Cooperative Processing for the WLAN Uplink

Marc Kuhn, Jörg Wagner, and Armin Wittneben
ETH Zurich
Communication Technology Laboratory, CH-8092 Zurich, Switzerland
Email: {kuhn, wagner, wittneben}@nari.ee.ethz.ch

***Abstract*—We study the potential of cooperative processing in WLAN uplink scenarios where the access points are connected to a backhaul with limited capacity. We evaluate different decoding strategies based on an outage criterion and discuss the influence of the available backhaul rate. Compared to the ergodic analyses in the literature we observe three major differences: Firstly, outage rates are much more robust to the backbone limitation. Secondly, Slepian-Wolf coding (compress & forward processing) does not improve the outage performance significantly compared to pure quantization and forwarding. Finally, quantization based approaches offer substantially higher gains compared to decoding based strategies.**

Because of the large number of existing WLANs, we conclude that cooperative processing is a key enabler for high rates on future WLAN uplinks: in cases of limiting backhaul capacities (e.g. ADSL broadband connections in residential environments) as well as in cases of large backhaul capacities (e.g. LAN connections in office environments).

I. Introduction

Nowadays, Wireless Local Area Networks (WLANs) according to the IEEE 802.11 standard [1] are widely used, and their number is still increasing fast. The vast majority of them is infrastructure based and connected to the internet using broadband connection as e.g. LAN, DSL or similar technologies. Moreover, the supported data rates are increasing. The upcoming MIMO WLAN standard IEEE 802.11n is going to allow rates up to 600 Mbit/s. Two challenges arise from these facts: In many cases the broadband connection is the bottleneck for a wireless station (STA) communicating via the access point (AP) of a high speed WLAN, e.g. in case the AP uses ADSL as backhaul. The second challenge is the frequency planning for an increasing number of APs in the same area. Currently, in 802.11 the Basic Service Sets (BSS) of WLANs are separated by using different frequency channels, i.e. the respective APs are operating in different frequency bands. But more and more BSSs have to coexist. Cooperation between neighboring APs for the wireless uplink (UL) has the potential to mitigate both problems. APs communicate via the backhaul with each other and are able to bundle their backhaul capacities to communicate with the destination. For this it is not necessary that the APs can decode the message, it is sufficient that the destination is able to decode. On the other hand, if two or more BSSs share a common frequency channel not only bandwidth is saved, but cooperative processing is also able to realize spatial multiplexing gains.

In this paper we consider different approaches to cooperative processing on the WLAN uplink: decode & forward, quantize & forward and a combination of both. We assume burstwise transmissions and frequency flat block fading. Due

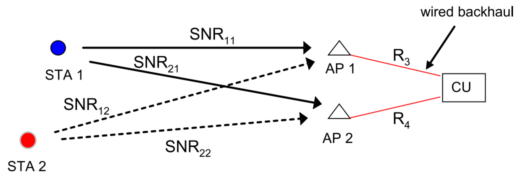

Fig. 1. Two users scenario: STA_1, STA_2, two APs.

to the slow fading channel model (motivated by the usual assumption of low mobility in a WLAN) we compare the approaches based on an outage criterion.

The first work on decentralized processing in the context of achievable rates is due to Schein [2]. In particular, this work is the first to report an achievable rate based on quanziation and distributed Slepian-Wolf compression (referred to as compress & forward in this paper) at the relays, i.e. APs in the context of this work. Sanderovich et al. generalized the result in various ways, e.g. for general numbers of access points [3] and multiple sources [4]. The latter two references distinguish whether the APs possess knowledge of the codebook or not. In the former case a combination of decode & forward and compress & forward strategy is proposed that allows for increasing the rate-regions in general. A main difference between our work and those by Sanderovich et al. lies in that we consider outage rather than ergodic rates. Generally, the problem of decentralized decoding is closely related to the CEO problem [5], which deals with minimizing distortion measures at a central unit rather than maximizing achievable rates.

II. Compress & Forward vs. Quantize & Forward

We consider a low mobility communication scenario as depicted in Fig. 1. We are interested in the uplink. A Central Unit (CU) is the destination, two Access Points (AP) are connected to the CU via lossless links of limited capacity R_3 and R_4; STAs are communicating via the APs to the CU. All nodes are equipped with a single antenna. The results are easily extended to the case of more than two APs and multiple antenna nodes.

In case of the compress & forward (CF) processing the APs do not decode the message of STA_1, they quantize, compress and forward it afterwards to the CU, where it is decoded.

We denote the received signal at AP_1 and AP_2 as y_1 and y_2, respectively. The compressed versions of these signals are $\hat{y}_1$ and $\hat{y}_2$. The following constraints ensure reliable communication according to [2]:

$$I(y_1;\hat{y}_1) < R_3 + I(\hat{y}_1;\hat{y}_2) \tag{1}$$
$$I(y_2;\hat{y}_2) < R_4 + I(\hat{y}_1;\hat{y}_2) \tag{2}$$
$$I(y_1;\hat{y}_1) + I(y_2;\hat{y}_2) < R_3 + R_4 + I(\hat{y}_1;\hat{y}_2). \tag{3}$$

I denotes the mutual information. CF includes distributed source coding, requiring both APs to have perfect CSI of both channel coefficients between STA_1 and the two APs. A much simpler scheme without source coding may be of more practical interest to WLANs. The APs forward the quantized signals $\hat{y}_1$ and $\hat{y}_2$ without additional compression, no additional CSI is needed; we refer to this as quantize & forward (QF) processing. This scheme is sub-optimal but shows a much lower complexity. For this scheme the following constraints are valid:

$$I(y_1;\hat{y}_1) < R_3 \tag{4}$$
$$I(y_2;\hat{y}_2) < R_4. \tag{5}$$

The expressions for $I(y_1;\hat{y}_1)$ and $I(y_2;\hat{y}_2)$ are derived as:

$$I(y_i;\hat{y}_i) = \log_2\left(1 + \frac{\sigma^2_{y_i}}{\sigma^2_{q_i}}\right) \quad \text{for } i \in \{1,2\}, \tag{6}$$

where $\sigma^2_{q_i}$ is the variance of the quantization noise n_{q_i}: $\hat{y}_i = y_i + n_{q_i}$. We assume $n_{q_i} \sim \mathcal{CN}(0,\sigma^2_{q_i})$. Solving (6) for $\sigma^2_{q_i}$ and applying the bounds (4), (5) yields:

$$\sigma^2_{q_1} > \frac{\sigma^2_{y_1}}{2^{R_3}-1} \tag{7}$$
$$\sigma^2_{q_2} > \frac{\sigma^2_{y_2}}{2^{R_4}-1} \tag{8}$$

An approximation is given for equality in (7) and (8) (it is possible to make the quantization noise arbitrarily close to this limit). This approximation is used in the following. We denote the channel coefficient between STA_1 and AP_1 as h_{11}, between STA_1 and AP_2 as h_{21} (stacked in the channel matrix $\mathbf{H}$), the thermal noise power as σ_n^2, and the transmit power of STA_1 as P_t.

The achievable UL sum rate using QF is approximated by

$$R^{QF}_{UL} = \log_2\left(\det\left(\mathbf{I} + P_t \mathbf{\Lambda}_N^{-1}\mathbf{H}\mathbf{H}^H\right)\right), \tag{9}$$

where the noise covariance matrix $\mathbf{\Lambda}_N$ is diagonal with $\sigma^2_{q_i} + \sigma^2_n$ on the main diagonal.

A. QF Loss: Interpretation as a Jensen Penalty

Without Slepian-Wolf source coding the achievable rate based on QF is generally bound away from the cut-set bound on the backhaul rates, irrespective of the average SNR at the APs (cf. Fig. 2), i.e. even for $P_t \to \infty$. The only exception is an infinite number of STAs, $K \to \infty$.

For the case that all backhaul rates are equal ($R_3 = R_4 = \ldots = R$) this is proven in the following. We normalize the i.i.d. Rayleigh fading channel matrix $\mathbf{H}$ according to $\mathbf{H} = \mathrm{diag}(\sqrt{\beta}_1, \ldots, \sqrt{\beta}_N)\tilde{\mathbf{H}}$ such that all rows of $\tilde{\mathbf{H}}$ are of unit

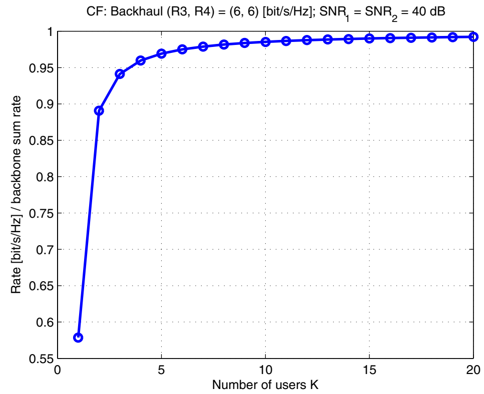

Fig. 2. Rate vs. number of users, 2 APs, QF: Jensen penalty.

Eukledian norm (N denotes the number of APs). This implies that the sum of eigenvalues $\sum_{n=1}^{N} \lambda_n\{\tilde{\mathbf{H}}\tilde{\mathbf{H}}^{\mathrm{H}}\} = N$. With this notation we can write the achievable rate as

$$\begin{aligned} C &= \log_2 \det\left(\mathbf{I}_N + \mathrm{diag}\left(\mathrm{snr}_1, \ldots, \mathrm{snr}_N\right) \frac{1}{N}\tilde{\mathbf{H}}\tilde{\mathbf{H}}^{\mathrm{H}}\right) \\ &= \sum_{n=1}^{N} \log_2\left(1 + \mathrm{snr}_n \lambda_n\{\tilde{\mathbf{H}}\tilde{\mathbf{H}}^{\mathrm{H}}\}\right), \end{aligned} \tag{10}$$

where the SNR at the n-th AP after quantization is defined as (7), (8)

$$\mathrm{snr}_n = \frac{\beta_n P_t}{\sigma^2_{q_i} + \sigma^2_n} = \frac{\beta_n P_t}{\frac{\beta_n P_t + \sigma_n^2}{2^R - 1} + \sigma^2_n}. \tag{11}$$

Taking $P_t \to \infty$ yields:

$$\begin{aligned} \lim_{P_t\to\infty} C &= \sum_{n=1}^{N} \log_2\left(1 + (2^R - 1)\lambda_n\{\tilde{\mathbf{H}}\tilde{\mathbf{H}}^{\mathrm{H}}\}\right) \\ &\leq N \log_2\left(1 + (2^R-1)\frac{1}{N}\sum_{n=1}^{N}\lambda_n\{\tilde{\mathbf{H}}\tilde{\mathbf{H}}\}\right) \\ &= N\log_2\left(2^R\right) = NR. \end{aligned} \tag{12}$$

The applied Jensen inequality holds with equality iff $K \to \infty$. This reveals a Jensen penalty for the QF scheme compared to CF with Slepian-Wolf compression. However, this penalty vanishes in case of a given SNR and a large backhaul capacity R:

$$\begin{aligned} \lim_{\mathrm{R}\to\infty} C &= \log_2 \det\left(\mathbf{I}_N + \mathrm{diag}\left(\frac{\beta_1 P_t}{\sigma^2_n}, \ldots, \frac{\beta_N P_t}{\sigma^2_n}\right)\frac{1}{N}\tilde{\mathbf{H}}\tilde{\mathbf{H}}^{\mathrm{H}}\right) \\ &= \log_2 \det\left(\mathbf{I}_N + \frac{P_t}{\sigma^2_n N}\mathbf{H}\mathbf{H}^{\mathrm{H}}\right), \end{aligned} \tag{13}$$

which is the co-located MIMO rate. Finally, in case of deep fades the Slepian-Wolf compression does not improve the outage performance significantly, because the observations at the APs tend to be uncorrelated. This renders (1) – (3) and (4), (5) to be equivalent.

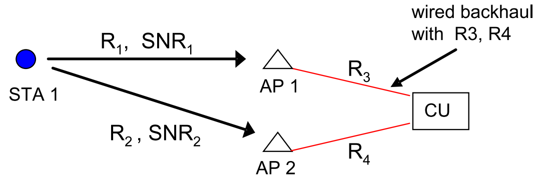

Fig. 3. One user scenario: STA_1, two APs.

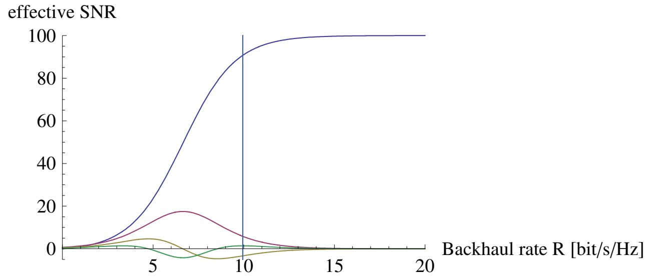

Fig. 4. Effective SNR and its first, second and third (green color) derivative vs. backhaul rate, $\frac{P_t|h|^2}{\sigma_n^2} = 20$ dB. The value R^* is shown as a parallel to the $\mathrm{SNR_{eff}}$ axis.

III. WLAN Uplink: One User, Two APs

The one user scenario is depicted in Fig. 3. The CU is the destination, two APs are connected to the CU via lossless links of limited capacity R_3 and R_4; STA_1 is communicating via one AP or both APs to the CU. All nodes are equipped with a single antenna.

We investigate different cooperative processing strategies: decode & forward (DF), quantize & forward (QF) and a combination of both (DF + QF).

A. Quantize & Forward (QF)

For the case of one STA the variance of y_i is given by:

$$\sigma_{y_i}^2 = P_t|h_{i1}|^2 + \sigma_n^2. \tag{14}$$

The QF uplink rate follows from (9).

In the following we assume the backhaul capacities to be high compared to the achievable rates of the wireless links between STA_1 and the APs. In this case the APs could use the whole capacity of the backhaul to realize a fine quantization of the received signals. But in many practical cases the backhaul capacity is expensive, i.e. the APs should not demand more backhaul capacity than necessary. In the following we investigate the influence of the used backhaul rates R_3 and R_4 on the received SNR at the CU using QF.

For each AP the effective SNR using QF is given by:

$$\mathrm{SNR_{eff}} = \frac{P_t|h|^2}{\sigma_n^2 + \sigma_q^2} = \frac{P_t|h|^2}{\sigma_n^2 + \frac{P_t|h|^2+\sigma_n^2}{2^R-1}}, \tag{15}$$

where R is the backhaul rate of the considered AP. As shown in Fig. 4 the effective SNR increases with R before it saturates. We define the backhaul rate R^* to be the point where $\mathrm{SNR_{eff}}$ saturates. More specifically, we characterize this point by the second maximum of the third derivative of the effective SNR with respect to the backhaul rate R. This choice of R^* is motivated by the fact that at this point the decrease of the curvature is maximum. We obtain R^* explicitly from (15):

$$R^* = \log_2\left(\frac{P_t|h|^2(5+2\sqrt{6})}{\sigma_n^2}\right) \tag{16}$$

Limiting the backhaul rate to R^* ensures that the quantization operates in a regime where $\mathrm{SNR_{eff}}$ is saturating, i.e. a further increase of the backhaul rate leads only to small gains in $\mathrm{SNR_{eff}}$.

An AP may choose R^* according to (16) based on the observed average SNR. This ensures a close to optimal performance whenever the instantaneous SNR is lower than the average SNR. Hence, the outage performance is unaffected by the rate limitation to R^*.

B. Decode & Forward (DF)

In contrast to Schein [2], who uses an optimal broadcast code, we use a sub-optimal DF strategy with lower complexity and CSIT requirements: Either one or both APs decode the message and transmit it to the CU. If the backhaul is the bottleneck then in case both decode they can bundle their backhaul rates by transmitting half of the message each. In other situations it may be beneficial to choose only the AP with the better channel to forward the message. In general, DF is able to achieve a diversity gain but not a spatial multiplexing gain.

We denote R_i the achievable rate on the wireless links between STA_1 and AP_i. The rates between STA_1 and the CU via AP_1 or AP_2 are given by:

$$R_{13} = \min\{R_1, R_3\}, \tag{17}$$
$$R_{24} = \min\{R_2, R_4\}. \tag{18}$$

Either only one AP is selected, or both APs decode and forward the decoded data to the CU. In both cases STA_1 needs CSIT or at least rate feedback from the APs. In case of selecting the better AP, the user STA_1 has to adapt its UL rate to R_{max}^{1R}:

$$R_{max}^{1R} = \max\{R_{13}, R_{24}\}. \tag{19}$$

The UL rate is limited by the cut-set bound R_3 or R_4 on the backhaul depending on the selected AP. If both APs are used for DF, STA_1 adapts its rate to the minimum rate that is supported by both APs:

$$R_{min}^{WL} = \min\{R_1, R_2\}. \tag{20}$$

Each AP is forwarding half of the decoded data, e.g. AP_1 the even and AP_2 the odd bits. Thus, the maximum UL rate is limited by the cut-set bound $(R_3 + R_4)$.

In case $R_{max}^{1R} > R_{min}^{WL}$ AP selection is optimal, otherwise both APs are used. The achievable rate writes as:

$$R_{UL}^{DF} = \max\{R_{max}^{1R}, \min\{R_{min}^{WL}, (R_3 + R_4)\}. \tag{21}$$

C. Combination of DF and QF (DF + QF)

To combine DF and QF, STA_1 uses superposition coding of two signals. In this paper, we consider a simple strategy: One part is decoded by one AP or both APs as described in Section III-B; for the other part QF is used by the APs as described in Section III-A. The transmit signal of STA_1 is given by

$$x_1 = \sqrt{\alpha} x_1^{DF} + \sqrt{1-\alpha} x_1^{QF}, \quad (22)$$

where $0 \leq \alpha \leq 1$. Hence, αP_t is the DF power, $(1-\alpha)P_t$ is the QF power.

The received signal and the receive SINR of the DF part at AP_i follow as

$$y_i = h_{i1}(\sqrt{\alpha} x_1^{DF} + \sqrt{1-\alpha} x_1^{QF}) + n \quad (23)$$

$$\text{SINR}_i = \frac{\alpha P_t |h_{i1}|^2}{(1-\alpha) P_t |h_{i1}|^2 + \sigma_n^2}, \quad (24)$$

where n is additive white Gaussian noise with variance σ_n^2. R_1, R_2 in (17) and (18) are given by:

$$R_1^{DF} = \log_2(1 + \text{SINR}_1), \quad (25)$$

$$R_2^{DF} = \log_2(1 + \text{SINR}_2). \quad (26)$$

The achievable rate of the DF part $R_{UL}^{DF'}$ is given by (21). The APs subtract the decoded DF signal contributions in y_1 and y_2:

$$y_1' = y_1 - h_{11}\sqrt{\alpha} x_1^{DF}, \quad (27)$$

$$y_2' = y_1 - h_{21}\sqrt{\alpha} x_2^{DF}. \quad (28)$$

AP_1 and AP_2 use QF to transmit y_1' and y_2', respectively. Compared to (14) for pure QF, a power reduction is found:

$$\sigma_{y_i'}^2 = (1-\alpha) P_t |h_{i1}|^2 + \sigma_n^2 \quad (29)$$

Part of the backhaul capacity is already used to transmit the decoded DF part of y_i. In the case that only one AP decodes (cf. sub-section III-B), the backhaul rate of this AP is reduced by the DF rate (optimal compression), while the other AP can use the whole backhaul capacity for QF. If both APs apply DF, the backhaul rates R_3, R_4 are reduced by half of the DF rate.

The approximated rate of the QF part $R_{UL}^{QF'}$ is given by (9) taking into account the reduced backhaul rates. Thus, the achievable rate for the combination of DF and QF follows as

$$R_{UL}^{DF+QF} = \max_{\alpha}\{R_{UL}^{DF'} + R_{UL}^{QF'}\}. \quad (30)$$

D. Performance Results

We analyze the outage probability $P_{out} = P\{R_{UL} < R_{out}\}$ and the 1% outage rate for the different cooperative processing strategies in the one user scenario. The results are based on Monte Carlo simulations. The channel model is slow Rayleigh fading, i.e. we model the channel to be frequency flat and constant for one transmitted block containing one WLAN burst.

For DF and DF+QF schemes the STAs need to have at least rate feedback to achieve the presented rates. The average receive SNR at AP_i is given by SNR_i.

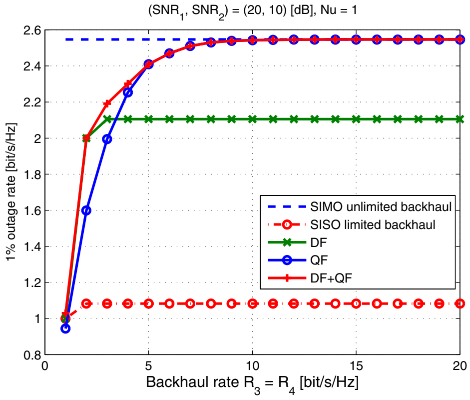

Fig. 5. 1% outage rate vs. backhaul rate, comparison of different cooperative processing strategies, $\text{SNR}_1 = 20$ dB, $\text{SNR}_2 = 10$ dB.

Fig. 5 shows the 1% outage rate with respect to the available backhaul rate for different cooperative decoding strategies, $\text{SNR}_1 = 20$ dB and $\text{SNR}_2 = 10$ dB. For the sake of comparison two additional rates are plotted: the 1% outage rates of a SIMO system with unlimited backhaul and of the single AP case with limited backhaul. In the single AP case only AP_1 decodes the message of STA_1 (labeled as "SISO limited backhaul").

All cooperative strategies outperform the single AP case for backhaul rates $\geq$ 2 bit/s/Hz. At low backhaul rates the DF and DF+QF schemes show the highest 1% outage rate. Pure DF shows the lowest 1% outage rate for high backhaul rates. For $R_3 = R_4 \geq 3$ bit/s/Hz the DF 1% outage rate is no longer limited by the backhaul and therefore constant. For $R_3 = R_4 \geq 9$ bit/s/Hz the 1% outage rates of QF and DF+QF achieve the maximum possible value, i.e. the same value as the system with the unlimited backhaul. The lower performance of the DF scheme is explained as follows: The 1% outage rate gives a rate that is supported with 99% probability, i.e. even in the presence of substantial fading. The performance of the DF strategy for $R_3 = R_4 \geq 9$ bit/s/Hz is in those cases dominated by

$$\log_2(1 + \max\{\text{SNR}_1, \text{SNR}_2\}), \quad (31)$$

while the performance of the QF scheme is given by

$$\log_2(1 + \text{SNR}_1 + \text{SNR}_2) \quad (32)$$

and therefore always higher.

Fig. 6 shows the ergodic rate vs. the backhaul rate for the different cooperative processing strategies. In comparison to Fig. 5 it shows that the loss in ergodic performance for the DF scheme is not so pronounced as in outage performance. For small backhaul rates the slope of the 1% outage rate is much steeper than for the ergodic rate. This shows that the outage performance is less affected by limited backhaul rates.

Fig. 7 shows the average of the value of α^* optimizing the DF+QF UL rate according to (30). For small backhaul rates the power of the DF part is higher than the power assigned to QF. For higher backhaul rates the QF scheme gets more and more important until DF is no longer used.

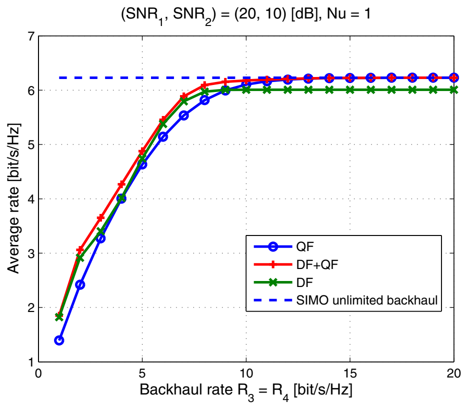

Fig. 6. Average rate vs. backhaul rates: One user, different cooperative processing strategies. Compare to Fig. 5.

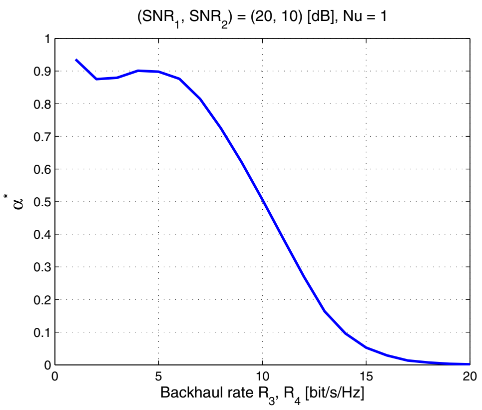

Fig. 7. DF + QF: optimal choice of α, i.e. weighting between DF and QF according to (22): mean value $\overline{\alpha}$ vs. backhaul rate.

Fig. 8 shows the outage probability vs. outage rate for the QF scheme at two different backhaul rate configurations. Firstly, the backhaul rate $R_3 = R_4 = 3$ bit/s/Hz is available as an example for the case where the backhaul is the bottleneck; secondly the backhaul rates R_3^* and R_4^* according to (16) based on the average SNR$_i$ are used, as example for a backhaul with large capacity. In the latter case a similar outage performance as for the unlimited backhaul is achieved. APs can limit the backhaul rates to R_3^* and R_4^* if higher backhaul rates are available.

IV. WLAN Uplink: Two Users, Two APs

In this section we consider the uplink of a low mobility communication scenario as depicted in Fig. 1. Two stations STA$_1$ and STA$_2$ are associated to the two access points AP$_1$ and AP$_2$; they are sharing the same frequency channel, interfering each other[1]. Each node uses only one single antenna.

We analyze similar processing strategies as in Section III. For the DF and DF+QF schemes we assume that only the associated AP can decode, i.e. AP$_1$ for STA$_1$ and AP$_2$ for STA$_2$. In contrast to Section III we do not consider AP selection.

For QF the equations (4) - (8) and (9) are still valid, only the variance of y_i at AP$_i$ assuming same transmit power P_t at each STA is here given by:

$$\sigma_{y_i}^2 = P_t|h_{i1}|^2 + P_t|h_{i2}|^2 + \sigma_n^2. \tag{33}$$

In the case of DF, each AP has to decode the message of the associated STA in the presence of interference caused by the other STA reducing the available SINR and the associated rates R_1 and R_2. The UL rate is given by (19).

For the combination of DF and QF both STAs use superposition coding:

$$x_1 = \sqrt{\alpha_1}x_1^{DF} + \sqrt{1-\alpha_1}x_1^{QF} \tag{34}$$

$$x_2 = \sqrt{\alpha_2}x_2^{DF} + \sqrt{1-\alpha_2}x_2^{QF} \tag{35}$$

At AP$_i$ the DF part of STA$_i$ has to be decoded in the presence of interference given by the QF part of STA$_i$ and the message of the other STA:

$$\text{SINR}_i = \frac{\alpha_i P_t|h_{i1}|^2}{(1-\alpha_i)P_t|h_{i1}|^2 + P_t|h_{i2}|^2 + \sigma_n^2}. \tag{36}$$

The DF+QF UL sum rate is given by:

$$R_{UL}^{DF+QF} = \max_{\alpha_1,\alpha_2}\{R_{UL}^{DF'} + R_{UL}^{QF'}\} \tag{37}$$

With DF processing a spatial multiplexing gain can not be achieved. However, QF (as well as CF) is able to achieve such a gain (provided the backhaul rate is large enough), because the decoding is done at the CU based on the observations of all APs.

A. Performance Results

We analyze the outage probability $P_{out} = P\{R_{UL} < R_{out}\}$ and the 1% outage rate for the different cooperative processing strategies in the two users scenario. The results are based on Monte Carlo simulations. The channel model is slow Rayleigh fading, i.e. we model the channel to be constant for one transmitted block containing one WLAN burst.

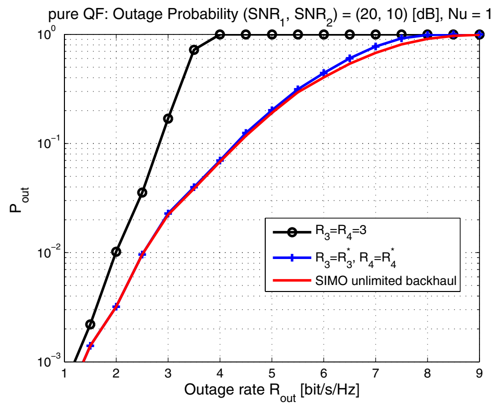

Fig. 8. One user, 2 APs: Outage probability vs. outage rate, QF ; different backhaul rates, SNR$_1$ = 20 dB, SNR$_2$ = 10 dB.

[1]Note, that this would need an extension of the current IEEE 802.11 MAC layer.

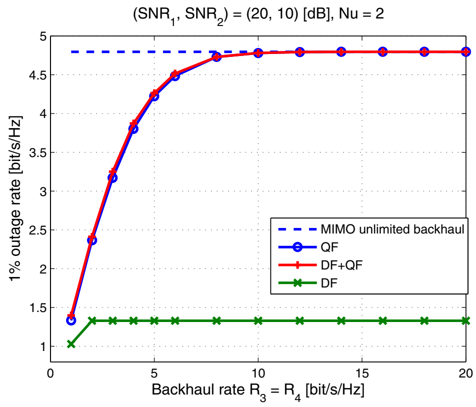

Fig. 9. Two users, 2 APs: 1% outage rate vs. backhaul rate, comparison of different processing strategies.

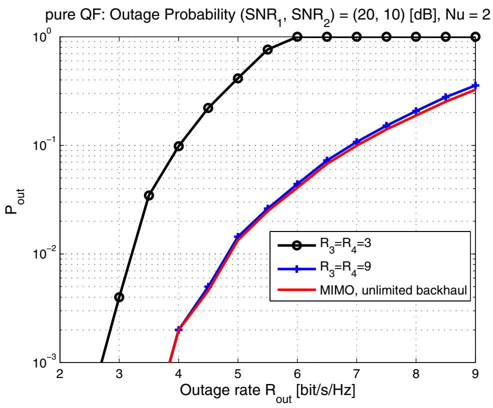

Fig. 10. Two users, 2 APs: Outage probability vs. outage rate, QF with simple quantization; different backhaul rates, $\mathrm{SNR}_1 = 20$ dB, $\mathrm{SNR}_2 = 10$ dB.

For DF and DF+QF schemes the STAs need to have at least rate feedback to achieve the presented rates.

In the case of two STAs we assume a symmetric scenario in which for each user the average receive SNR at the associated AP is SNR_1 and the receive SNR at the other AP is SNR_2; c.f. Fig. 1: for STA_1 $\mathrm{SNR}_{11} = \mathrm{SNR}_1$ and $\mathrm{SNR}_{21} = \mathrm{SNR}_2$, for STA_2 $\mathrm{SNR}_{12} = \mathrm{SNR}_2$ and $\mathrm{SNR}_{22} = \mathrm{SNR}_1$. Compared to the one user scenario, each STA uses only half the transmit power P_t.

Fig. 9 and Fig. 10 show similar results as they were found for the one user scenario. With the exception that in Fig. 9 DF performs worse compared to the other two schemes due to the increased interference and the fact that no spatial multiplexing gain is achieved. Whereas QF and DF+QF achieve the full spatial multiplex gain for backhaul rates large enough. For increasing SNR_2 the performance of the DF scheme decays, because the interference at each AP gets stronger. However, the outage performance of the QF schemes improves with increasing SNR.

V. Conclusions

We studied the potential of cooperative processing in WLAN uplink scenarios where the access points are connected to a backhaul of limited capacity, e.g. a DSL broadband connection. We evaluated different decoding strategies based on an outage criterion and discussed the influence of the available backhaul rates. Processing strategies based on quantization have the potential to achieve diversity as well as spatial multiplexing gains. Using them in environments where several WLANs are coexisting leads to higher spectral efficiency as well as to an significantly improved outage performance – even for low complex quantize & forward schemes without distributed source coding. In cases where the backhaul is the bottleneck, the APs can bundle their backhaul capacities; for high speed backhauls MIMO gains can be achieved. Compared to the ergodic analyses in the literature we observed that the outage performance is much more robust to the backbone limitation; in particular this is interesting for low mobility scenarios as e.g. WLAN. Generally, we observed that a simple quantize and forward scheme achieves significantly higher gains over decode & forward processing.

Because of the large number of existing WLANs in cities as well as residential and office environments, we conclude that cooperative processing is a key strategy to support high rates on future WLAN uplinks and to enable the coexistence of a large number of neighboring WLANs.

References

[1] IEEE802.11, "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," 1999 Edition (ISO/IEC 8802-11:1999).
[2] B. E. Schein, *Distributed Coordination in network information theory*. MIT, Dissertation, Oct. 2001.
[3] A. Sanderovich, S. Shamai, Y. Steinberg, and G. Kramer, "Communication via decentralized processing," in *Proc. IEEE Int. Symposium on Inf. Theory*, (Adelaide, Australia), pp. 1201–1205, Sept. 2005.
[4] A. Sanderovich, S. Shamai, Y. Steinberg, and M. Peleg, "Decentralized receiver in a MIMO system," in *Proc. IEEE Int. Symposium on Inf. Theory*, (Seattle, WA), pp. 6–10, July 2006.
[5] T. Berger, Z. Zhang, and H. Viswanathan, "The CEO problem," vol. 42, pp. 887–902, May 1996.