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Downlink MIMO in IEEE 802.11ac-based Infrastructure Networks

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Abstract

The new IEEE 802.11ac standard offers improvements like the use of large bandwidth and advanced Multiple-Input and Multiple-Output (MIMO) signal processing. However, the use of wide channels in a dense 802.11 network increases co-channel interference and contention. Fortunately, MIMO signal processing enables interference management where Access Points (AP) on the same channel can cancel their interference at each other's Stations (STA), while beamforming their signal to their own STA.

We focus on the Downlink (DL) of 802.11ac-based infrastructure networks with unequal network load at the APs and show that a combination of the two physical layer MIMO techniques, namely DL multi-user MIMO and interference nulling, can significantly improve the DL performance. The proposed algorithm performs in two steps. First, it identifies in each cell the spatial compatible STA groups which can be served by MU-MIMO in the DL. Second, the unused degree of freedom of lightly loaded APs is utilized to perform interference management by means of null steering towards STAs in highly loaded adjacent cells. The algorithm takes the overhead due to 802.11ac compliant channel sounding into account when computing the set of STAs to be nulled.

Our simulation results from an indoor hotspot environment conclude that the proposed scheme outperforms state-of-the-art protocols especially in high density AP deployments. Moreover, the proposed method is fully compatible with commodity 802.11ac network cards that implement MU-MIMO and requires only slight modifications to the 802.11 MAC layer.

Contents

Chapter 1

Introduction

Wireless traffic explodes as novel applications like multimedia streaming applications and cloud storage appear. Offloading network traffic to wireless small cells using technologies like IEEE 802.11 proves to be useful. The new WiFi amendment is 802.11ac which offers very high peak data rate by using MIMO transmissions (up to 8 antennas), higher order modulation (256-QAM), and larger bandwidth (up to 160 MHz). Increasing the channel width is attractive because it increases the peak data rate for individual Stations (STA). But, using wide channels in a dense 802.11 network can have the opposite effect by reducing the total number of channels available for reuse among co-located and adjacent Access Points (AP) and can reduce overall network capacity due to co-channel interference and contention.

The 802.11ac standard includes a variety of MIMO modes which can be divided into open- and closed-loop schemes. The latter is more efficient but requires a complex channel sounding procedure to obtain Channel State Information (CSI) at transmitter side. However, the wireless channel varies over time due to the mobility which causes a deterioration in performance of closed-loop beamforming schemes. Therefore, the CSI needs to be updated frequently. The overhead to keep CSI up-to-date can become severe especially in a Multi-User MIMO (MU-MIMO) scheme, where the channel needs to be sounded towards multiple STAs.

In practice, the number of active STAs served by an AP is not the same. There are locations where APs serve only a small number of STAs, i.e. floors, and hotspots where only a few APs have to serve a large number of STAs, i.e. conference rooms. The lightly loaded APs, i.e. those where the number of active STAs is smaller than the number of antennas at the AP, can use their unused degree of freedom to perform interference management. In particular such APs can perform interference nulling towards STAs located in adjacent hotspot cells resulting in reduced co-channel interference and improved SINR. Hence, to keep the channel sounding overhead meaningful low, the STAs to be nulled must be carefully selected.

Contributions: In this paper we show that the combination of two physical layer MIMO techniques, i.e. MU-MIMO and nulling, is beneficial in the downlink (DL) of dense 802.11ac-based infrastructure WiFi networks with unequal network load. The proposed algorithm performs in two steps. First, the set of active STAs in each cell (AP) are grouped in spatially compatible groups which can be served by DL MU-MIMO. These STAs are periodically sounded by the AP they are associated with in order to keep instantaneous CSI up-to-date. Second, to achieve high spectral efficiency a frequency reuse one scheme together with interference management where the unused degree of freedom of lightly loaded cells/APs is utilized to perform null steering towards STAs in highly loaded adjacent cells. In order to keep the channel sounding overhead low, the proposed algorithm estimates the STAs to be nulled using just the average received power values. The proposed method is analyzed by means of simulations in an indoor hotspot environment and compared to state-of-the-art.

Chapter 2

MIMO signal processing

In the following we give a short introduction into MIMO processing techniques. In general, we can distinguish between open- and closed-loop MIMO transmissions. With the later the transmitter has channel state information and can therefore use precoding to change how its signal is received at a particular receiver node. With 802.11ac the precoding matrix can be selected to beamform the signal towards a single user (SU-MIMO), whereas with MU-MIMO also known as Space-Division Multiple Access (SDMA) the transmitter can send different signals simultaneously towards multiple users without causing interference by using the transmit beams (Fig. 2.1). A common beamforming technique is the Zero-Forcing [3] that introduces nulls in the directions of the interferers.

For the focus of this paper the possibility to use MIMO for interference management is important. With the help of beamforming a transmitter can perform interference nulling which allows him to completely cancel (i.e., null) its signal at a particular receiver (Fig. 2.1). This is a promising way to manage interference between co-located cells/APs using the same RF spectrum.

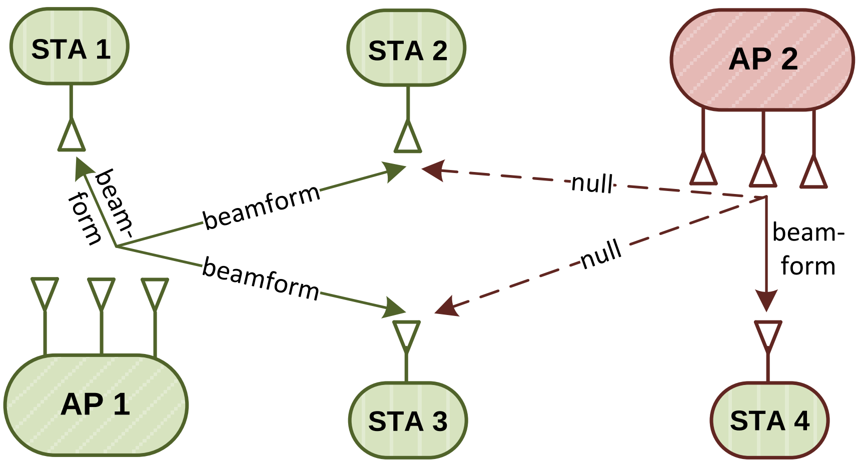

Figure 2.1: AP 1 performs MU-MIMO by steering multiple beams towards its STAs 1-3 whereas AP 2 beamforms its signal to STA 4, while nulling interference to STA 2 & 3.

Chapter 3

Channel Sounding in IEEE 802.11ac

802.11ac defines a standard way to perform channel sounding in order to obtain CSI at transmitter side to be able to perform closed-loop MIMO schemes. To measure the channel the transmitter, usually the AP, sends a sounding packet including only preambles and receives a Compressed Beam (CB) frame with modified CSI from the probed receiver(s), usually STA(s). Fig. 3.1 shows the required frame exchange to perform channel sounding in 802.11ac. Single user sounding is performed by sending a NDPA and NDP frame which is replied by the STA with CB frame. In multi-user sounding additional users can be sounded. For each additional user a BF-Poll is transmitted which is replied by a CB.

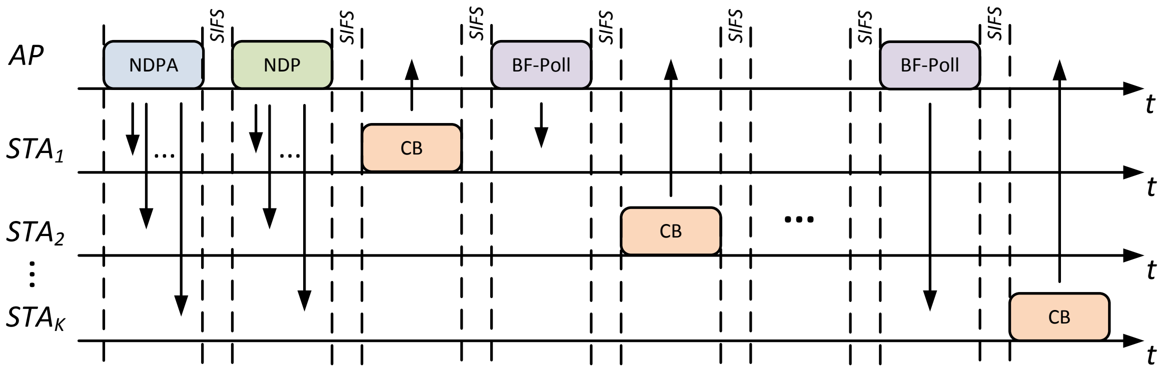

Figure 3.1: Channel sounding in IEEE 802.11ac.

Fig. 3.2 shows the channel sounding overhead for different of antennas, number of probed STAs and sounding update interval σ. Here we assumed a channel bandwidth of 20 MHz and the STAs to be sounded having medium SNR, i.e. the CB packets are encoded using 64-QAM 2/3. From the results we can see that as long as the update interval δ for the sounding procedure is low, i.e. $\delta = 10\,\mathrm{Hz}$, the overhead remains well below 2.5% even with 12 STAs to be probed and 12 antennas at AP. The situation dramatically changes if the sounding has to be performed 100 times per second e.g. due higher mobility. In such a scenario the overhead can already consume 25% of the airtime and hence leaving only 75% for data communication.

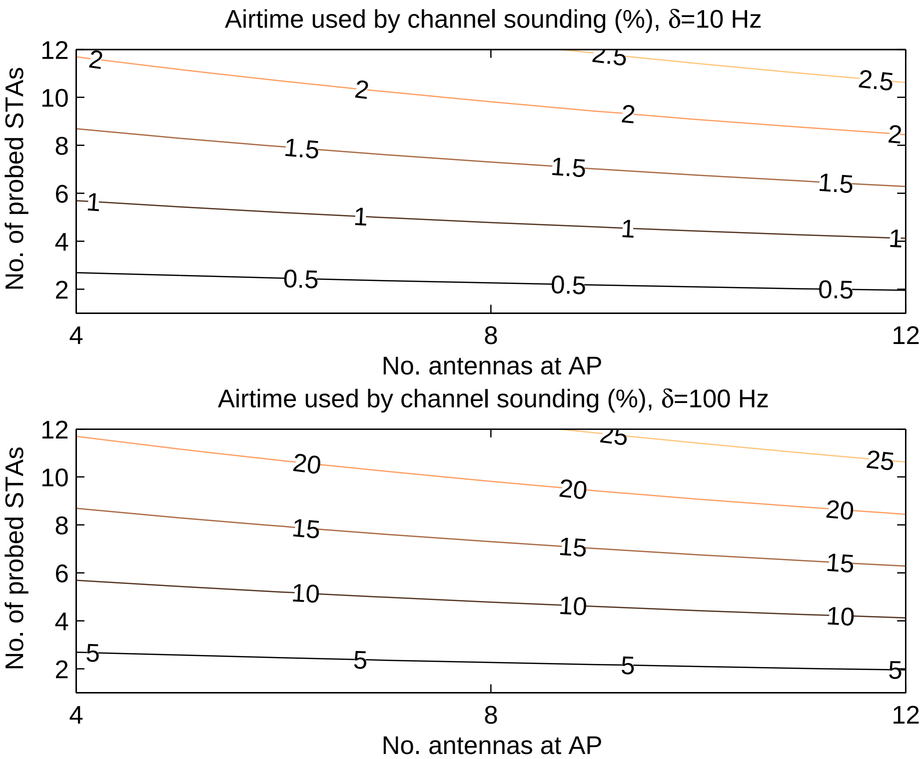

Figure 3.2: Channel sounding overhead in IEEE 802.11ac.

Chapter 4

System Model

We consider the Downlink (DL) of a dense 802.11ac infrastructure network consisting of multiple APs with overlapping cells. Each AP is equipped with M antennas (Uniform Linear Array, ULA) whereas the STAs have just a single antenna. Next, the number of active STAs served by each AP is not the same. There are locations where APs serve only a small number of STAs, i.e. floors, and hotspots where only a few APs have to serve a huge number of STAs, i.e. conference room. Further, we assume that the total available spectrum can be used simultaneously in an efficient way (e.g. using channel bonding as specified in 802.11ac). Finally, all the APs are connected to a wired backbone, e.g. Ethernet, and hence can be efficiently controlled by a centralized controller.

Chapter 5

Problem Statement

Our main objective is to maximize the average DL rate in each cell which indicates the overall effectiveness of an AP. As we assumed a WiFi network with unequal network load our objective can be achieved by optimizing the DL throughput of highly loaded APs. In particular lightly loaded APs can perform interference nulling towards STAs located in adjacent hotspot cells/AP resulting in reduced co-channel interference and hence increased rate in hotspot cells.

However, selecting the most suitable MIMO transmission modes for each DL transmission in each cell is a complex task which depends on a multitude of aspects. Therefore, in order to reduce complexity we propose the following heuristic which leads us to a two-step approach (ref. Fig. 5.1):

1. ***Space-Division Multiple Access (SDMA) within a cell***: Serve the active STAs within each cell/AP using SDMA (also known as DL MU-MIMO) which is very effective as the APs are equipped with antenna arrays (ULA) whereas the STAs have just a single antenna. In particular we have to create spatially compatible SDMA groups, where each group consists of a set of active STAs which can be separated in the space domain.

2. ***Interference management***: Utilize unused degree of freedom of lightly loaded cells/APs. This is achieved by null steering towards STAs in highly loaded adjacent cells. In particular we have to estimate for each AP the most promising group of STAs to be nulled while taking the additional channel sounding overhead into account.

In *step one* we aim to optimize the resource allocation within a cell without considering any interference from neighboring cells. The objective is to find an optimal grouping (partition) of the set of active STAs into spatially compatible groups of STAs which can be efficiently served using SDMA [7]. The grouping of STAs can be accomplished by each AP independently and requires no coordination between APs. As all active STAs within a cell will be served via SDMA instantaneous CSI is already available at the AP side and can be used by the grouping algorithm to calculate the accurate SINR and bitrate.

In *step two* we aim to manage inter-cell interference. This requires a coordination in the channel access between co-located APs. As mentioned in [7] different SDMA groups need to be orthogonalized in time or frequency domain. Without loss of generality we assume time multiplexing whereas the channel is divided into superframes, each containing θ time slots one for each SDMA group, where θ is determined by the cell/AP with the largest number of SDMA groups, i.e. $\theta = max(\{|\mathscr{G}^k|, \forall k \in \text{AP}\})$. Note, in cells with less than θ groups, the same group is assigned to more than one time slot. Consider the following example with five and two SDMA groups in each cell respectively: $\text{AP} = \{1,2\}, \hat{\mathscr{G}}^1 = \{G_1^1, G_2^1, G_3^1, G_4^1, G_5^1\}, \hat{\mathscr{G}}^2 = \{G_1^2, G_2^2\}$. Here is $\theta = 5$ and the assignment of SDMA groups to time slots is as follows:

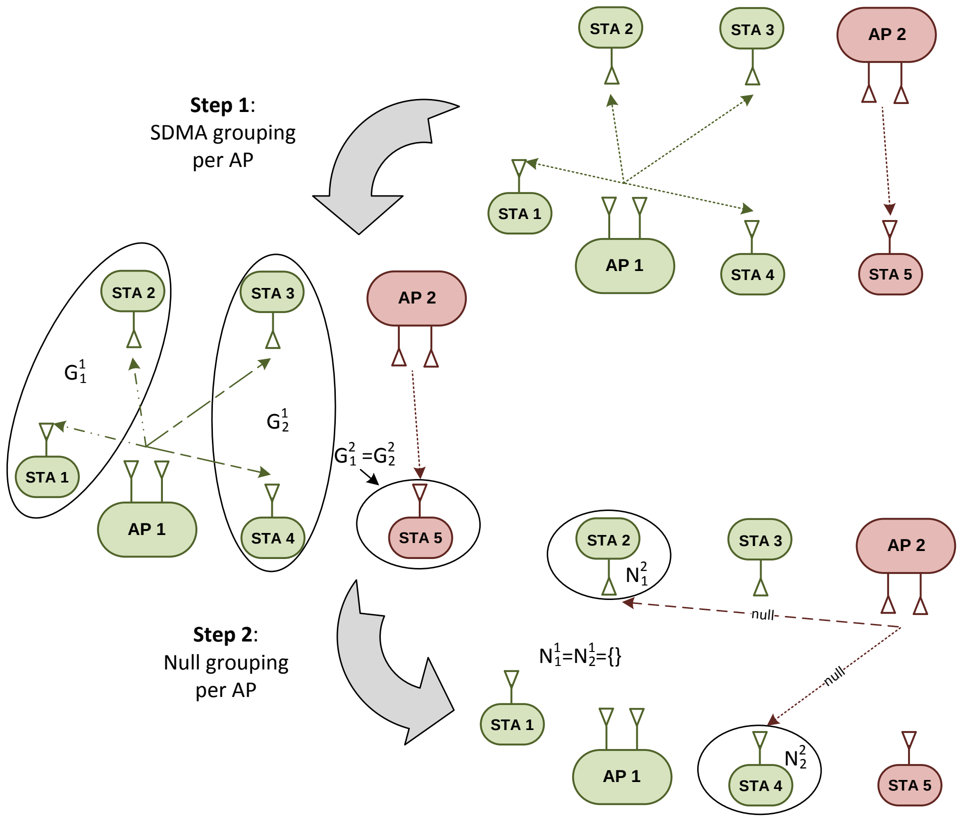

Figure 5.1: Illustrative example showing the two steps involed.

- AP 1: $\mathscr{G}^1 = \{G_1^1, G_2^1, G_3^1, G_4^1, G_5^1\}$
- AP 2: $\mathscr{G}^2 = \{G_1^2, G_2^2, G_1^2, G_2^2, G_1^2\}$

The actual interference management includes the estimation of the optimal set of STAs to be nulled by any AP in each time slot. This step cannot be performed by each AP independently; instead a global view on the network is required. Interference nulling requires instantaneous CSI at transmitter side. However, in contrast to SDMA nulling offers just a SINR gain and no spatial multiplexing gain. Therefore, the set of STAs to be nulled must be even more carefully selected to avoid the situation where the channel sounding overhead exceeds the gain from nulling. Note, the channel sounding from two different APs towards the same STA has to be serialized in time which further increases the overhead. This also means that any algorithm for computing the nulling groups cannot assume the availability of instanteneous CSI towards STAs in adjacent cells, i.e. the selection must be done using long-term channel statistics.

Next we give a formal description of our problem:

Instance: Given a set of APs $k \in \mathrm{AP}$ and the assignment of their SDMA groups to time slots, i.e. $\mathscr{G}^k = \{G_1^k, G_2^k, ..., G_\theta^k\}$, i.e. $1 \ldots \theta$ is the time slot index.

MCS index	Modulation	Code rate	SINR [dB]
0	BPSK	1/2	-3.83
1	QPSK	1/2	0
2	QPSK	3/4	2.62
3	16-QAM	1/2	4.77
4	16-QAM	3/4	8.45
5	64-QAM	2/3	11.67
6	64-QAM	3/4	13.35
7	64-QAM	5/6	14.91
8	256-QAM	3/4	17.99
9 (interpolated)	256-QAM	5/6	19.6

Table 5.1: Required SINR values for different MCS in 802.11ac (from: [6]).

Objective: Find set of nulling groups $\mathscr{N}^k = \{N_1^k, N_2^k, ..., N_\theta^k\}$ for each AP k and time slot $i = 1 \dots \theta$, $\mathscr{N} = \{\mathscr{N}^k | k \in \text{AP}\}$, such that the mean DL rate over the APs is maximized. Here $N_i^k \subseteq \{u | u \in U^h, \forall h \in \text{AP}, h \neq k\}$, i.e. the set of potential candidates which can be nulled by AP k in time slot i.

This optimization problem can be formulated as follows:

$$\mathscr{N} = \arg\max_{\mathscr{N}} \Big\{ \text{mean}(\{R_u^{k,j} \mid \forall u, \forall j\}) \mid \forall k \in \text{AP} \Big\} \tag{5.1}$$

subject to the maximum size of a null group which is limited to $|N_i^k| \leq M - |G_i^k|, \forall N_i^k \in \mathscr{N}^k$, i.e. the number of STAs being beamformed or nulled is restricted by the available number of antennas M at the AP. Moreover, $R_u^{k,j}$ is the DL rate achieved by STA u in group / time slot j served by AP k and is calculated as follows:

$$R_u^{k,j} = (1 - \Delta^k) \times \frac{1}{|\mathscr{G}^k|} \times \text{rate}(\gamma_u^{k,j}) \tag{5.2}$$

where $\gamma_u^{k,j}$ is the instantaneous SINR of STA u in group / time slot j after precoding by serving AP k and possibly nulling by adjacent APs, i.e. $u \in N_j^{k'}, k' \in \text{AP}$, which allows us to select the proper MCS and hence to calculate the bitrate at the physical layer rate$(\cdot)$. Moreover, we account for the overhead due to channel sounding by the term $(1 - \Delta^k)$ representing the available free airtime for data communication:

$$\begin{aligned}\Delta^k = \delta_{\text{UpdateRate}} \times \Big(& \sum_i \text{chan\_sound}(G_i^k, N_i^k) \\ & + \sum_{\forall k' \neq k, \mathscr{N}^{k'} \cap \mathscr{N}^k \neq \emptyset} \sum_i \text{chan\_sound}(G_i^{k'}, N_i^{k'}) \Big)\end{aligned} \tag{5.3}$$

where $\delta_{\text{UpdateRate}}$ is the required number of channel soundings per second which depends on the timescale of channel variations (e.g. due to mobility). Here we see that if a STA need to be sounded by more than AP the channel sounding process has to be serialized in time which further increases the overhead due to sounding.

Chapter 6

Proposed Approach

Next we give a detailed description of our proposed practical solution to the optimization problem from the previous section.

6.1 SDMA within a cell

The performance of SDMA depends heavily on the used terminal grouping algorithm. The optimal solution was shown to be NP-complete in [4]. Therefore, from the practical point of view we recommend to use a grouping heuristic like the Best Fit Algorithm (BFA) or even the lower complexity First Fit Algorithm (FFA) [4]. The channel towards each STAs in each terminal groups is sounded and the obtained instantaneous CSI is used to calculate the beamforming weights for each terminal group using e.g. the well-known Zero-forcing technique, i.e. $V = (H' \cdot \mathrm{inv}(H \cdot H'))$, normalized beamforming vectors with equal power allocation and number of users.

6.2 Interference management

Nulling groups must be carefully selected since the STAs to be nulled are in adjacent cells and therefore in general have a low SNR resulting in a large channel sounding overhead (r.t. Sec. 3). Our proposed algorithm tackles this challenge as following. First, it uses the already available DL instantaneous CSI from each APs towards the STAs in the SDMA groups (previous section). Second, it requires only average CSI from each AP towards each STA located in adjacent cells to be able to estimate the proper nulling groups. Note, that the average CSI can be efficiently obtained by overhearing packets uplink transmissions from neighboring cells. Hence, according to our approach the instantaneous CSI only towards the STAs to be nulled need to be estimated.

The full algorithm is given in Listing 1. It searches for the best nulling to be added to the global nulling configuration, i.e. $k \rightarrow u(h,i)$ which indicates a nulling by AP k towards STA u served by AP h on time slot i. The algorithm stops if the minimum average cell rate in the network cannot be further improved due to additional nulling. Function avg_rate($\cdot$), which calculates the expected average cell rate in DL is given in Listing 2. This function takes the additional channel sounding overhead due to nulling, the number of DL slots as well as intra- and inter-cell interference into account when calculating the average DL cell rate for a given cell/AP. Note, that due to the lack of instantaneous CSI from STA towards adjacent APs we use the average receive power to assess inter-cell interference (see line 18).

Complexity: The proposed algorithm has a complexity of $\mathcal{O}(|\mathrm{AP}|^4|\mathrm{STA}|^3)$, i.e. quartic with the number of APs and cubic with the number of STAs.

Algorithm 1 Algorithm estimates the nulling configuration, i.e. which STA will be nulled by which AP in which time slot, used by the interference management phase.

Require:
- $\mathrm{CSI}_{k\to u}, \forall k \in \mathrm{AP}, G_i^k \in \mathscr{G}^k, u \in G_i^k$ - the instanteneous CSI to each STA in each SDMA group (ref. step 1).
- $\tilde{P}^{\mathrm{rx}}_{k\to u}, \forall k \in \mathrm{AP}, u \in U^k$ - the average receive power from each AP towards any STA in communication range.

Ensure:
- $\mathscr{N}$ - the nulling configuration for each AP.

```
procedure nullGroupEst( )
    N_i^k ← ∅, ∀k ∈ AP, i = 1...θ                          ▷ nulling gr. per AP k + time slot i.
    while true do
        k*, i*, u* ← ∅                                      ▷ best: nulling AP, time slot, STA being nulled
        δ* ← 0                                              ▷ current average cell rate in weakest cell
        for h ∈ AP do                                       ▷ for each AP
            δ* ← min{δ*, avg_rate(𝒩, h)}                    ▷ avg. cell rate h using nulling 𝒩
        end for
        for h ∈ AP do                                       ▷ nulling towards STAs served by AP h
            for k ∈ AP do                                   ▷ nulling performed by AP k
                for G_i^h ∈ 𝒢^h do                          ▷ for each SDMA group of AP h
                    for u ∈ G_i^h do                        ▷ each STA in SDMA group
                        if crange(u, k) then                ▷ if u is comm. range of k
                            Ñ_{i'}^{k'} ← N_{i'}^{k'}, ∀k', i'    ▷ copy curr. nulling cfg
                            Ñ_i^k ← N_i^k ∪ {u}             ▷ add nulling STA u
                            δ ← 0                           ▷ recalc min avg. rate
                            for h' ∈ AP do
                                δ ← min{δ, avg_rate(𝒩̃, h')}
                            end for
                            if δ > δ* then                  ▷ save best solution
                                δ* ← δ, k* ← k, u* ← u, i* ← i
                            end if
                        end if
                    end for
                end for
            end for
        end for
        if u* ≠ ∅ then                                      ▷ there is gain from nulling u*
            N_{i*}^{k*} ← N_{i*}^{k*} ∪ {u*}                ▷ add u* to corr. nulling group
        end if
        return N_i^k, ∀k, i = 1...θ
    end while
end procedure
```

Algorithm 2 Algorithm used to calculate the expected average cell rate in DL.

Require:

$\mathcal{N}$ - the nulling configuration for each AP.

$\mathcal{G}^h$ - the SDMA grouping in this cell/AP

h - The cell or AP ID.

Ensure:

R - the expected average cell rate in DL for AP h.

procedure avg_rate( )

  $\Delta^h \leftarrow \delta_{\text{UpdateRate}} \times (\sum_i \text{chan\_sound}(G_i^h, N_i^h) + \sum_{\forall h' \neq h, \mathcal{N}^{h'} \cap \mathcal{N}^h \neq \emptyset} \sum_i \text{chan\_sound}(G_i^{h'}, N_i^{h'}))$ ▷ Channel sounding overhead in cell h

  $R \leftarrow \emptyset$ ▷ set of DL STA rates

  for $G_i^h \in \mathcal{G}^h$ **do** ▷ for each SDMA group in this cell/AP

    for $u \in G_i^h$ **do** ▷ each STA in SDMA group

      $\sigma \leftarrow 0$ ▷ co-channel interference

      for $h' \in$ AP **do**

        if $h' \neq h$ **then** ▷ collect interference from other APs.

          if $\neg\text{isnulling}(h', u, \mathcal{N})$ **then** ▷ h' is not nulling u.

            $\psi \leftarrow \psi + \tilde{P}^{\text{rx}}_{h' \rightarrow u}$ ▷ add average signal strength

          end if

        end if

      end for

      $\gamma_u \leftarrow \frac{||W_u^{\text{H}} \cdot H_u||_2^2}{\sigma^2 + \chi + \psi}$ ▷ expected SINR at STA u where the numerator represents the effective channel gain after precoding (H_u and W_u is the channel and the precoding used by the serving AP respectively) and the denominator represents the total interference, i.e. sum of noise σ^2, intra-cell interference χ (=0 if ZF is used) and expected inter-cell interference ψ.)

      $r \leftarrow (1 - \Delta^h) \times \frac{1}{|\mathcal{G}^h|} \times \text{rate}(\gamma_u)$ ▷ eff. DL rate of u

      $R \leftarrow R \cup r$

    end for

  end for

  return mean(R) ▷ average DL rate in cell h

end procedure

6.3 Medium Access Control

The proposed method requires a special medium access control different from the random access scheme in 802.11 DCF. In particular we have to coordinate the channel access in the downlink (DL) of adjacent APs to make sure that the null steering by an adjacent AP is time aligned with the corresponding beamforming of the serving AP. Such coordination is achieved by dividing the medium into DL time slots where a central controller schedules in each time slot an SDMA group together with potential interference nulling. The proposed MAC framing is depicted in Fig. 6.1. Here the medium access is divided into superframes. Each superframe consists of a DL and UL subframe. The DL subframe is further divided into DL slots. A particular terminal/nulling group is scheduled in each DL slot. The total number of DL slots equals the largest number of SDMA groups (ref. step 1) over all APs, i.e. $\theta = max(\{|\mathscr{G}^k|, \forall k \in \text{AP}\})$. Fig. 6.1 illustrates an example with two APs. Here AP2 is highly loaded and serves just its own STAs by SDMA whereas AP1 can utilize the unused degree of freedom to perform interference nulling.

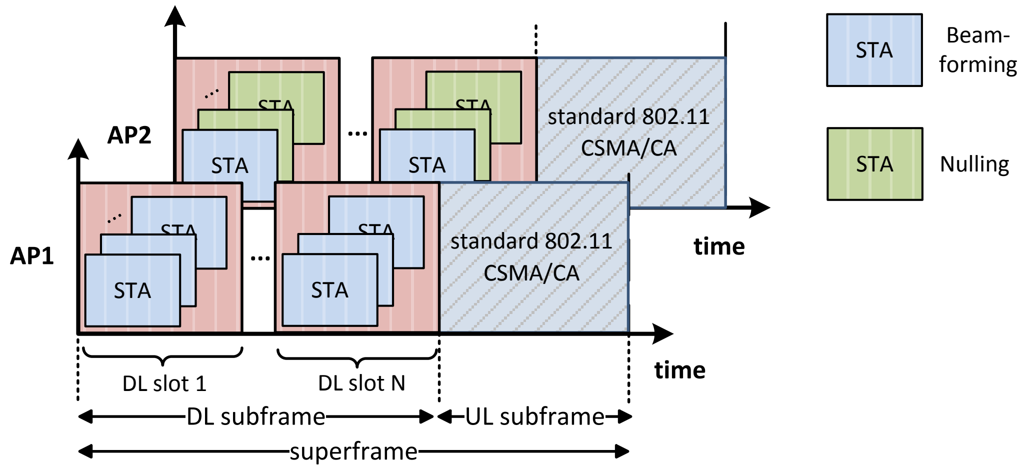

Figure 6.1: MAC framing.

6.4 Architecture

In Fig. 6.2 a flow chart illustrating the data and control flow in the proposed architecture is given. Each AP independently estimates the set of active STAs within his own cell, i.e. associated STAs having active flows. Those STA are periodically sounded to obtain up-to-date instantaneous CSI. For the interference management only the average CSI, i.e. average received power, towards STAs in adjacent cells is required which can obtained efficiently using passive overhearing. Note, this is possible since all APs in the envisioned method use the whole available spectrum and operate on the same channel. Both CSI data is sent to a central controller which performs the tasks of terminal grouping (SDMA) and interference management (nulling). This scheduling information is sent back to the corresponding APs. An additional step is required. Since the instantaneous CSI towards the STAs to be nulled is not known, those STAs need to be sounded. Having up-to-date CSI towards

STAs to be served an AP is able to calculate the correct MIMO precoding vector and transmit the data frames.

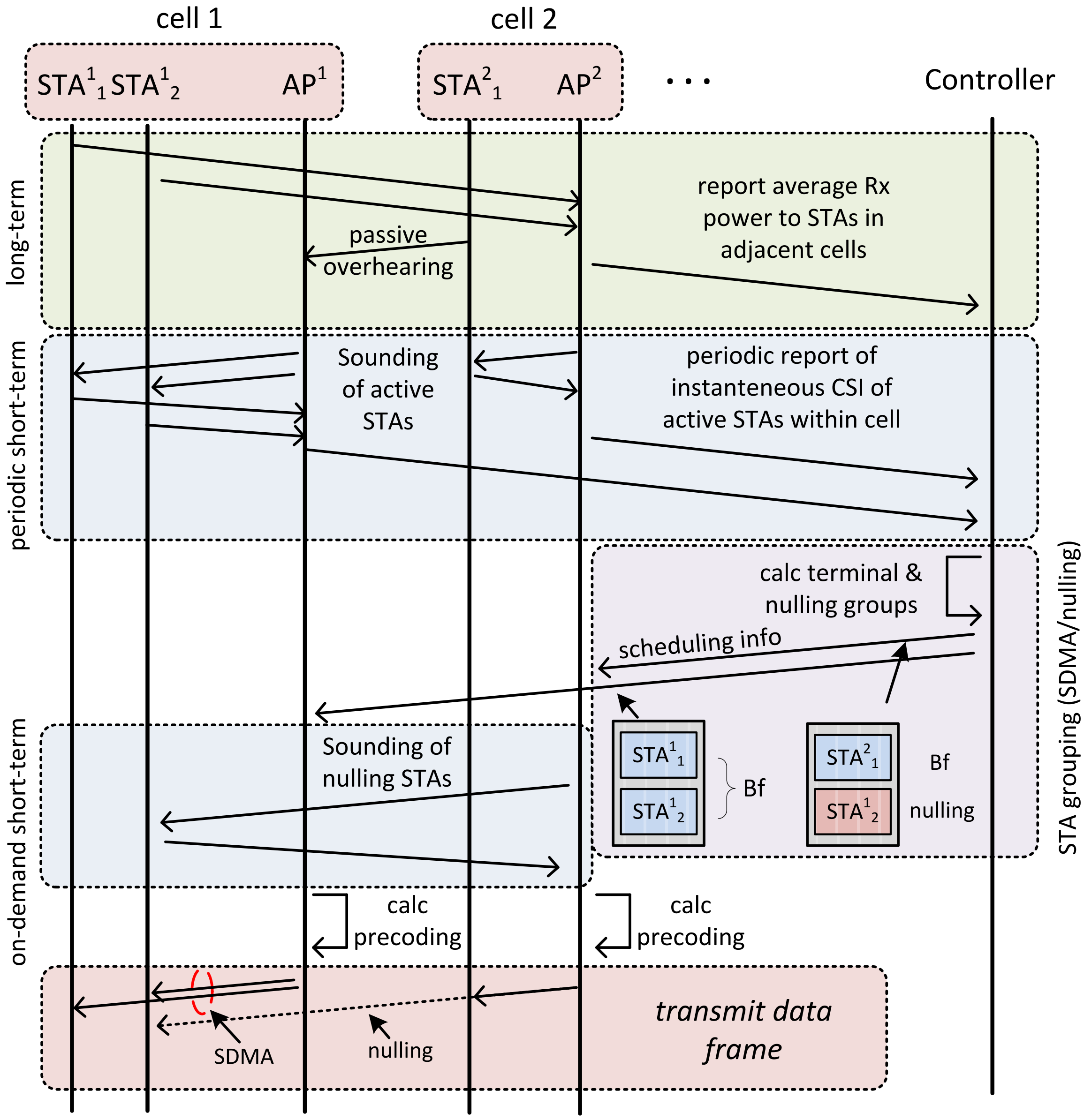

Figure 6.2: Data and control flow in the proposed architecture.

Chapter 7

Performance Evaluation

The performance of the proposed algorithm is analyzed by means of simulations in an indoor hotspot environment.

7.1 Methodology

7.1.1 Placement & Channel Model

Fig. 7.1 shows the placement of APs and STAs. It is an indoor scenario with a hotspot cell in the middle, i.e. a full congress or conference room, with 20 active STAs. The adjacent APs are only lightly loaded, i.e. each AP is serving just a single STA. Different distances, $d = 13-54\,m$, between APs were considered. The placement of STAs within each room was uniform random. The minimum distance of STA towards the closest AP was $5\,m$. As path loss model we selected the IEEE 802.16m indoor small office(A1) scenario, adapted to 5 GHz [1]. The propagation scenario describes both LOS and NLOS situations, hence we use a random mix of LOS and NLOS scenarios with the probability of selecting a LOS scenario given as (d is in meters):

$$p_{\mathrm{LOS}}(d) = \begin{cases} 1 & \text{if } d < 10 \\ \exp(-(d-10)/45) & \text{otherwise} \end{cases}$$

The pathloss is different for LOS and NLOS:

$$\mathrm{PL}_{\mathrm{dB}}(d) = \begin{cases} -(18.7 \times \log_{10}(d) + 46.8) & \text{for LOS} \\ -(36.8 \times \log_{10}(d) + 38.8) & \text{for NLOS} \end{cases}$$

Furthermore, we calculated 12 dB loss for wall penetration. For NLOS and LOS different Shadowing σ were taken: 3.1 db and 3.5 db respectively. The small scale fading was chosen to be independent identically distributed (i.i.d) complex gaussian variables with zero mean and unit variance. In our simulations we explicitly calculated the SNIR taking into account the channel H and the precoding W from each cells. Moreover, we assumed that all active STAs had full packet buffers. The remaining most important parameters used in our simulations are summarized in Table 7.1. Moreover, the SNR thresholds used in the simulation are given in Table 5.1.

7.1.2 Performance Metric

As mentioned in the optimization problem formulated in Sec. 5 (eq. 5.1) we are interested in optimizing the average DL rate in the weakest cell. In the considered indoor hotspot scenario it is sufficient

[1] `http://www.ieee802.org/16/tgm/contrib/C80216m-07_086.pdf`

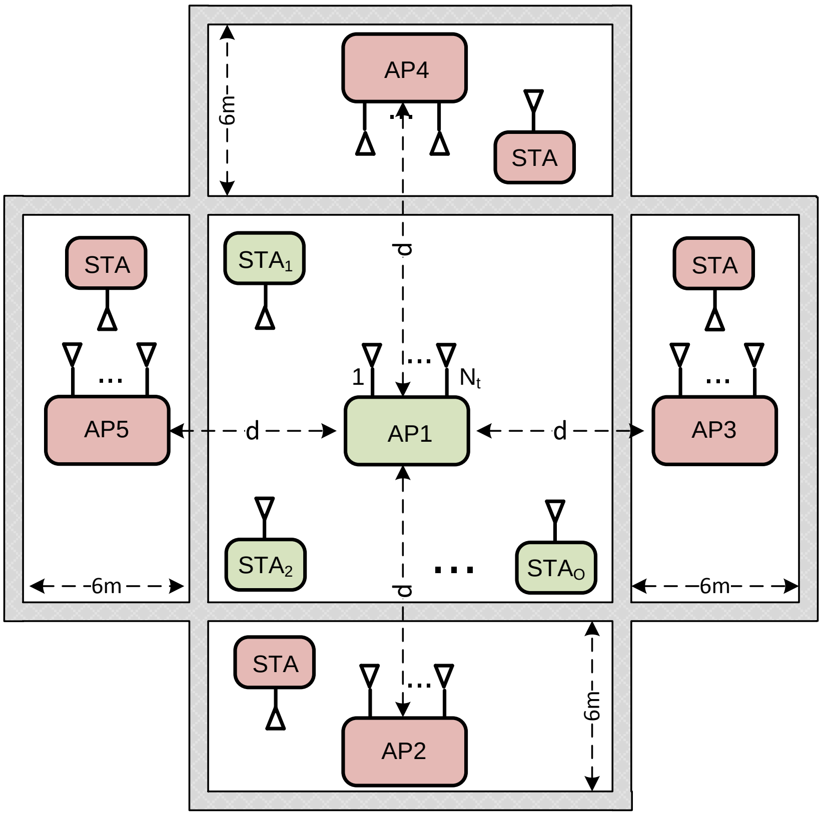

Figure 7.1: Indoor scenario (view from top). An AP is located in each of the five rooms. AP1 in the centered room is highly loaded serving 20 active STAs, whereas the other APs are only lightly loaded serving just a single STA.

to report the DL rates within the hotspot cell. In addition we also present results from the adjacent lightly loaded cells if necessary.

7.1.3 Channel Sounding Procedure

The channel sounding procedure was performed as specified in 802.11ac. Only STAs in communication range can be sounded, i.e. a SNR is required to that a STA can be served at least on the most robust MCS. The full sounding handshake was simulated. The airtime occupied by an CB packet depends on the uplink SNR from the STA to the AP. Here we assumed RX diversity in uplink. Furthermore, channel sounding in cells can only be performed in parallel if there are no overlapping STAs to be sounded, i.e. STAs which are sounded by more than one AP. I.e. sounding in target cell has to be performed sequentially if each neighboring AP is sounding at least one STA from the target cell. So the sounding duration is summed up.

7.1.4 Methods under Study

Our proposed approach is compared with the following state-of-the-art solutions:

Parameter	Value
System bandwidth	100 MHz & 5×20 MHz
PHY	IEEE 802.11ac (long preamble)
MAC	TDMA (proposed), CSMA/CA 802.11ac (baseline)
Center frequency	5.32 GHz
Transmit power	10 dBm
STA noise density (dBm/Hz)	-167 dBm/Hz
STA noise figure	6 dB
Direction	Downlink
Channel sounding	explicit, 802.11ac
Pathloss model	802.16m indoor small office (A1), adapted to 5 GHz
MU-MIMO precoding	Zero-forcing
MU-MIMO grouping	Best-fit algorithm
Carrier sensing threshold (CSMA)	SINR=-3 dB (BPSK 1/2)
Inter AP distance	13-54 m
STA placement	uniform
Number of antennas at AP	4,8,12
Number of antennas at STA	1
Number of STAs in hotspot cell	20
Number of STAs in adjacent cells	1
No. of placement seeds	1000

Table 7.1: Simulation Parameters.

- **Baseline (5x20 MHz)**: standard 802.11ac with dedicated 20 MHz channel in each cell/AP,
- **Baseline (CSMA)**: standard 802.11ac where each cell/AP uses the total available bandwidth of 100 MHz (frequency reuse 1) and CSMA activated,
- **Indep**: same as Baseline (CSMA) but with CSMA deactivated,
- **Proposed**: the proposed scheme using the total available bandwidth of 100 MHz and adaptive nulling.

7.2 Results

In this section we present a thorough evaluation of the performance of our proposed approach that is organized as follows. First, we analyze the average DL rate and the outage probability in the hotspot cell. Second, we take a closer look at the overhead due to explicit channel sounding procedure. Third, the impact of the number of antennas is analyzed. Finally, we show the impact on adjacent cells, i.e. the price to be paid by the STAs in adjacent cells.

7.2.1 Mean bitrate & outage probability of proposed scheme

The results for the different approaches under study are given in Fig. 7.2. Here, the number of antennas at each AP is $N_t = 8$ and a channel sounding update interval of $\delta = 10$ Hz, i.e. static environment or very low mobility, was selected. The following observations can be made. First, the proposed scheme always outperforms all others. The gain is especially high for very small inter-BS distances, e.g. up to 5× cmp. to baseline and 1.5× cmp. to a scheme without any coordination between neighboring APs (*Indep*). Even at a larger inter-BS distance of $d = 29\,m$ the proposed scheme outperforms *Indep* by around 16%.

Moreover, the outage probability, i.e. a STA cannot be served due to too low SNR, when using the proposed scheme remains low (Fig 7.3). It is highest when using *Indep*.

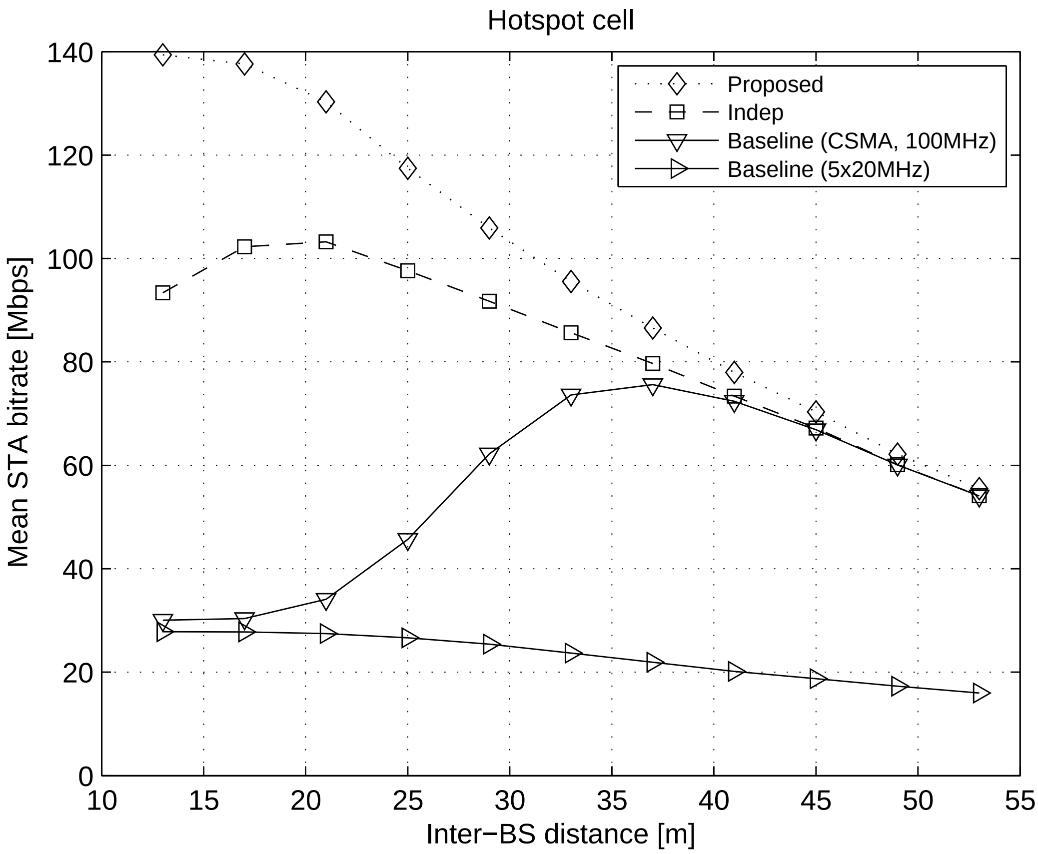

Figure 7.2: STA mean rate in hotspot cell.

7.2.2 Impact of Channel Sounding

Next, we analyze the impact of the channel sounding overhead. From Fig. 7.4 we can see that the channel sounding interval greatly impacts the performance of our proposed solution which can be explained by the additional sounding of STAs to be nulled. The main result is that as long as channel sounding interval δ is smaller than 25 Hz the proposed collaborative scheme outperforms all other schemes. Hence in a more mobile environment the *Indep* scheme offers higher performance. For a high channel sounding update rate, δ, the airtime occupied by channel sounding can reach more than 40% (Fig. 7.5). For larger inter-BS distances even the baseline 802.11ac approach offers comparable results.

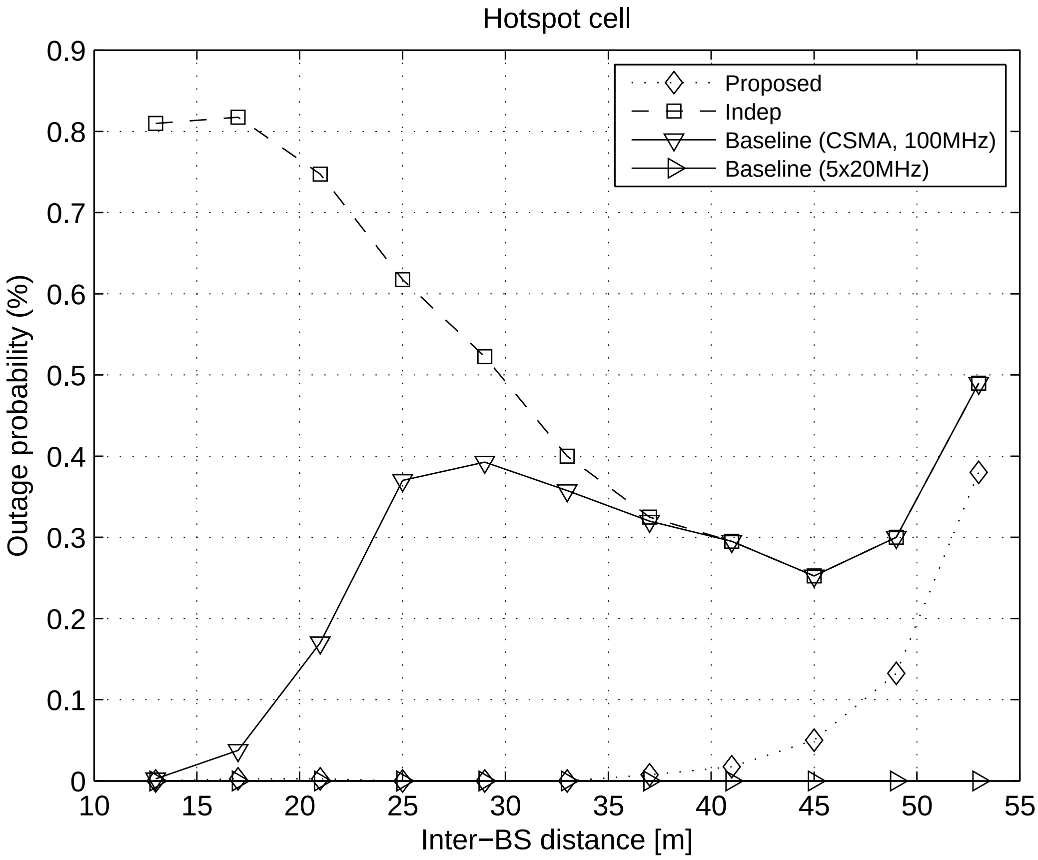

Figure 7.3: STA outage probability in hotspot cell.

7.2.3 Impact of Number of Antennas

Here we investigate the impact of the number of antennas M at the APs. This is important to analyze because the channel sounding overhead increases with M (ref. Sec. 3). In Fig. 7.6 we present results for $M = 4, 8, 12$ and $\delta = 10\,\mathrm{Hz}$. Here we can see that the proposed scheme scales with M.

7.2.4 Impact on adjacent cells

In the considered hotspot scenario the interference management is performed by the lightly loaded APs towards the hotspot cell. Hence, it is important to analyze whether there is performance degradation in adjacent cells. Fig. 7.7 shows the average rate in the adjacent cells for the configuration of $N_t = 8$ and $\delta = 10\,\mathrm{Hz}$. We see that only a little price is to be paid, cmp. *Proposed* with *Indep*. The outage probability for all methods under study was zero.

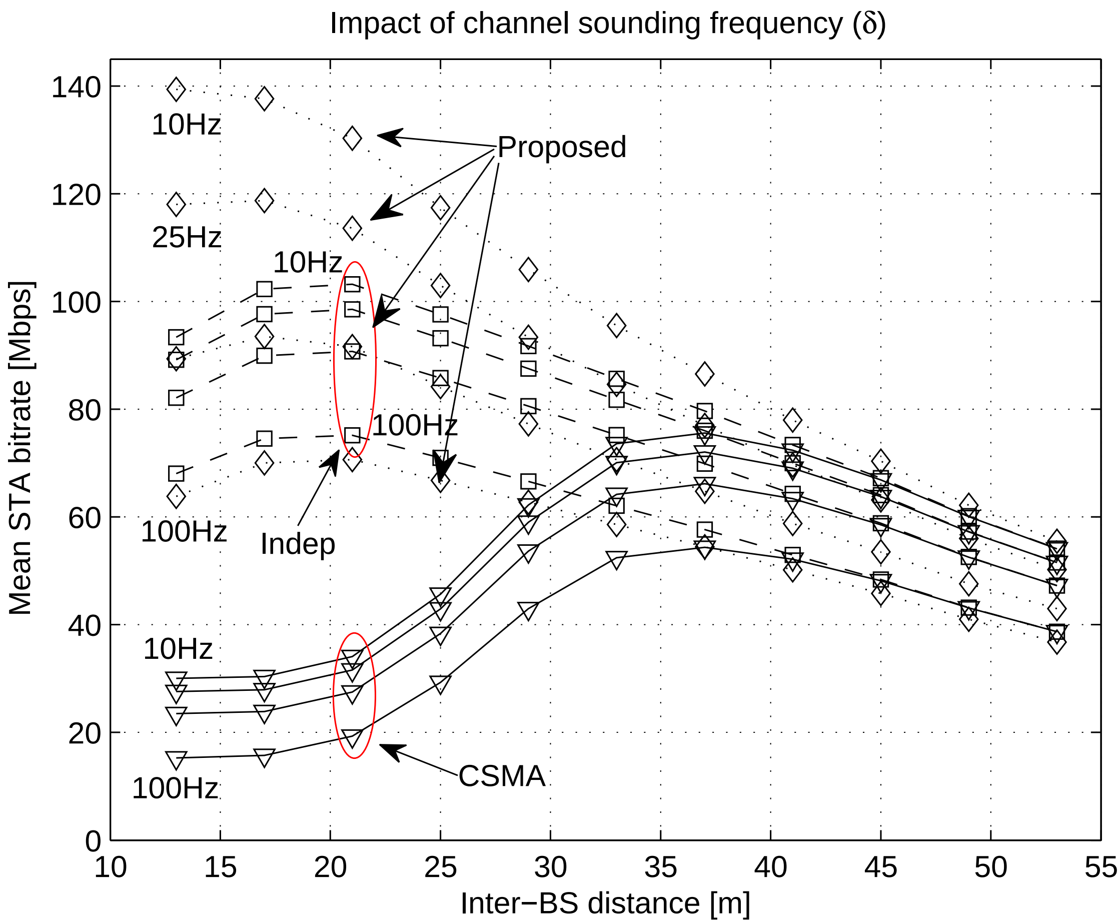

Figure 7.4: STA mean rate in hotspot cell for different channel sounding update rates δ.

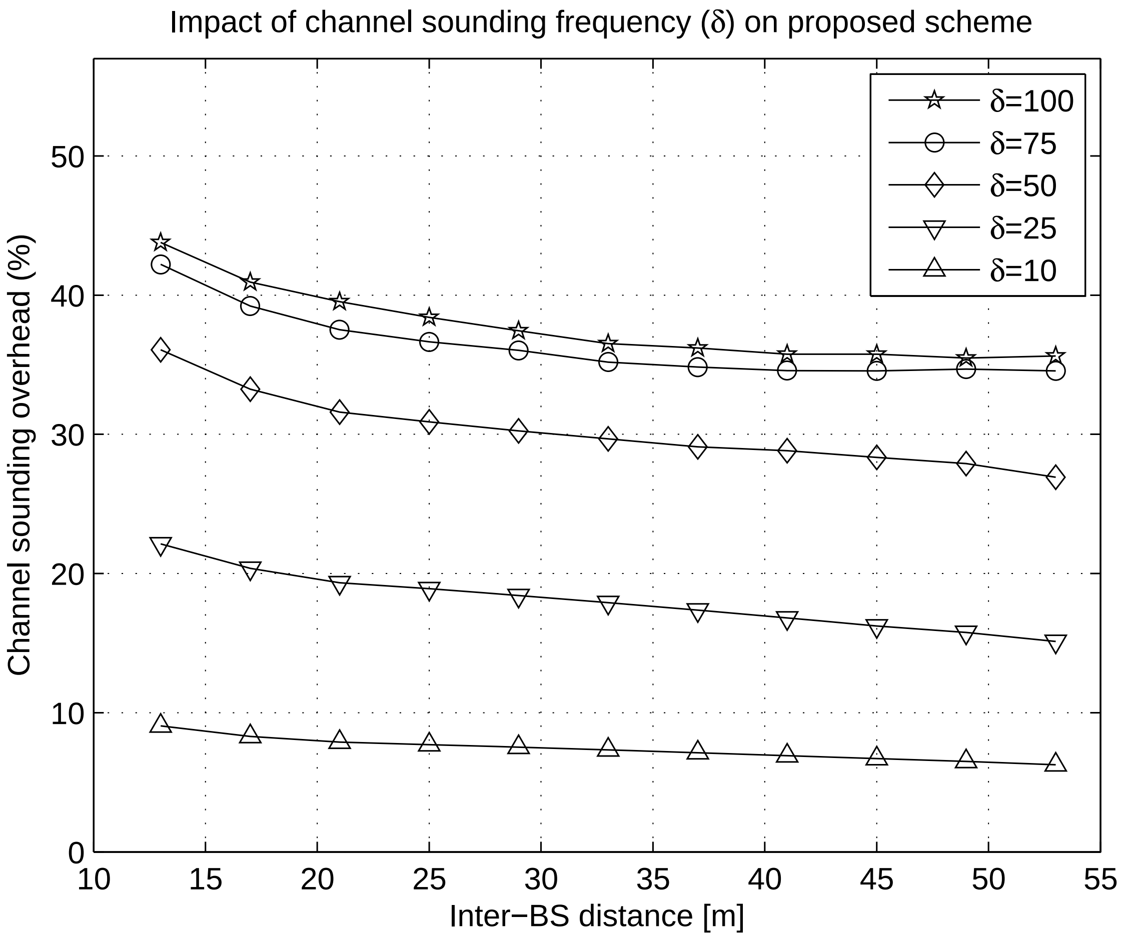

Figure 7.5: STA mean rate in hotspot cell for different channel sounding update rates δ. Relative airtime used by channel sounding.

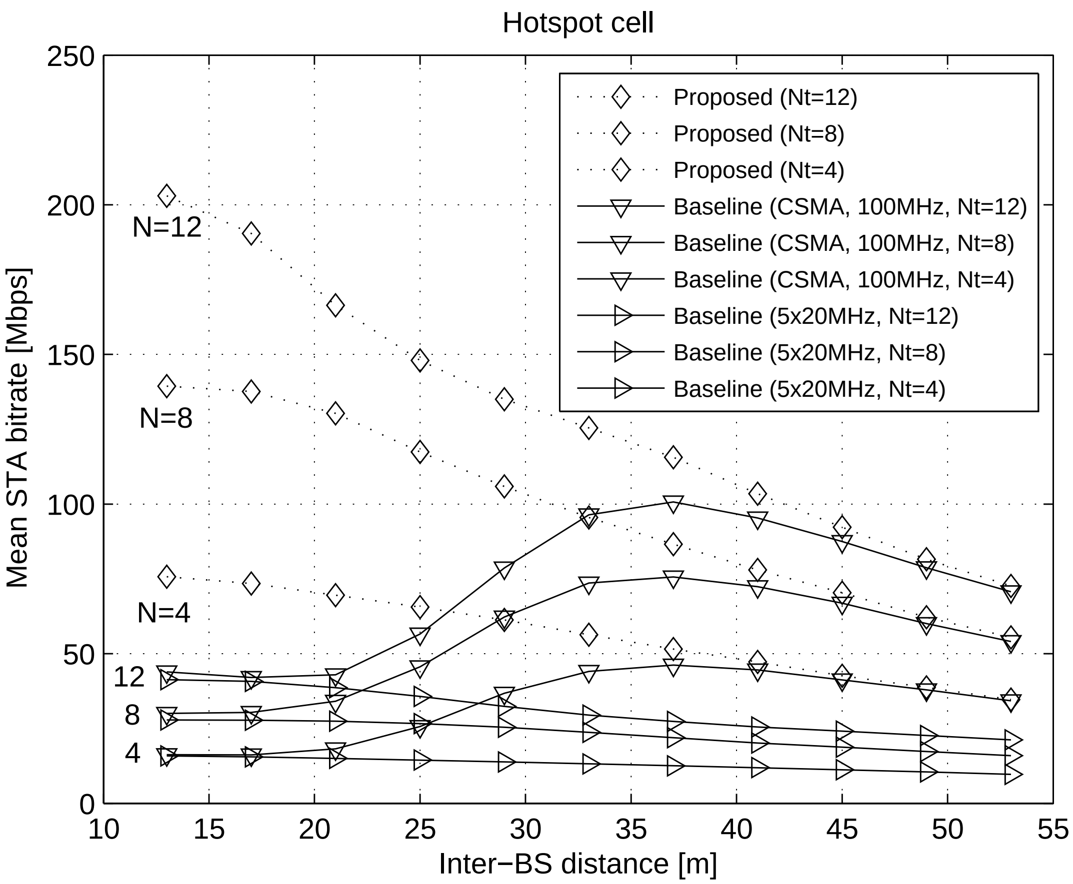

Figure 7.6: Impact of number of antennas (hotspot cell).

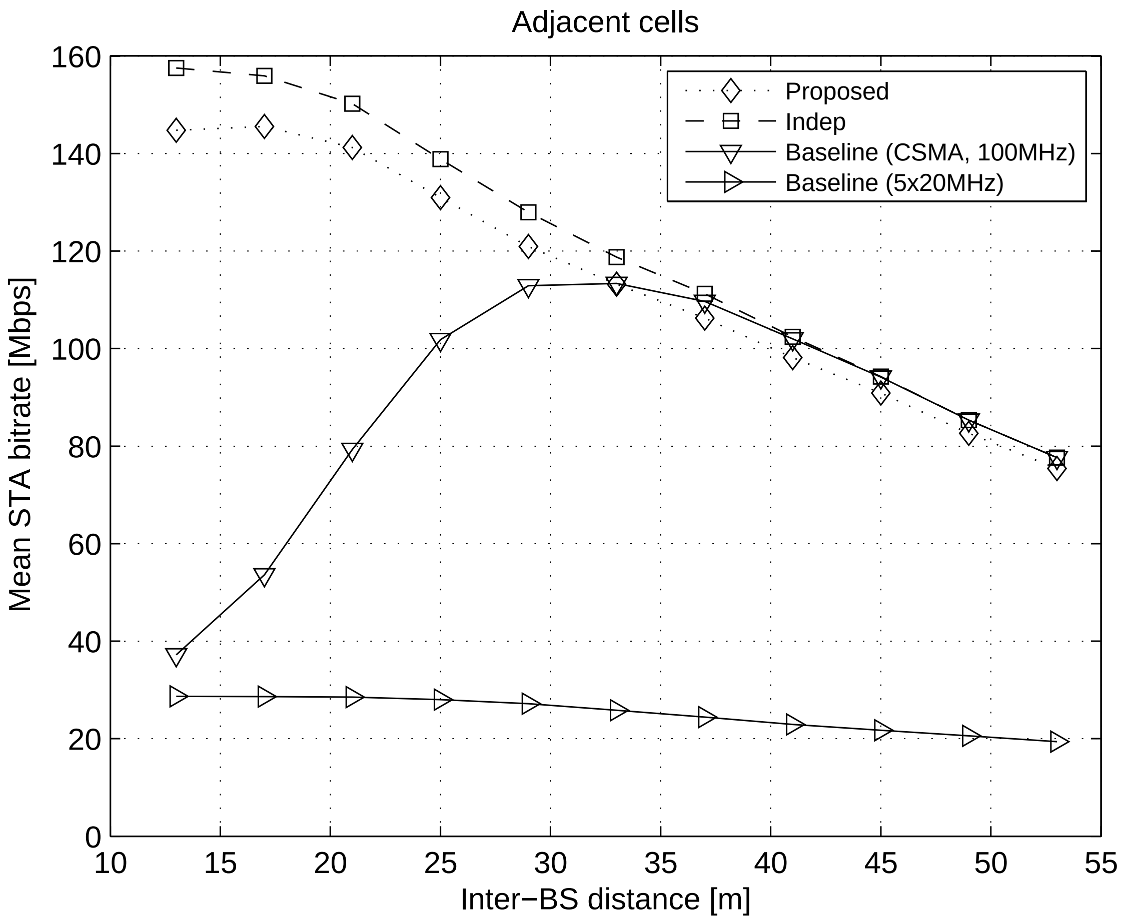

Figure 7.7: STA mean rate in adjacent cells for proposed scheme and baseline.

Chapter 8

Conclusions

In this paper we showed that the DL of 802.11ac-based infrastructure WiFi networks with unequal network load can be improved significantly when performing a combination of two physical layer MIMO techniques, namely MU-MIMO and nulling. The former mitigates interference within a cell whereas the latter is used to reduce intercell-interference. The proposed algorithm is performed in two steps, namely grouping of spatial compatible terminal groups which are served by DL MU-MIMO and interference management where the unused degree of freedom of lightly loaded cells/APs is utilized to perform null steering towards STAs in highly loaded adjacent cells. The proposed adaptive algorithm takes the overhead due to channel sounding into account when calculating the set of STAs to be nulled. Our simulation results from an indoor hotspot environment conclude that the proposed scheme outperforms state-of-the-art especially in high density AP deployments. The proposed method can be implemented using a cross-layer architecture like OpenRF [1]. It is fully compatible with commodity 802.11ac network cards that implement MU-MIMO. Furthermore, only slight modifications to the 802.11 MAC layer are required.

Chapter 9

Related Work

The following publications are relevant.

Kumar et al. showed that by managing MIMO signal processing, i.e. adaptively applying technique like transmit beamforming, interference nulling and alignment, the performance of 802.11 networks can be significantly improved [1]. Moreover, the proposed architecture can be used to implement the proposed scheme in this paper.

In context of LTE-Advanced Liu et al. find out that the cell edge client spectral efficiency may be reduced if MU-MIMO is used exclusively [2]. Hence, they proposed a dynamic switching between SU-MIMO and MU-MIMO to balance the cell edge client spectral efficiency and average cell user spectral efficiency.

Xiong et al. proposed a distributed MU-MIMO system for IEEE 802.11ac networks [5]. Here the transmitting antennas are located at different APs which is especially interesting if the number of antennas at the APs is small.

Yu et al. analyzed the relationship between packet length and throughput for SU- and MU-MIMO in IEEE 802.11ac in time-varying channels [6]. They showed that there is a severe performance loss when the transmission duration after channel sounding is too long which is the case under practical channel conditions with mobility. Hence, there is an optimal transmission durationwhich can be determined to maximize throughput.

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