CSI Feedback in OFDMA Wireless Networks with Multiple Sender-Receiver Pairs

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***Abstract*—In wired or wireless distribution systems, as well as wireless mesh networks, multiple senders often need to deliver data to multiple receivers in the same interference domain. OFDMA enables interference avoidance by assigning disjoint sets of subcarriers to each sender. However, optimal subcarrier allocation requires CSI feedback to the transmitters, thus incurring overhead. We evaluate an allocation mechanism inspired in subcarrier switching techniques, which allows nodes to locally decide which subcarriers they prefer. Hence, feedback is minimal, as only preference values need to be shared. We implement this approach on software defined radios and compare it to standard CSI feedback mechanisms. Despite our approach only requires local information, the results show that it performs close to an ideal solution based on full CSI knowledge.**

I. Introduction

As the number and density of wireless devices increases, interference mitigation techniques become key to support the required bandwidths. In order to keep up with these demands, wireless deployments become more dense and terminals are often in reach of multiple access points. Hence, classical $1 \times n$ scenarios with one base station and n terminals are turning increasingly into $m \times n$ setups, where m nodes need to deliver data to n receivers. This becomes interesting also beyond access networks, as similar setups arise for example in wireless mesh networks. Specifically, networks employing Corridor-based Routing [1] benefit from this approach.

Interference mitigation in $m \times n$ scenarios can be achieved by techniques such as interference alignment/cancellation [2] or MU-MIMO [3]. However, the requirements imposed by such approaches often include precise channel state information at the transmitters (CSIT) and high complexity. Interference avoidance based on Orthogonal Frequency Division Multiple Access (OFDMA) is a less complex approach where multiple transmitters in range of each other can send at the same time by using disjoint sets of OFDM subcarriers. While a random allocation of subcarriers would lead to the same performance than a plain time division (TDMA) system, assigning each subcarrier to the sender-receiver pair which experiences the best channel quality on the corresponding frequency can improve performance significantly. However, finding such an allocation requires CSIT and thus incurs overhead.

Despite interference avoidance schemes based on OFDMA have been adopted by LTE, $m \times n$ scenarios pose a more difficult challenge, as CSIT must be coordinated among multiple sender-receiver pairs. Hence, the overhead becomes even larger. This raises concerns regarding the efficiency of the scheme. Existing work [1], [4] often assumes that CSIT is available with negligible overhead due to long channel coherence time, but it is unclear how the actual overhead impact in a practical $m \times n$ scenario is.

In this paper, we analyze the aforementioned overhead impact in a practical 2×2 scenarios comparing different CSI feedback strategies. Additionally, we evaluate a feedback mechanism with minimal overhead based on subcarrier switching [5]. Essentially, this mechanism allows nodes to decide *locally* whether they are interested in using a certain subcarrier by comparing it with the average quality they experience on the complete channel. The first node sending in a certain interference domain chooses its best subcarriers and starts transmission, leaving the rest of subcarriers free. By sensing the medium, subsequent nodes choose their best subcarriers out of the remaining ones. The benefits of this approach are (a) nodes do not need to exchange costly CSI, but just subcarrier preferences and (b) by randomizing the order in which nodes select subcarriers in each transmission, allocation becomes fair in the long term, as each node has the opportunity to get its best subcarriers, irrespectively of the quality experienced by other nodes.

The crucial difference between our approach based on subcarrier switching and standard CSI feedback is that allocation decisions are taken locally instead of globally. Hence, nodes can consider additional parameters for allocation decisions, such as the current traffic load of the node, without having to use costly bandwidth to announce this information to a central controller. To the best of our knowledge, subcarrier switching in $m \times n$ OFDMA scenarios has not been considered so far nor practically implemented. Our contributions are as follows:

1) We exploit subcarrier switching in $m \times n$ networks
2) We implement this scheme on a Software Defined Radio (SDR) platform for a 2×2 network
3) We evaluate its performance in comparison with CSI feedback mechanisms inspired in LTE

The remainder of the paper is structured as follows. In Section II we briefly survey related work. Then, in Section III, we present the CSI feedback mechanisms we compare. After that, in Section IV we introduce our experiment setup based on the Wireless Open-access Research Platform (WARP) [6] SDR and discuss our practical measurement results. Finally, in Section V we conclude the paper.

II. Related Work

CSI feedback. There exists extensive work on providing CSI feedback to a transmitter in OFDM and OFDMA systems [7]. While we consider a similar problem, our mechanisms are specifically designed for an $m \times n$ scenario, while existing work focuses on $1 \times n$ systems, both for the case of OFDM [8] and OFDMA [9]. A distributed $m \times n$ scenario poses additional constraints and offers new possibilities for other topologies, such as mesh networks. Moreover, most of the existing work is either simulative or theoretical [10], while we implement and measure our techniques in practice on software defined radios. Practical issues have been studied for implementation of OFDMA in LTE [11], but again focusing on $1 \times n$ scenarios.

Subcarrier allocation. The LTE scenario has also motivated a number of works in the area of OFDMA subcarrier allocation [12], [13]. However, we consider a distributed environment, where the allocation and coordination problem becomes more complex. There exists work on this topic focusing on wireless multihop networks and OFDMA [14], [15], but it is often restricted to theory and simulation. Other approaches design a complete system for this scenario [16], but again restrict themselves to simulations. In contrast, in this work we implement subcarrier allocation algorithms and analyze the impact of CSI feedback strategies in practice .

III. System Design

A. Scenario

We consider a $m \times n$ setup with m senders and n receivers. Moreover, we assume a full buffer model, which means that all senders always have information for all receivers. In a TDMA approach, senders transmit in sequence without interference using the complete bandwidth available. When using OFDMA, all senders transmit at the same time, but on disjoint sets of subcarriers. There are N_c subcarriers available, which can be allocated to any sender-receiver pair, as all nodes share the same interference domain.

To maximize the overall throughput, an ideal allocation algorithm would assign each subcarrier to the sender-receiver pair which experiences the best channel quality on that frequency. However, this requires coordination among the senders and CSI feedback to determine the aforementioned disjoint sets. In the following, we describe four mechanisms to achieve this, out of which two are baseline schemes. For each, we define an abbreviation (TDMA, BOOMxN, Greedy, CB) to easily refer to them in the rest of the paper.

B. Coordination and Feedback Mechanisms

1) Baseline Schemes: In order to determine the gain achieved by allocating individual subcarriers to different nodes, we consider a plain **TDMA** scheme. In this case, all m senders transmit in sequence and a randomly chosen receiver decodes the data. Each frame includes pilot and data symbols. Hence, receivers can determine the corresponding zero forcing equalizer and decode the data. This scheme requires no CSIT nor coordination, except time synchronization, which is also assumed by all other schemes we consider.

Additionally, to determine how close our mechanisms get to the best possible allocation of subcarriers, we compare our results with an ideal scheme which has full CSIT knowledge and employs a *best-out-of-*$m \times n$ (**BOOMxN**) algorithm. For each subcarrier, the algorithm chooses the sender-receiver pair out of the $m \times n$ available links which provides the smallest $\left|\frac{N}{H(f)}\right|$. This coefficient is the amplitude of the noise added to a symbol after zero forcing, as stated by the linear system representing a transmission, i.e. $\frac{Y(f)}{H(f)} = X(f) + \frac{N}{H(f)}$. Note that this approach is unfair, as links experiencing low channel quality might not get any subcarriers at all, but it serves as an upper boundary of the achievable gain.

In BOOMxN, the receivers first send a short frame with pilot symbols to the senders. We assume channel reciprocity, which means that after this first step, all senders have CSIT to all receivers. The experiments in Section IV validate this assumption. Since BOOMxN is an ideal baseline scheme, we further assume that all transmitters have access to a high speed wired backbone over which they share their CSIT. Hence, in a second step, all transmitters can run the *best-out-of-*$m \times n$ algorithm and determine the best possible subcarrier allocation. Finally, the senders transmit data according to this allocation.

2) Subcarrier Switching: We now introduce our coordination and feedback scheme based on subcarrier switching. Since this approach enables each node to decide on its own which subcarriers it prefers, we refer to it as **Greedy**. Initially, operation is similar to the BOOMxN case, i.e. the transmitters learn CSIT by means of pilot symbols sent by the receivers. However, in this case each sender locally calculates the $\left|\frac{N}{H(f)}\right|$ coefficient for each of its subcarriers and determines the average over all coefficients. The subcarriers preferred by the node are the ones whose coefficient is *below* the average, as a smaller coefficient means less noise impact.

As a next step, transmitters send in sequence their preferred subcarriers. The required overhead is minimal, as transmitters just need to send a binary zero for subcarriers they are not interested in and a binary one for the ones they prefer. Hence, only a single BPSK-modulated OFDM symbol is needed by each transmitter. Note that this is an alternative approach to the carrier sensing technique introduced in Section I. Instead of sharing subcarrier preferences implicitly by occupying subcarriers, nodes share them explicitly. As explained in Section IV, we choose this approach for ease of implementation, but a carrier sensing technique would most probably be even more efficient and thus yield a lower overhead.

The frame containing the preferences of a sender also includes a pilot sequence, as the other transmitters need to learn the channel to the sender in order to decode its preferences. Since the receivers overhear this transmission, they can utilize the pilot sequence to learn their channels to the corresponding transmitter, which they later on use for decoding the actual data transmission. Once all transmitters have shared their subcarrier preferences, each sender can locally determine the final allocation. To this purpose, a priority order is needed, which can change in a well-defined manner for each transmission cycle. For example, to achieve a fair system, the order would rotate by one position for each cycle. Other priority mechanisms could be used to assign a larger bandwidth share to a certain node. A transmission cycle is the time interval during which the channel stays stable and data can be sent, before having to send again pilots to update zero forcing filters and node preferences.

Finally, the transmitters send the actual data according to the allocation determined based on the preferences of each node and the priority order. Note that no pilot symbols are needed anymore, as receivers have already learned the channels to each transmitter during the preference sharing phase.

3) CSI Feedback: Our last mechanism works similarly to the BOOMxN approach, but instead of sharing CSIT via a high speed backbone, transmitters send it over the wireless medium. Hence, this mechanism measures the actual cost of CSI feedback in a practical $m \times n$ scenario. Since plain transmission of CSI values would incur a large overhead, current systems such as LTE use a codebook approach [11], which means that sender and receiver share a set of possible quantized CSI values. In order to transmit a CSI value, receivers only need to indicate the index of the most similar value of the codebook, thus reducing overhead significantly. We adopt a similar approach for our CSI feedback scheme and thus refer to it as codebook scheme (**CB**).

Essentially, the operation of CB is identical to Greedy. However, instead of sharing preferences, each transmitter sends its CSI coded with a suitable codebook. Specifically, it sends its quantized $\left|\frac{N}{H(f)}\right|$ coefficient for each subcarrier. Thus, after the sharing phase, each transmitter has global CSI knowledge and can run the *best-out-of-*$m \times n$ algorithm to determine the best allocation. However, we expect the overhead to be significantly larger compared to Greedy, even when using a codebook. We assume that sender and receiver already share a codebook at the beginning of the transmission and thus do not include the codebook exchange as part of the overhead.

C. Overhead calculation

We count as overhead all OFDM symbols which do not contain data. Hence, we include the initial pilot symbols required by all schemes described in Section III-B. The main components of the overhead are however the preferences and the codebook-quantized CSI for Greedy and CB, respectively. Additionally, all schemes need to monitor channel conditions during data transmission in order to determine when the channel has changed. This can be achieved by including pilot symbols at selected time and frequency intervals in the data frames. However, we do not count this as overhead, as it does not affect the proportion of useful data to overhead in a frame. We do not include the processing time at the nodes either.

Overhead is incurred for each of the aforementioned transmission cycles. Hence, the longer these cycles become, the smaller is the overhead impact. The length of a transmission cycle is directly related to the channel coherence time, which in turn depends on the mobility of the network. For a static environment, coherence time becomes very long and thus overhead tends to zero. While we use a static network in the measurements presented in Section IV, we extrapolate the data to infer the throughput for different coherence time values. Essentially, we measure the bits correctly delivered by a scheme for a duration of t_{measure}, calculate how many times t_{measure} fits into the chosen $t_{\text{coherence}}$, extrapolate the correct bits accordingly and divide by $t_{\text{coherence}}$ to obtain the throughput *thp*. To account for the overhead, we subtract it from the number of correctly delivered bits, as shown in Equation 1.

$$\text{thp} = \frac{(\text{bits}_{\text{transmitted}} - \text{bits}_{\text{erroneous}} - \text{bits}_{\text{overhead}}) \cdot \frac{\text{t}_{\text{coherence}}}{\text{t}_{\text{measure}}}}{\text{t}_{\text{coherence}}} \quad (1)$$

This measurement technique enables us to analyze the overhead impact for different coherence times. In Section IV, we choose values corresponding to typical mobility speeds, ranging from 5 km/h (pedestrian) to 100 km/h (automotive).

IV. Performance Evaluation

A. Experimental Setup

1) Platform: We implement the four schemes introduced in Section III-B on the Wireless Open-Access Research Platform (WARP), which is a FPGA-based Softwared Defined Radio (SDR) developed at Rice University [6]. It enables us to perform experiments in similar settings to a wireless local area network, but with full control regarding the lower layers. We use the WARPLab Reference Design, which is a framework for rapid prototyping based on Matlab. Hence, instead of realizing the aforementioned schemes in hardware on the FPGA itself, we implement them in software, but still perform measurements on the actual wireless medium.

Essentially, we calculate the transmit samples in Matlab and send them via Ethernet to a first WARP node, which then transmits them over the air to a second WARP node. This board then sends the received samples again via Ethernet to Matlab, where we post-process them off-line. While this approach allows for high flexibility, it is not real-time, since the delay incurred in sending the samples via Ethernet and processing them in Matlab is orders of magnitude larger than if processing was done on the FPGA. Hence, channel state could vary during one Matlab iteration. However, we perform measurements in a static and stable testbed, which translates into large coherence times that allow us to assume that channel state remains approximately constant. While this limits our implementation of the greedy mechanism, since carrier sensing would require a real-time approach, we circumvent this problem providing minimal feedback, as described in Section III-B.

2) Scenario: We consider a 2×2 network. Since each WARP board has two radio interfaces, we connect the two senders and the two receivers to a single board, respectively, in order to synchronize them. However, data sent and received by each radio is treated independently, as if each one was a different node. We only exploit the shared WARP boards for synchronization, since this is a crucial requirement of OFDMA, but out of scope for our work. No MIMO or other multi-antenna techniques are used. We place the four node antennas on the corners of an empty table, separating the send and receive antennas 70 cm among and 1.5 m from each other. All experiments are carried out in this scenario over a time frame of 15 minutes. Each measurement is repeated 10 times to obtain average values and 95% confidence intervals, which are shown in the figures presented in Section IV-B.

3) Metrics: We evaluate our mechanisms according to four metrics, namely throughput, symbol error rate (SER) and bit error rate (BER). Throughput is calculated as explained in Section III-C, i.e. the throughput values already include the overhead. The BER and SER are the error rates obtained for a t_{measure} interval.

4) Parameters: In our experiments, we analyze the influence of the bits per symbol (BPS $= \{4, 6, 8, 10\}$), the coherence time ($t_{\text{coherence}} \in [2; 45]$ ms) and the codebook size for CB (8, 16, 64 and 128 codebook values). For LTE, the standardized codebook size is 16 [11].

B. Results

1) Throughput: Figure 1 shows the throughput for each of the modulation schemes we consider. For low BPS values, TDMA outperforms all other schemes, since it requires no overhead and the distance between constellation points is large enough to ensure that nearly no errors occurs on any subcarrier, i.e. the impact of noise and fading is insignificant. In our setup, this happens for 16-QAM. For all schemes, throughput increases with longer coherence times, since the impact of the overhead becomes smaller as frames become larger.

However, at higher BPS values the overhead of subcarrier allocation starts to pay off. For 64-QAM, at low coherence times the channel still changes too fast to justify the overhead of Greedy and CB, but for $t_{\text{coherence}} > 4$ ms both schemes outperform TDMA significantly. For larger BPS, this happens for all coherence times we consider. Note that, while Greedy only uses minimal feedback, it consistently achieves higher throughput rates than CB. Moreover, the throughput values are close to the ideal BOOMxN, yielding gains of up to 25% compared to TDMA. In Figure 1 we show the performance for a codebook size of eight for the CB scheme, which is the case with smallest overhead we consider. We choose this codebook size because Experiment IV-B4 shows that larger codebook sizes perform equal or even worse.

2) BER: The BER measurements match our observations in the throughput experiments. Figure 2(a) presents the BER for each mechanism for the four modulation schemes we consider. Note that the scale of the 16-QAM case is orders of magnitude smaller than the others. As expected, for all BPS values BOOMxN performs best, as it uses the best possible allocation at the expense of assuming full channel knowledge at each node. On the contrary, TDMA does not use any channel knowledge at all and thus consistently performs worst. For Greedy and CB there is barely any difference for all modulation schemes above 16-QAM. Hence, we conclude that for OFDMA subcarrier allocation even minimal feedback as used in Greedy is enough for achieving BER performance similar to LTE-inspired codebook-based CSI feedback.

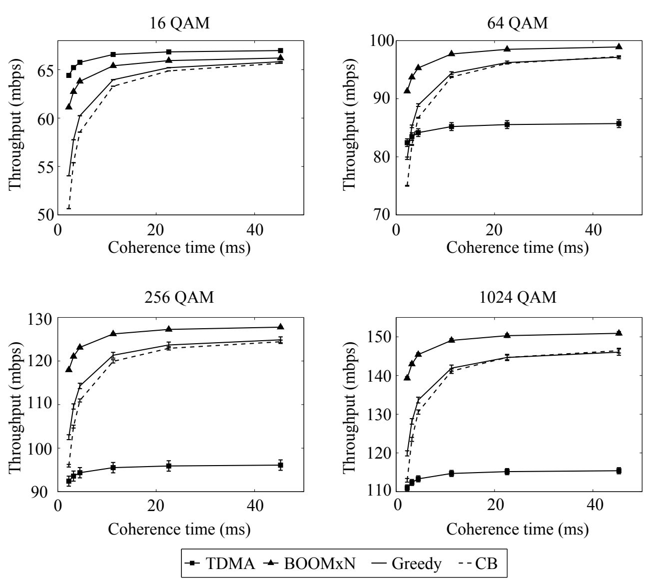


Fig. 1: Throughput gains are only achieved above 16-QAM.

TABLE I: Codebook size impact on throughput (in mbps).

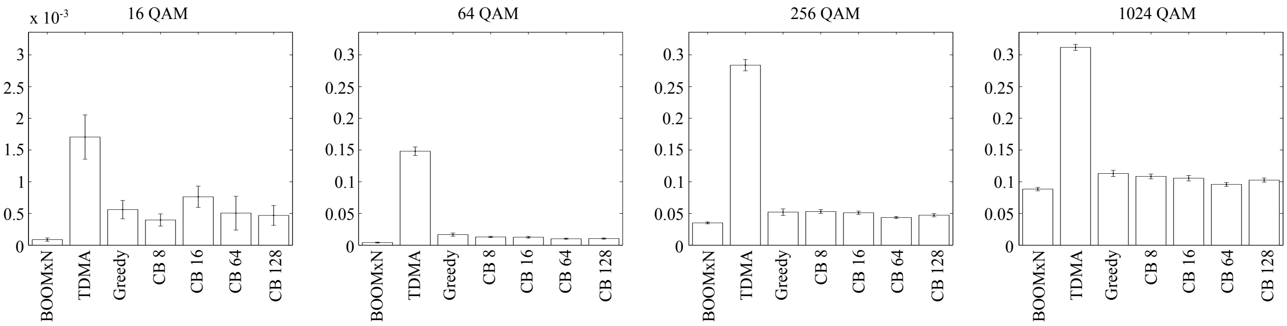
Size	$t_{\text{coherence}} = 2$ ms	Improvement	$t_{\text{coherence}} = 45$ ms	Improvement
8	75.02 ± 0.07	0%	97.25 ± 0.09	0%
16	72.52 ± 0.09	-3.33%	97.17 ± 0.12	-0.08%
64	67.65 ± 0.06	-9.82%	97.16 ± 0.08	-0.09%
128	65.10 ± 0.06	-13.22%	97.01 ± 0.09	-0.24%

3) SER: As shown in Figure 2(b) the SER shows a similar behavior to the BER. However, the values for high order modulation schemes become significantly larger, since Gray coding helps mitigating the effect on the BER. For BPS values just above the threshold beyond which TDMA suffers a large SER, the allocation of subcarriers becomes especially interesting. In our setup, this happens for 64-QAM, where TDMA raises to nearly 70% symbol errors, while Greedy and CB remain at reasonable 10%. The same effect occurs for higher modulation schemes, but in that case the SER values become very large even with subcarrier allocation. However, again Greedy performs very close to CB for all modulations.

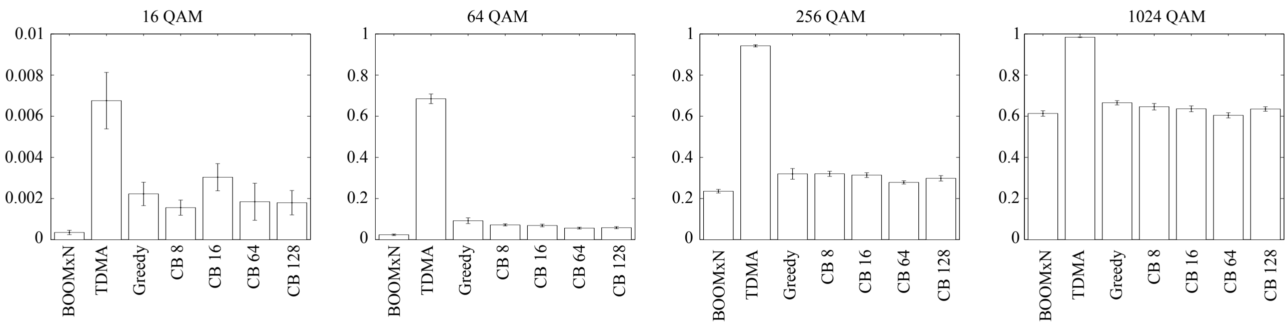
4) Codebook size: We now investigate the impact of the codebook size on throughput. The larger the codebook, the more detailed is the CSI feedback. However, as shown in Table I, coarse CSI is enough for deciding on subcarrier allocation. While increasing the codebook size leads to a better allocation, the gain is smaller than the overhead, ultimately yielding lower throughput values. Hence, the improvement achieved by using larger codebooks is negative. The impact is particularly large for short coherence times. When large data frames are possible, the incurred overhead is very low.

This might lead to the conclusion that smaller codebooks are better, as they have less overhead and still perform good. However, in the experiments we learned that a codebook size of e.g. four causes severe practical issues regarding the *peak to average power ratio* (PAPR). Specifically, a codebook of size four would code four CSI states with two bits. As neighboring subcarriers have similar channel quality, there would be long sequences of the same state, which in half the cases would be alternating ones and zeros. In the time domain, this translates into large peaks in signal amplitude. Hence, after normalization the average signal power is very small. To solve this, we use a scrambler to avoid long alternating sequences. This approach works well for codebook sizes equal or larger than eight, but is unreliable for smaller values. If CSI is not fed back reliably to the sources, the allocation algorithms cannot work correctly.

While CB suffers from channel coherence in the frequency domain, Greedy benefits from it, since it only codes two states. Nodes are either interested or not in a certain subcarrier. Thus, similar quality on neighboring subcarriers translates into large constant sequences of ones or zeros, which cause no PAPR issues. As a result, preference vectors are transmitted not only with minimal overhead, but also reliably to the transmitters.



(a) BER. Symbols are Gray coded, which reduces the noise impact on the BER.



(b) SER. In our setup, noise becomes severe for modulation schemes larger than 256-QAM.

Fig. 2: Note that the vertical scale of the 16-QAM case is different from the other modulations.

V. Conclusion

We analyze the overhead required to coordinate nodes in an OFDMA scenario with m transmitters and n receivers. The goal is assigning OFDMA subcarriers to the best available source-destination pairs. To this end, CSI knowledge is required at the transmitters. We compare LTE-inspired CSI feedback based on codebooks with a mechanism which only requires nodes to signalize whether they are interested in a certain subcarrier or not, thus incurring minimal overhead. We implement both approaches on a software defined radio and show that they perform similarly despite the different overhead requirements. Both perform close to the optimal throughput gain even in scenarios with small coherence times. Hence, we conclude that OFDMA subcarrier allocation in $m \times n$ scenarios can provide large gains despite requiring CSI.

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