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

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***Abstract*—In wireless systems, multiple transmitters 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 transmitter. However, optimal subcarrier allocation requires CSI feedback to the transmitters, thus incurring overhead. We evaluate an allocation mechanism inspired by 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. Although our approach only requires local information, the results show that it performs close to a solution based on full CSI knowledge.**

I. Introduction

As the number and density of wireless devices increases, interference mitigation techniques are key to support the required data rates [1]. 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 $n \times 1$ scenarios with one base station and n terminals are turning increasingly into $m \times n$ setups, where m transmitters send data to n possible receivers.

Interference mitigation in $m \times n$ scenarios can be achieved by techniques such as interference alignment/cancellation [2] or multi-user multiple-input multiple-output (MU-MIMO) [3]. However, the requirements imposed by such approaches often include precise channel state information at the transmitters (CSIT) and high complexity [3]. Optimized resource allocation based on Orthogonal Frequency Division Multiple Access (OFDMA) is a less complex approach where multiple transmitters in range of each other can also send at the same time by using disjoint sets of OFDM subcarriers. Assigning each subcarrier to the transmitter-receiver pair which experiences the best channel quality on the corresponding frequency can improve performance significantly [4]. However, finding such an allocation requires CSIT and thus incurs overhead.

Although resource allocation schemes based on OFDMA have been adopted for cellular scenarios, $m \times n$ scenarios pose a more difficult challenge, as global CSIT must be known at multiple transmitter-receiver pairs. Hence, the overhead becomes even larger. This raises concerns regarding the efficiency of the scheme. Existing work [4], [5] often assumes that CSIT is available with negligible overhead due to long channel coherence time, but it is unclear how large the actual overhead in a practical $m \times n$ scenario is.

In this paper, we compare the overhead of different CSI feedback strategies for general $m \times n$ scenarios. To that end, we analyze them in a practical 2×2 setup. Additionally, we propose and evaluate a feedback mechanism with minimal overhead based on subcarrier switching [6]. Essentially, this mechanism allows transmitters 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 transmitter sending in a certain interference domain chooses its best subcarriers and starts the transmission, leaving the remaining subcarriers free. By sensing the medium, subsequent transmitters choose their best subcarriers out of the remaining ones. The benefits of this approach are (a) transmitters do not need to exchange costly CSI, but just subcarrier preferences and (b) by switching the order in which transmitters select subcarriers in each transmission, the allocation becomes fair in the long term, as each transmitter has the opportunity to get its best subcarriers, irrespective of the quality experienced by other transmitters.

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, transmitters can consider additional parameters for allocation decisions, such as the current traffic load of the node, without having to use costly bandwidth to share this information. 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 by 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 experimental setup 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 wireless systems [7]. For both OFDM and OFDMA, there exist mechanisms [8], [9] which provide only one bit CSI using a low-rate feedback channel. Even with such minimal feedback, they achieve large enhancements in system performance. Moreover, in [9] the tradeoff between feedback rate and sum capacity is studied. While we consider a similar problem, we extend it to $m \times n$ scenarios and measure our techniques in practice. This sets appart our work from existing approaches, which are predominantly simulative or theoretical [10]. Practical issues have been studied for OFDMA in LTE [11], but again for $n \times 1$ 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. There exists related work focusing on wireless multihop networks and OFDMA [14], [15], but it is often restricted to theory and simulation. For example, in [15] the authors hierarchically decouple the subcarrier and power allocation problem of OFDMA in WMNs into two independent subproblems. Other approaches design a complete system for this scenario, such as in [16], where the authors propose a cross-layer approach ranging from a subcarrier selection algoritm at physical layer to a new medium access control scheme adressing the synchronization requirements of OFDMA. They show throughput gains by means of simulation. 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 general uplink $m \times n$ setup with m transmitters and n receivers which does not necessarily have to be a cellular setting. Moreover, we assume a full buffer model, which means that all transmitters always have information for all receivers. In a time division multiple access (TDMA) approach, transmitters send in sequence without interference using the complete bandwidth available. When using OFDMA, all transmitters send at the same time, but on disjoint sets of subcarriers. Available subcarriers can be allocated to any node pair, as all nodes are in range of each other. No water filling is applied, as the same power is allocated to all subcarriers.

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

B. Coordination and Feedback Mechanisms

1) TDMA: In order to determine the gain achieved by allocating individual subcarriers to different transmitter-receiver pairs, we consider a plain **TDMA** scheme as a baseline. In this case, all m transmitters send in sequence and a randomly chosen receiver decodes the data. This allows us to obtain the average performance in a 1×1 scenario without spatial diversity. Each frame includes pilot and data symbols. This scheme requires neither CSIT nor coordination, except time synchronization, which is assumed by all schemes we consider.

2) BOOMxN: In order to determine how close our mechanisms get to the best possible allocation of subcarriers, as a second baseline we compare our results with an ideal scheme which has full CSIT knowledge and employs a *best-out-of-*$(m \times n)$ (**BOOMxN**) algorithm. Given a certain transmitter i, receiver j, average noise power N, channel transfer function $H_{ij}(f)$, sent signal $X_i(f)$ and received signal $Y_j(f)$, the algorithm chooses for subcarrier at frequency f the transmitter-receiver pair out of the $m \times n$ available links which provides the smallest $\left|\frac{N}{H_{ij}(f)}\right|$. This coefficient is the average noise power added to a symbol after zero forcing, as stated by the linear system representing the transmission, which is $\frac{Y_j(f)}{H_{ij}(f)} = X_i(f) + \frac{N}{H_{ij}(f)}$. 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 bound of the achievable performance. While we consider noise power to be equal at all nodes, we include N in the criterion for subcarrier allocation because in a practical setup the actual SNR expriencied by a node is influenced by its amplifier gain, which needs to be adjusted individually at each receiver.

In BOOMxN, the receivers first send a short frame with pilot symbols to the transmitters. We assume channel reciprocity, which means that after this first step, all transmitters have CSIT to all receivers. Our experiments 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 transmitters send data according to this allocation.

3) Greedy: We now propose our coordination and feedback scheme based on subcarrier switching. Since this approach enables each transmitter to decide on its own which subcarriers it prefers, we refer to it as **Greedy**. Note that transmitters still need to coordinate by letting each other know which subcarriers they prefer. Initially, similar to the BOOMxN case, the transmitters learn CSIT by means of pilot symbols sent by the receivers. However, in this case each transmitter locally calculates the $\left|\frac{N}{H_{ij}(f)}\right|$ coefficient for each of its subcarriers and determines the average over all coefficients. The subcarriers preferred by the transmitter are the ones whose coefficient is *below* the average, as a smaller coefficient means less noise impact. Note that the threshold could also be chosen according to different criteria, e.g. a transmitter could set it in order to only choose subcarriers which support a certain modulation.

As a next step, each transmitter sends in sequence its preferred subcarrier indices to the other transmitters in order to coordinate which one will be allowed to send on which subcarrier. 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 as an intuitive explanation of Greedy. Instead of sharing subcarrier preferences implicitly by occupying subcarriers, transmitters share them explicitly by sending a message. We choose this approach for ease of implementation, but a carrier sensing technique would most probably be even more efficient.

The frame containing the preferences of a transmitter also includes a pilot sequence, as the other transmitters need to learn the channel to the transmitter 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 transmitter can locally determine the final allocation. To this purpose, a priority order is needed. The node with the highest priority allocates all subcarriers it prefers, while the next ones can only choose out of the remaining subcarriers. Hence, no subcarrier is allocated twice. To achieve a fair system, the order would rotate by one position for each transmission cycle. A transmission cycle is the time interval during which the channel stays stable and data can be sent before having to send again pilots. Priority schemes are negotiated in advance for many transmission cycles and thus exchanging them incurs a negligible overhead. Finally, the transmitters send data according to the allocation. As we assume an uplink scenario, receivers can share CSI via a wired link to deduce which subcarrier is intended for which node.

4) CB: As a last mechanism, we introduce a CSI feedback approach inspired by LTE. Note that we use LTE as a guideline as it also employs OFDMA, but we do not specifically focus on a cellular scenario. The aim is providing a reference for measuring the performance of Greedy in comparison to an existing approach. It works similarly to the BOOMxN scheme, but instead of sharing CSIT via a high speed backbone, transmitters send it over the wireless medium. Since plain transmission of CSI values would incur a large overhead, existing systems use a codebook approach [11], which means that transmitter 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. We adopt a similar approach for our reference scheme and thus refer to it as codebook scheme (**CB**).

As opposed to Greedy, instead of sharing preferences, each transmitter sends its CSI coded with a suitable codebook. Specifically, it sends its quantized $\left|\frac{N}{H_{ij}(f)}\right|$ 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. We assume that transmitter and receiver already share a codebook and thus do not include its 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. While TDMA and BOOMxN do not have such feedback overhead, we count for both the overhead due to pilot symbols. Moreover, BOOMxN requires double the amount of pilots, as the channels need to be known both at transmitters and receivers. All schemes need to monitor channel conditions during transmission in order to determine when the channel has changed. However, we do not take this into account as overhead since it affects all schemes in the same manner.

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 our testbed only allows us to perform measurements in a static environment, 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.

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

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 an FPGA-based Softwared Defined Radio (SDR) developed at Rice University [17]. It enables us to perform experiments 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 on the FPGA itself, we implement them in software. Still, measurements are performed on the actual wireless medium and are *not* simulative. The only limitation imposed by the WARPLab framework is that the implementation is not real-time. Thus, channel state could vary during one experiment. However, we perform our experiments in a static and stable testbed, which allows us to assume large coherence times. Continous channel measurements over a time frame of 30 minutes reveal that channel state remains approximately constant in our setup.

2) Scenario: We consider a 2×2 network. Since each WARP board has two radio interfaces, we connect the two transmitters 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 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. The channels are thus line-of-sight (LOS) and follow a Rician distribution. Measurements reveal a freqency selective behavior and an average SNR of about 30 dB. These parameters are imposed by the experimental environment and cannot be varied. 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.

TABLE I: System parameters.

Parameter	Value	Parameter	Value
FFT size	1024	Symbol duration	25,6 μs
Usable subcarriers	484	Guard space	3,2 μs
Pilot symbols	3	Subcarrier spacing	38,147 kHz
Data symbols	10	Passband bandwidth	18,463 MHz

TABLE II: 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) Metrics: We evaluate our mechanisms according to three metrics, namely throughput (see Section III-C), symbol error rate (SER) and bit error rate (BER). The BER and SER reflect the uncoded error performance obtained for an interval of t_{measure}. Channel coding is orthogonal to our approach, as we focus on the gains achievable by subcarrier allocation.

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]. Regarding the BPS parameter, we also considered BPSK and QPSK, but the results were similar to 16-QAM and did not provide any additional insights. Hence, we left them out for clarity. Additional system parameters are specified in Table I.

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 occur on any subcarrier. In our setup, the impact of noise and fading does not justify the overhead of subcarrier allocation up to 16-QAM. For all schemes, throughput increases with larger 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 achieves the same or even 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 our measurements show that larger sizes perform equal or even worse. The codebook elements are chosen in a channel dependent manner, i.e. we code the most frequent ranges of the $\left|\frac{N}{H_{ij}(f)}\right|$ coefficient with more detail than the less frequent ones.

2) BER: Figure 2(a) presents the BER for each mechanism for the four modulation schemes we consider. As expected, for all BPS values BOOMxN performs best, as it uses the best possible allocation. On the contrary, TDMA does not exploit spatial diversity at all and thus consistently performs worst. For Greedy and CB, note that confidence intervals overlap for all modulation schemes. Slight variations are due to t_{measure} being limited to 256 μs. It may happen that no errors occur during that interval, especially for lower modulation schemes, which translates into a coarser error rate measurement. Hence, the performance of Greedy and CB is essentially the same. We conclude that for subcarrier allocation even minimal feedback is enough, i.e. while larger codebooks do provide more precise CSI, our allocation mechanism produces a similar result than with coarse CSI. Hence, also the performance is likewise.

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.

4) Codebook size: We now investigate the impact of the codebook size on the throughput. The larger the codebook, the more detailed is the CSI feedback. However, as shown in Table II, coarse CSI is enough for deciding on subcarrier allocation. While increasing the codebook size leads to more precise CSI, 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.

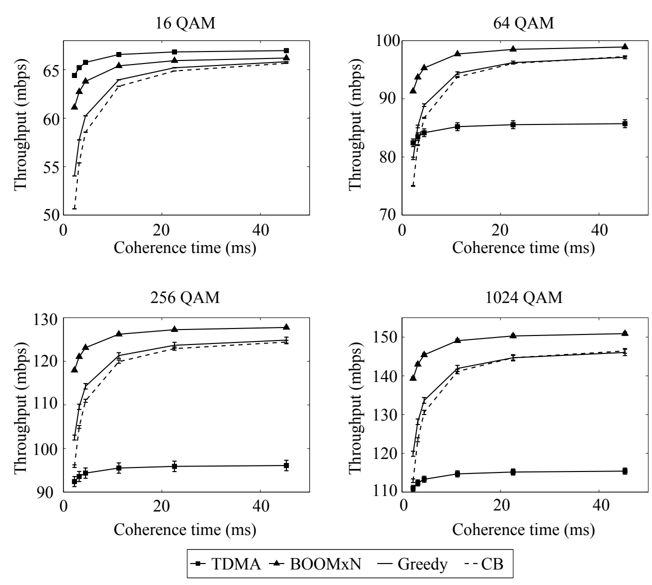
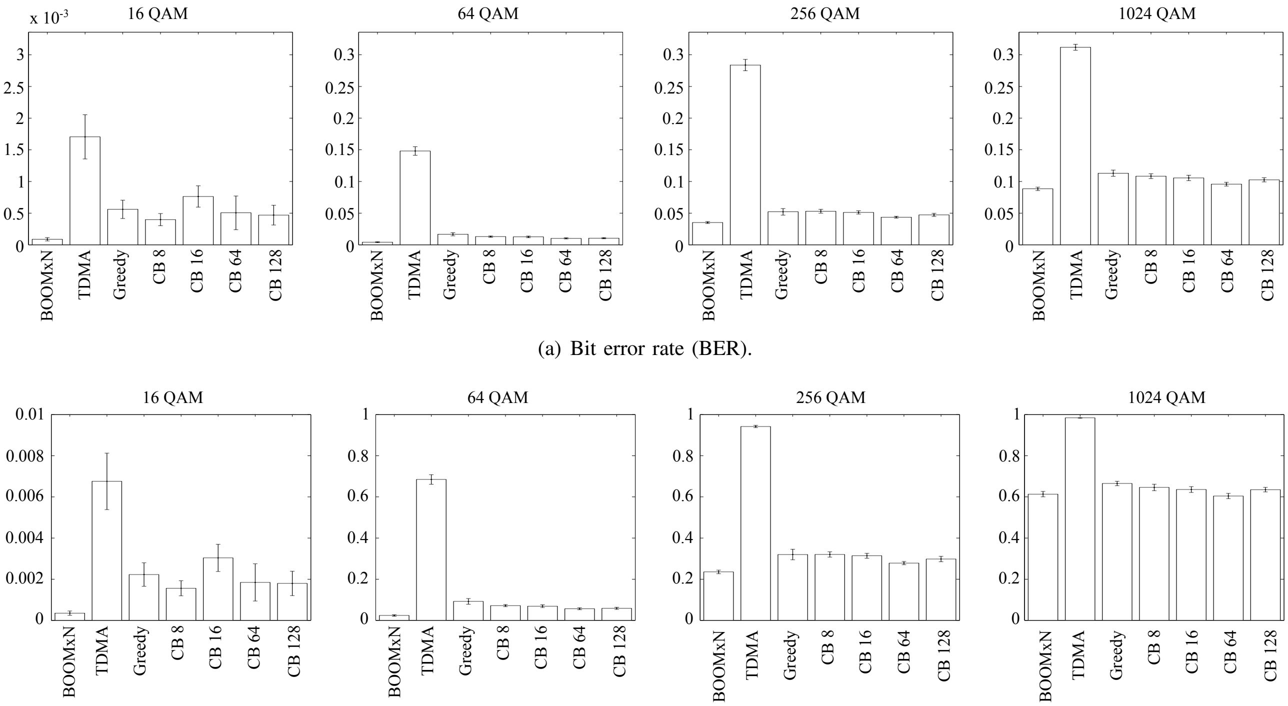


Fig. 1: Throughput vs. coherence time for BPS $= \{4, 6, 8, 10\}$



(a) Bit error rate (BER).

(b) Symbol error rate (SER).

Fig. 2: Error rates in a 2×2 scenario. Note scale difference for the 16-QAM case.

V. Conclusion

We analyze the overhead required for coordination in an OFDMA scenario with m transmitters and n receivers. The goal is assigning OFDMA subcarriers to the best available transmitter-receiver pairs. To this end, CSI knowledge is required at the transmitters. We compare LTE-inspired CSI feedback with a mechanism which only requires transmitters to signal whether they are interested in a certain subcarrier, thus incurring minimal overhead. We implement both approaches on a software defined radio platform 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 subcarrier allocation can provide large gains in scenarios with multiple transmitter-receiver pairs despite requiring CSI.

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