

Resource Allocation Schemes for Infrastructure Based Relay Networks

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Abstract—In this paper, three different resource allocation schemes (RASs) are introduced for the FDD downlink of an infrastructure based amplify-and-forward relay network in a multi-cell Manhattan street grid scenario. Firstly, a non-adaptive RAS with predefined and fixed TDMA frame structures for all cells of the network is introduced. Secondly, the non-adaptive RAS is extended by an intra-cell reuse of radio resources. Thirdly, an adaptive RAS is proposed which adapts to changing traffic load distributions in each single cell of the network. It is shown that applying coordination across cells yields in a significant performance gain in terms of cell throughput for both non-adaptive RASs. The adaptive RAS improves the overall performance especially for networks with few high-rate subscriber stations (SSs) and provides more fairness among all SSs. When deactivating coordination across cells, which is an interesting case for practical applications, the adaptive RAS shows the least relative performance degradation among all RASs.

I. INTRODUCTION

Infrastructure based relaying is a promising approach to provide the high data rate coverage requirements of beyond 3G mobile radio systems and to overcome the signal range problem for high center frequencies [1]. In relay networks, a base station (BS) and a subscriber station (SS) which is out of reach of its BS communicate via a relay station (RS). In this paper, an amplify-and-forward (AF) relay network is considered, where the RS retransmits an amplified version of its receive signal from the BS to the SS and vice versa. Compared to decode-and-forward (DF) relay networks, which require decoding and re-encoding at the RS, AF relay networks require simpler and cheaper RSs which makes them promising for practical applications [2].

Currently, a task group develops a proposal for standardization of relaying in IEEE 802.16 metropolitan area networks (MANs) [3][4]. In this paper, the performance in terms of user and cell throughput (TP) of an infrastructure based AF relay network for IEEE 802.16 with multiple cells in the frequency division duplex (FDD) downlink of a Manhattan street grid scenario is analysed. Assuming a network with two hops in maximum, each SS is supplied by the best received access point (AP) in terms of average signal power, which is either a BS in case of a one hop BS-SS link or a RS in case of a two hop BS-RS-SS link. Since there are multiple transmitting APs in the downlink of a single cell and since two mutually orthogonal

channel resources are required for a two hop BS-RS-SS link, resource allocation schemes (RASs), which are adapted to these requirements, have to be developed for infrastructure based AF relay networks.

In [5], Schultz et al. propose a non-adaptive time division multiple access (TDMA) RAS in infrastructure DF relay networks. They introduce coordination across cells (CAC) where TDMA frames of adjacent cells are coordinated in time that way that strong mutual interferers from adjacent cells are assigned to different time-slots (TSs). Through CAC, inter-cell interference can be reduced significantly which allows to reuse the same frequency spectrum in all cells of the network leading to an increase of the spectral efficiency of the system. However, the RAS in [5] cannot be applied in AF relay networks as it is designed for BS-RS links which use higher modulation and coding schemes (MCSs) than the RS-SS links, i.e., the RS-SS links require more TSs than the BS-RS links. Furthermore, the non-adaptive RAS shows reduced flexibility to non-uniform traffic load distributions in the cells, as it does not adapt the frame structure to the traffic load [6].

In this paper, three new RASs are proposed which are suitable for AF relay networks. For the first RAS, which is non-adaptive, the available TSs are shared equally among all APs of a cell and no intra-cell reuse is applied. CAC is applied with two different fixed types of frame structures. The two different types can be distinguished by the order of the transmitting APs and are used that way that inter-cell interference is reduced in adjacent cells. For the second RAS, similar to [5], the available TSs per AP of the non-adaptive RAS is increased by introducing intra-cell reuse of TSs for RSs which are weak mutual interferers in the same cell. For the third RAS, the number of TSs assigned to each AP is adapted to the traffic load distribution of the cells, i.e., to an AP with a high number of assigned SSs more TSs are allocated than to an AP with less assigned SSs. As CAC requires high effort in practical applications, the impact of deactivating CAC is analysed for all proposed RASs in this paper, too.

The paper is organized as follows: In Section II, the considered Manhattan street grid scenario and its impacts on the design of the TDMA frame structures are described. Section III introduces the new TDMA RASs which are analysed by means of simulations in Section IV. Section V finally concludes this work.

II. RELAY NETWORK SCENARIO

In this section, the considered Manhattan scenario which is typical for dense urban environments, is described in detail. Although its topology directly influence the design of the TDMA frame structures in Section III the basic conclusions can be transferred to other scenarios. The Manhattan scenario consists of regularly arranged blocks of houses in an orthogonal street grid. The BSs and RSs are assumed to be located at crossing centers, each providing line-of-sight (LOS) links to SSs in one horizontal and one vertical street. The BSs as well as the RSs are installed below the average rooftop height, e.g., on lamp masts or traffic lights, giving the characteristics of a typical dense urban micro cell around each AP. As depicted in Fig. 1(a), cell k , $k = 1, \dots, K$, consists of one BS^(k) and four RSs, RS m ^(k), $m = 1, \dots, M$ with $M = 4$, each having a LOS link to BS^(k). Fig. 1(b) gives

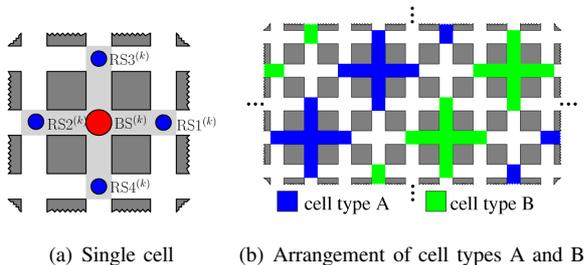


Fig. 1. Manhattan grid street grid scenario with grey blocks of houses, one BS (large dot) and four RSs (small dots) per cell

the arrangement of multiple of these cells in a multi-cell scenario where the center and the endings of the crosses indicate the BS and RSs positions in a single cell, respectively. Let us consider a single cell which is surrounded by 8 directly adjacent cells. The adjacent cells can be distinguished into 2 different kinds. (Note that this distinction is different to the distinction of cell types A and B in Fig. 1(b) which is required and introduced in Section III.) Firstly, there are 4 adjacent cells which have a BS located on the same street as the BS of the considered cell. This kind of adjacent cells has 3 APs which have LOS links to 3 APs of the considered cell and two APs each with LOS links to one of the remaining two APs of the considered cell. Secondly, there are 4 adjacent cells which have a BS located on a connection line to the BS of the considered cell with a relative angle of 45 degrees. In this kind of adjacent cells, each RS has only one LOS link to one RS of the considered cell. Note that for LOS links the propagation pathloss is much smaller than for non-line-of sight (NLOS) links of the same distance, which directly influences the interference performance. Among other criteria, this characteristic of the cell arrangement is taken into account for the TDMA frame design in Section III.

III. TDMA RESOURCE ALLOCATION SCHEMES

In this section, the FDD downlink in an AF relay network with the topology described in Section II is considered. In order to achieve a high spectral efficiency

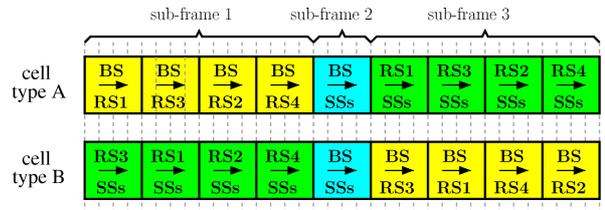


Fig. 2. Frame structures of cell type A and cell type B for NRA with $N = 36$ and $N_{RS}^{NRA} = N_{BS}^{NRA} = 4$

of the system, as in [5] it is assumed that the available frequency spectrum of the FDD downlink is used in all cells of the network. If it is necessary, the transmission of the different APs of the same cell can be separated in time domain, i.e., each AP transmits during a specified number of TSs which are arranged in a TDMA frame consisting of N orthogonal TSs in total. In the following, three different RASs are proposed where a single TDMA frame can be always subdivided into three sub-frames: one for the first hop of all BS-RS-SS links, one for the second hop of all BS-RS-SS links and one for the direct BS-SS links.

A. Non-Adaptive Resource Allocation

For non-adaptive resource allocation without intra-cell reuse (NRA), it is assumed that the TS allocation in the frame is fixed for each cell. To each RS^(k) in the network the same number $N_m^{(k)}$ of TSs is allocated, i.e., $N_m^{(k)} = N_{RS}^{NRA}$. In an AF network, this means that there are N_{RS}^{NRA} TSs for the BS-RS links of each RS as well as N_{RS}^{NRA} TSs for the RS-SS links of each RS. The number $N_0^{(k)}$ of TSs allocated to BS^(k) is also the same in all cells, i.e., $N_0^{(k)} = N_{BS}^{NRA}$, but can be different to N_{RS}^{NRA} . Under these assumptions, the overall number of TSs per frame in NRA is given by

$$N = N_{BS}^{NRA} + 2MN_{RS}^{NRA}. \quad (1)$$

The factor 2 in Eq. (1) comes from the fact that two orthogonal TSs are required for the BS-RS-SS links. At each AP, for packet switched services the SSs are served according to a round-robin scheduler [7] independent of the other APs. For this scheduler, all SSs at one AP are arranged in a queue which is polled in a cyclic order, i.e., at each AP, the assigned SSs share the available TSs uniformly among each other.

In the following, it is assumed that CAC is activated. Using CAC, inter-cell interference in the network can be planned and reduced to a minimum. For this purpose, two different cell types A and B are introduced which use TDMA frames with different orders of the transmitting APs. The cell types A and B are arranged in the Manhattan grid as depicted in Fig. 1(b). All TSs in the frame are allocated that way that mutually weak interferers from cell types A and B use the same TSs which leads to the two different frame structures for cell types A and B depicted in Fig. 2. In sub-frame 1, the BSs of cell type A transmit to their RSs while the RSs of

cell type B transmit to their assigned SSs. In sub-frame 2 of both cell types A and B the BSs transmit to the SSs which have direct BS-SS links. In sub-frame 3, the RSs of cell type B transmit to their assigned SSs while the BSs of cell type A transmit to their RSs. Through this frames structures, firstly the SSs are always interfered by the BSs of adjacent cells and are never interfered by a LOS RS of an adjacent cell, which would be the worst case interference in the considered Manhattan scenario. Secondly, the RSs are always interfered by weak NLOS RSs from adjacent cells, e.g., while $RS1^{(k_A)}$ from cell type A receives from its $BS^{(k_A)}$, $RS3^{(k_B)}$ from cell type B, transmits to its assigned SSs.

NRA is an efficient RAS for uniform traffic load distribution over all APs in the network as interference is reduced to a minimum if CAC is activated. However, it is not efficient for changing traffic load distributions in the network since its frame structure is fixed which leads to a waste of resources if, e.g., a RS has no assigned SSs at a time. If the frames in each cell have random and independent starting times which is defined as the case of deactivated CAC inter-cell interference increases and the performance of NRA degrades.

B. Non-Adaptive Resource Allocation with Intra-Cell Reuse

In order to increase the available TSs per AP, the principle of NRA is extended by an intra-cell reuse leading to non-adaptive resource allocation with intra-cell reuse (NRAR). Similarly to NRA, in sub-frame 1 of NRAR each BS transmits consecutively to its assigned RSs using the same number $N_m^{(k)}$ of TSs for each RS, i.e., $N_m^{(k)} = N_{RS}^{NRAR}$. Sub-frame 2 is allocated to the direct BS-SS links and consist of $N_0^{(k)} = N_{BS}^{NRAR}$ TSs, which can be different to N_{RS}^{NRAR} . In sub-frame 3, two RSs of the same cell are allocated to the same TSs. Assuming the AP locations from Fig. 1(a), $RS1^{(k)}$ and $RS3^{(k)}$ on the one hand and $RS2^{(k)}$ and $RS4^{(k)}$ on the other hand are allocated to the same TSs since SSs assigned to $RS1^{(k)}$ and $RS2^{(k)}$ have NLOS links to interfering $RS3^{(k)}$ and $RS4^{(k)}$ and vice versa. Under these assumptions, the overall number of TSs in NRAR is given by

$$N = N_{BS}^{NRAR} + \frac{3}{2}MN_{RS}^{NRAR}. \quad (2)$$

The factor 3/2 in Eq. (2) comes from the fact that two orthogonal TSs are required for the BS-RS-SS links while sub-frame 3 is only half as long as sub-frame 1 due to the intra-cell reuse. The resulting frame structure of NRAR is depicted in Fig. 3.

On the one hand, assuming the same frame duration in NRAR and NRA to each AP a higher number of TSs is allocated in NRAR than in NRA due to the reuse in sub-frame 3. On the other hand, additional intra-cell interference appears which degrades the performance of SSs which are located near crossings that have LOS links to the supplying RS as well as to the intra-cell

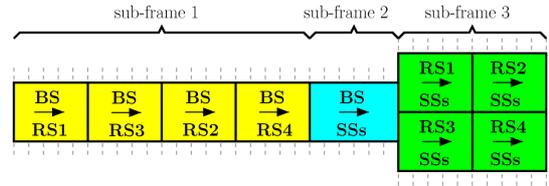


Fig. 3. Frame structure for NRAR with $N = 36$, $N_{RS}^{NRAR} = 5$ and $N_{BS}^{NRAR} = 6$

interferer. Since NRAR is non-adaptive, it is not efficient for changing traffic load distributions in the network.

C. Adaptive Resource Allocation

The following adaptive resource allocation (ARA) overcomes the inefficiency of NRA and NRAR for non-uniform traffic load distributions. For ARA, the TSs are allocated according to the traffic load distribution in each cell, i.e., to an AP which has a high number of supplied SSs a higher number of TSs is allocated than to an AP of the same cell with only few supplied SSs. Hence, if an AP has no SSs to supply, it gets no TSs and the resources are not wasted. The frame structure of ARA is designed independently in each cell of the network and depends on the number of SSs at each AP of the cell. Assuming $U_m^{(k)}$ SSs at $RSm^{(k)}$ and $U_0^{(k)}$ SSs at $BS^{(k)}$, the number of TSs $N_m^{(k)}$ and $N_0^{(k)}$ at each $RSm^{(k)}$ and $BS^{(k)}$, respectively, is individually given by

$$N_l^{(k)} = \left\lfloor N \frac{U_l^{(k)}}{2 \sum_{m=1}^M U_m^{(k)} + U_0^{(k)}} \right\rfloor \quad l = 0, \dots, M \quad (3)$$

where $\lfloor x \rfloor$ denotes the highest integer value which is smaller than or equal to x . The factor 2 in Eq. (3) comes from the fact that two orthogonal TSs are required for the BS-RS-SS links. If there are unused TSs after processing (3) for all $l = 0, \dots, M$, the remaining TSs

$$N_{rest}^{(k)} = N - N_0^{(k)} - 2 \sum_{m=1}^M N_m^{(k)} \quad (4)$$

are shared among all SSs in cell k , i.e., the next SSs in the round-robin scheduler are allocated to these TSs. As for NRA, two different frame structures for cell types A and B can be introduced also for ARA with activated CAC. In sub-frame 1 of cell type A, the RSs receive from their BS, in sub-frame 2 of cell type A, the BSs transmit to their assigned SSs and in sub-frame 3 of cell type A, the RSs transmit to their assigned SSs. For cell type B, sub-frame 1 and 3 are exchanged. However, since the number of TSs allocated to each AP is time-variant, the length of the sub-frames is determined individually in each frame and cell. Fig. 4 gives a random snapshot on two frame structures of cell types A and B. It can be seen that even if CAC is activated, mutual interference between LOS interferers cannot be avoided. In Fig. 4 for example, $RS2^{(k_B)}$ from cell type B transmits while $RS2^{(k_A)}$ from cell type A receives from its $BS^{(k_A)}$ although these two RSs are strong LOS interferers. However, since for AF

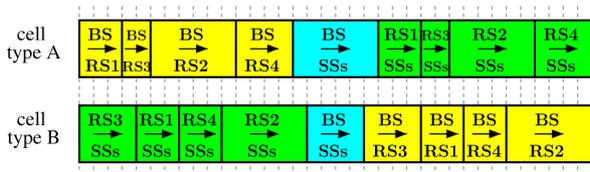


Fig. 4. Random snapshot on frame structures of cell types A and B for ARA with $N = 36$

TABLE I

ESSENTIAL PARAMETERS OF SIMULATED SCENARIO

Parameter	Value
Street width in Manhattan street grid	30 m
Block length in Manhattan street grid	200 m
BS / RS antenna height	5 m
SS antenna height	1.7 m
Model for BS-RS links	WINNER scenario B5b
Model for RS-SS links and BS-SS links	WINNER scenario B1
RS receive antenna gain	10 dBi
RS receive antenna front-to-back ratio	20 dBi
BS / RS transmit power	35 dBm
Noise power	-102 dBm
Center frequency	5 GHz
System bandwidth	3.5 MHz

relaying sub-frame 1 and 3 have equal length and since sub-frame 2 isolates sub-frame 1 from 3, as for NRA SSs are only interfered by BSs of adjacent cells which causes less interference at the SSs than interfering LOS RSs.

On the one hand, the performance of ARA in comparison to NRA is degraded due to additional interference at the RSs, but on the other hand, the available resources are used most efficiently in ARA as no TSs are wasted.

IV. SIMULATION RESULTS

In the following, the trade-off between resource efficiency and inter-cell interference for the introduced RASs is analysed in the Manhattan street grid scenario for the downlink of an IEEE 802.16 MAN [4] by means of simulations. The system consists of 32 cells arranged as indicated in Fig. 1(b) and the cells are wrapped around on a torus to avoid border effects. The SSs are uniformly distributed across the streets. The BSs and the RSs have omni-directional transmit antennas and the SSs have omni-directional receive antennas. However, in order to achieve significant coverage extension by relaying, directional receive antennas at the RSs are established [8]. The BS-RS links are modeled as stationary feeder links from street-level to street-level and the BS-SS links as well as the RS-SS links are modeled as in typical dense urban micro cells. The pathloss models are taken from IST WINNER project [9]. The essential simulation parameters are summarized in Tab. I. The signal-to-interference-and-noise ratio (SINR) at the SSs is mapped on the cell and user TP by means of the rapid estimation method for data capacity [10], where the TP vs. SINR curves are approximated by step-functions. IEEE 802.16 standard provides 7 MCSs summarized in Tab. II, which also gives the achieved TP depending on the minimum required SINR [10]. The frame duration is assumed to be 10 ms consisting of 147 OFDM symbols per frame where one OFDM symbol corresponds to one TS. 3

TABLE II

MODULATION CODING SCHEMES, TP VS. REQUIRED SINR [10]

MCS	Modulation	Code Rate	SINR	TP
1	BPSK	1/2	0.0 dB	1.40 Mbit/s
2	4-QAM	1/2	2.5 dB	2.82 Mbit/s
3	4-QAM	3/4	6.0 dB	4.22 Mbit/s
4	16-QAM	1/2	9.0 dB	5.64 Mbit/s
5	16-QAM	3/4	12.0 dB	8.46 Mbit/s
6	64-QAM	2/3	16.0 dB	11.29 Mbit/s
7	64-QAM	3/4	21.0 dB	12.69 Mbit/s

OFDM symbols per frame are used for the preamble and the frame control header in IEEE 802.16, while 144 OFDM symbols are available for data traffic. Note that further OFDM symbols will be required for signalling the downlink traffic map, but signalling for relaying is still an open issue in IEEE 802.16 [3]. However, since the signalling loss for the effective TP is the same for all RASs, signalling needs not to be considered for a fair comparison between the RASs. The 144 available TSs are shared equally among all APs including the BSs, which results in $N_{RS}^{NRA} = N_{BS}^{NRA} = 16$ for NRA, $N_{RS}^{NRAR} = 20$ and $N_{BS}^{NRAR} = 24$ for NRAR. Note that for simplicity but without loss of generality a full buffer data traffic model is assumed, i.e., each SS always requests and receives data in the downlink. Additionally, the round robin scheduler leads to significantly different transferred data volumes per SS in the considered cellular scenario, since SSs under good radio link conditions achieve higher data rates than SSs under poor radio link conditions. Consequently, the achieved cell TP is too optimistic [10].

In the following, the impact of CAC to the different RASs is considered. Figures 5(a) and 5(b) give the cumulative density function (cdf) of the cell TP for the introduced RASs with 300 SSs and 1000 SSs in the overall network, respectively. The solid lines correspond to RASs with activated CAC and the dashed lines correspond to RASs with deactivated CAC. For deactivated CAC, the inter-cell interference for all RASs is increased since strong LOS interference cannot be avoided which leads to a degradation of the cell TP. Obviously, CAC significantly improves the cell TP for all RASs. However, the least relative performance improvement through CAC appears for ARA, since different cells have different frame structures in ARA which already leads to higher intercell-interference even in case of activated CAC.

In the following, the 3 RASs are compared with each other. NRAR with activated and deactivated CAC outperforms NRA in terms of cell TP. Hence, the gain from additional TSs per AP due to the intra-cell reuse is higher than the performance degradation due to additional intra-cell interference. Comparing NRA and ARA shows that the performances of both RASs strongly depends on the number of SSs in the network. For 300 SSs which corresponds to the case of few high-rate SSs in the network, NRA has a lower cell TP than ARA. This comes from the fact that there is a high probability for APs in NRA, which have no assigned SSs. This leads to unused TSs and the available resources are wasted. For realistic data traffic models and systems, which are

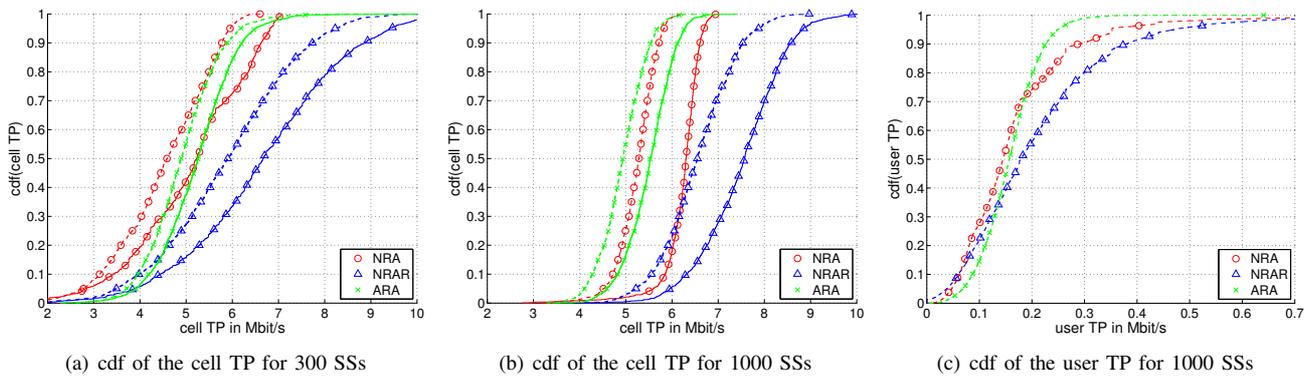


Fig. 5. cdf of cell and user TP, solid lines: RASs with activated CAC, dashed lines: RASs with deactivated CAC

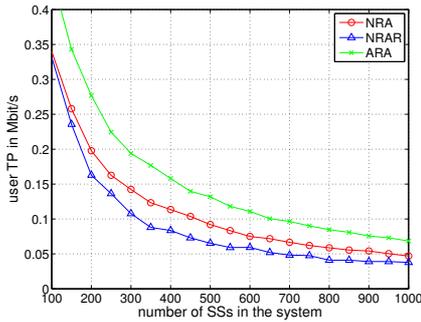


Fig. 6. maximum user TP for the 5th percentile of SSs depending on the number of SSs in the network; deactivated CAC

not fully loaded, it is expected that this effect is even more pronounced. For 1000 SSs which corresponds to the case of multiple low-rate SSs in the network, NRA with activated CAC outperforms ARA since the inter-cell interference is significantly reduced and the probability of unused TSs is close to zero. Even in case of deactivated CAC, NRA performs slightly better than ARA since the number of TSs assigned to all APs for NRA is constant in all cells which reduces the probability of strong LOS interference for NRA.

The following considerations focus on the case of deactivated CAC since CAC requires high effort in practical applications. For the high-rate SSs in Fig. 5(a), the cell TP of NRAR is even lower than the cell TP of ARA in about 10% of the cases for deactivated CAC. This comes from the fact that there are few SSs with excessive interference for NRAR due to the intra-cell reuse. Hence, the good overall performance in NRAR comes at the cost of few SSs with poor radio link conditions. This observation is confirmed by the user TP of all RASs with deactivated CAC for 1000 SSs which is depicted in Fig. 5(c). Here, it can be seen that ARA outperforms NRAR for 30% of the SSs and NRA for 73% of the SSs which means that ARA also achieves a higher fairness among the low-rate SSs. For NRAR, even 1% of the SSs does not get into the system as its SINR is too low. In Fig. 6, the maximum user TP for the 5th percentile of the cdf of the user TP is plotted depending on the number of SSs in the network, i.e., the plot gives the minimum user TP which is exceeded by 95% of the SSs. For all numbers of SSs in the network, NRA shows a higher user TP than NRAR, while NRAR has a higher user TP than NRAR which significantly

suffers from strong intra-cell interference. Hence, ARA provides more fairness among the SSs.

V. CONCLUSION

In this paper, different RASs for an infrastructure AF relay network in a Manhattan street grid scenario are introduced. It is shown that applying CAC yields in significant performance gain in terms of cell TP for non-adaptive RASs with fixed frame structures in all cells of the network. However, since non-adaptive RASs do not adapt to changing traffic load in the cells, allocating the radio resources depending on the traffic load distribution improves the overall performance especially for networks with few high-rate SSs. The proposed adaptive RAS shows the least relative performance degradation for deactivated CAC, what is important from the practical point of view as CAC requires a high effort. Additionally, the adaptive RAS provides more fairness among the SSs as there are less SSs with low user TP.

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