cooperation combined with traffic offloading is a reasonable approach to serve users in a remote traffic hotspot outside but close to a city. Large gains can be achieved compared to a TDMA approach. However, due to the high path

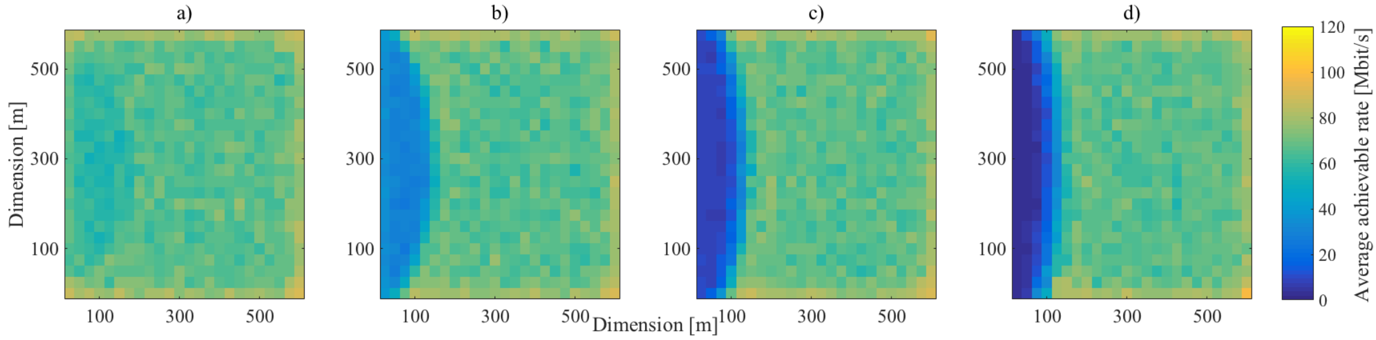

Fig. 6. Spatial distribution of LU rates of the original scheme, averaged over the EX and AC phases for $N_{\mathrm{MS}} = 100$ and $N_{\mathrm{s}} = 50$ at different distances: a) 100 meters, b) 400 meters, c) 700 meters, d) 1000 meters.

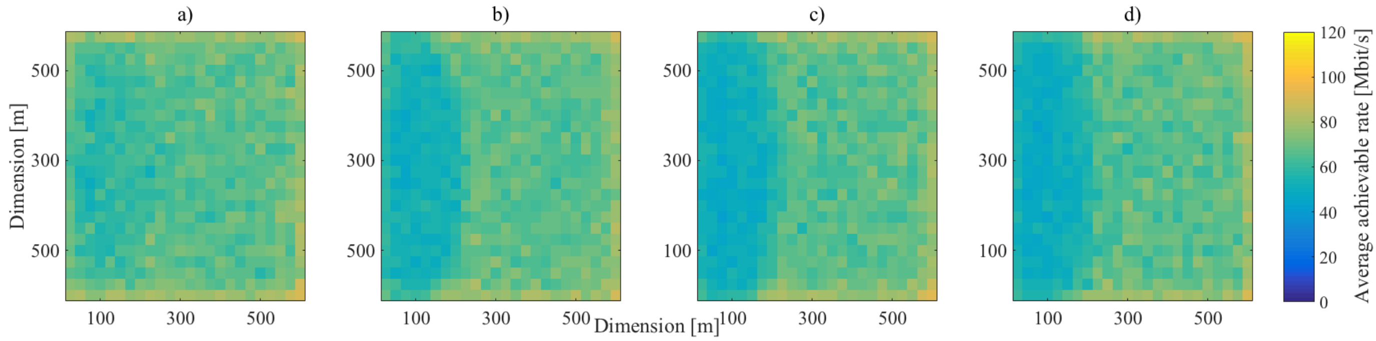

Fig. 7. Spatial distribution of LU rates for FRAS, averaged over the EX and AC phases for $N_{\mathrm{MS}} = 100$ and $N_{\mathrm{s}} = 50$ at different distances: a) 100 meters, b) 400 meters, c) 700 meters, d) 1000 meters.

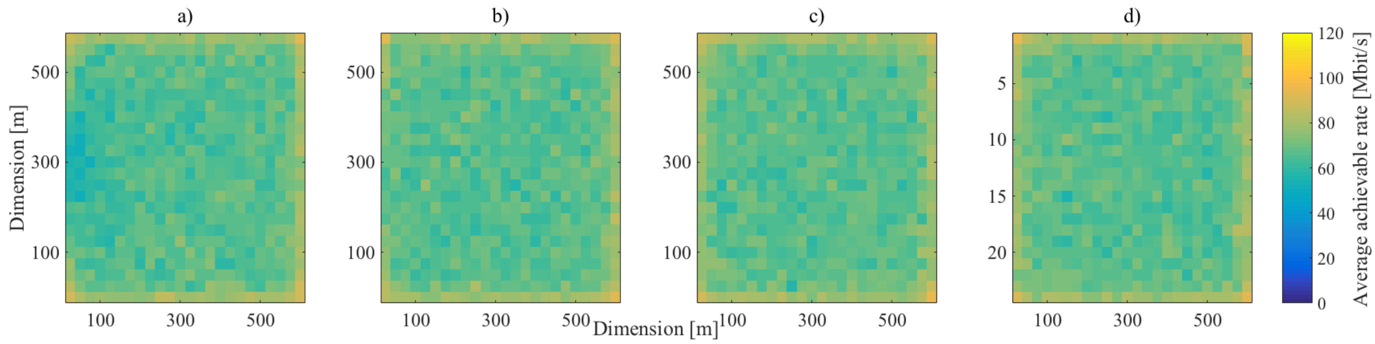

Fig. 8. Spatial distribution of LU rates for SICS, averaged over the EX and AC phases for $N_{\mathrm{MS}} = 100$ and $N_{\mathrm{s}} = 10$ at different distances: a) 100 meters, b) 400 meters, c) 700 meters, d) 1000 meters.

loss at large distances, the AC phase becomes the bottleneck of the protocol and the performance strongly drops. As the signal from the hotspot is very weak at large distances, the scheme is very sensitive to interference. Therefore, if the interference of the LUs is not reduced, the hotspot performance strongly suffers. On the other hand, if the LUs are turned off frequently for interference reduction, their performance is significantly decreased. With reasonable schemes, the performance of the LUs and the MSs can be carefully traded off. Note, that the drastic performance drop with distance is partially caused by the rather pessimistic channel model with very high path loss coefficient (Winner II, scenario C2 [9]).

References

[1] Ericsson, "Ericsson mobility report," (2015). [Online]. Available: www.ericsson.com

[2] I. Hwang, B. Song, and S. Soliman, "A holistic view on hyper-dense heterogeneous and small cell networks," *Communications Magazine, IEEE*, vol. 51, no. 6, pp. 20–27, June 2013.

[3] A. Ghosh *et al.*, "Millimeter-wave enhanced local area systems: A high-data-rate approach for future wireless networks," *Sel. Areas in Comm., IEEE Journal on*, vol. 32, no. 6, pp. 1152–1163, June 2014.

[4] F. Rusek *et al.*, "Scaling up MIMO: Opportunities and challenges with very large arrays," *Signal Processing Magazine, IEEE*, vol. 30, no. 1, pp. 40–60, Jan 2013.

[5] T. Rüegg, Y. Hassan, and A. Wittneben, "User cooperation enabled traffic offloading in urban hotspots," in *Submitted*, February 2016.

[6] P. Mitran, H. Ochiai, and V. Tarokh, "Space-time diversity enhancements using collaborative communications," *Information Theory, IEEE Transactions on*, vol. 51, no. 6, pp. 2041–2057, June 2005.

[7] M. Dohler, "Virtual antenna arrays," *Ph.D. dissertation, Kings College London, Univ. London*, Nov 2003.

[8] M. Sadek, A. Tarighat, and A. Sayed, "A leakage-based precoding scheme for downlink multi-user MIMO channels," *IEEE Trans. on Wireless Communications*, vol. 6, no. 5, pp. 1711–1721, 2007.

[9] P. Kyösti *et al.*, "WINNER II channel models," *Tech. Rep. IST-4-027759 WINNER II D1.1.2 V1.2 Part I Channel Models*, Sep 2007.