

Practical OFDMA for Corridor-based Routing in Wireless Multihop Networks

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Abstract—Corridor-based Routing enables advanced physical layer schemes in Wireless Multihop Networks (WMNs). It widens paths in order to span multiple nodes per hop. As a result, groups of nodes cooperate locally at each hop to forward packets. Recent theoretical work suggests using Orthogonal Frequency-Division Multiple Access (OFDMA) in combination with Corridor-based Routing to improve throughput in WMNs. However, results focus on achievable capacity and do not consider practical issues such as modulation and coding schemes. In this paper, we study OFDMA for corridors in practice and implement it on software-defined radios. We show that OFDMA corridors provide significantly larger throughput gains when considering realistic modulation and coding, achieving up to 2x throughput gain compared to traditional routing not based on corridors.

Keywords—wireless multihop; corridor-based routing; ofdma

I. INTRODUCTION

Using state-of-the-art physical layer techniques in Wireless Multihop Networks (WMNs) is challenging. Such techniques often require Channel State Information (CSI) at the transmitter but disseminating it over multiple hops is usually prohibitive in terms of overhead. Moreover, by the time nodes have exchanged CSI, it is typically outdated. The underlying problem is that the network and the physical layers operate at different timescales, that is, channel conditions change much faster than the time required to establish end-to-end paths. As a result, adapting routing paths to the conditions of the wireless channel is hard.

Recent work introduces Corridor-based Routing [12], [15] to enable advanced physical layer techniques in WMNs. Essentially, this approach *widens* traditional paths to *corridors* which span multiple nodes at each hop. Figure 1 shows an example. Each widened hop is called a *stage* and includes m transmitters and n receivers, which is a topology on top of which many state-of-the-art physical layers can operate. Hence, CSI only needs to be shared among direct neighbors within a stage, instead of over multiple hops. Moreover, the physical layer can exploit spatial diversity to adapt to the wireless channel in each stage without rebuilding the end-to-end corridor.

The authors of [12], [13] build on Corridor-based Routing to enable Orthogonal Frequency-Division Multiple Access (OFDMA) in WMNs. OFDMA divides the bandwidth available for communication into orthogonal subcarriers and allows to assign each subcarrier to individual links. In particular, [12],

[13] allocate each subcarrier at each stage to the link providing best quality in terms of signal-to-noise ratio (SNR), which in turn translates into lower bit error rates (BERs) and, ultimately, higher throughput. In other words, the $m \times n$ links of a stage share the available subcarriers. The aforementioned papers study the achievable *capacity* of OFDMA corridors in WMNs by means of simulation and theoretical analysis. The resulting gains compared to traditional routing lie in between 1.1x and 1.3x for typical indoor SNRs [12], [13].

However, the performance of *practical* wireless systems is typically not measured in terms of capacity but *throughput*. The problem is that the capacity does not include the effect of modulation and coding schemes (MCSs), that is, it does not consider that the destination has to be able to correct all bit errors. In this paper, we use software-defined radios (SDRs) to show that realistic MCSs are beneficial to OFDMA corridors, allowing up to 2x throughput gain compared to traditional routing. Specifically, our contributions are as follows:

- 1) We design the operation of a practical stage mechanism for Corridor-based Routing based on OFDMA.
- 2) We show that OFDMA benefits from practical constraints compared to existing theoretical and simulation results.
- 3) We implement our scheme on SDRs and deal with practical issues at the physical layer such as CSI feedback.

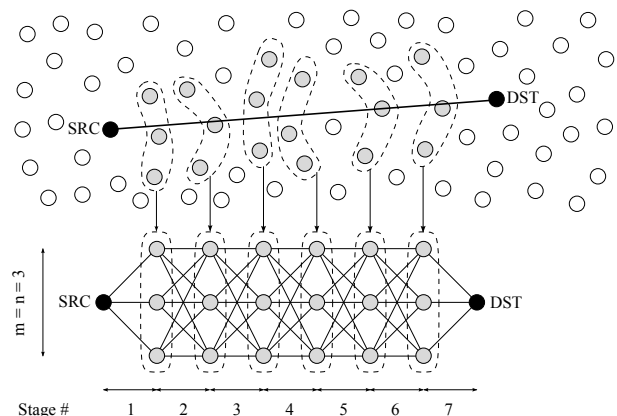


Fig. 1. Corridor example. Lower part shows a structured diagram for clarity.

The rest of this paper is structured as follows. We survey related work and explain the generic operation of Corridor-based Routing in Section II. Section III introduces our OFDMA stage mechanism for corridors. Section IV gives an overview of our implementation and in Section V, we discuss our results. Finally, Section VI concludes the paper.

II. RELATED WORK AND BACKGROUND

Research on combining **OFDMA** with WMNs without using Corridor-based Routing can be classified in two categories. On the one hand, existing work analyzes subchannel allocation algorithms [7], [14] to find the optimal resource allocation in a WMN. On the other hand, some authors deal with building complete systems to exploit OFDMA in WMNs [18], [19]. Still, they do not take routing into account. OFDMA itself has been widely studied for cellular networks [17] but we focus on the multihop case. We do not try to improve the already largely studied domain of resource allocation but focus on the practical performance of OFDMA in WMNs. This includes **concurrency at the physical layer**, i.e., allowing simultaneous transmissions of different nodes. Concurrency is the underlying technique to many state-of-the-art lower layer techniques and has proven [4], [8] to overcome the well-known limitations described in [6]—namely, that throughput in WMNs does not scale with network size. This motivates our research on a practical OFDMA stage mechanism for Corridor-based Routing.

Previous work presents the notion of **corridors** [12], [11] and analyzes in theory whether they can be beneficially combined with OFDMA. In particular, in [12] the authors optimize the network capacity by means of resource and power allocation in a given corridor with up to five stages, whereas in [11] they devise a scheme to select the nodes of a random network topology that shall participate in the corridor. Still, they do not investigate the practical constraints and operation of OFDMA for Corridor-based Routing, but focus on a theoretical and simulative analysis of the achievable capacity and BER performance. A concept similar to corridors was introduced by Gui et al. [5]. However, they study traditional multipaths within the corridor instead of OFDMA. Such closely grouped multipaths often have to deal with self-interference among paths, which is not the case of OFDMA. In earlier work [3], the same authors analyze the outage performance of OFDMA in a topology analog to a corridor, but as opposed to [12], they do not find optimal solutions for subchannel and power allocation. While these papers deal with corridor-like structures, they do not consider the practical operation of a WMN based on OFDMA corridors. We believe this is the first work in this direction.

Reference [15] introduces the operation of **Corridor-based Routing**, which can be split into five steps. First, the *corridor construction* step builds the end-to-end corridor with a certain corridor width, ensuring that all nodes in a stage are direct neighbors. The achievable corridor width depends on the density of the network. Similarly to previous work [12], [13], we assume an existing corridor established, e.g., using the mechanism presented in [11]. Secondly, *stage maintenance* monitors each stage and locally adapts, if necessary, the parameters of

the transmission at that stage. Thirdly, the *stage mechanism* selection chooses the physical layer technique used to forward data in a stage. In our case, we design a stage mechanism based on OFDMA. Fourthly, *stage coordination* ensures correct node cooperation both within one stage (intra-stage) and among subsequent stages (inter-stage). For instance, in OFDMA intra-stage cooperation ensures that each subcarrier is only used by one node at a time, while intra-stage coordination makes sure that each node of a stage does not receive more data than it can forward in the next stage. Finally, *data transmission* sends data along the corridor using the chosen stage mechanism.

III. OFDMA FOR CORRIDOR-BASED ROUTING

In this section, we describe the design of our OFDMA stage mechanism for Corridor-based Routing and explain where its gain in terms of throughput stems from in a WMN using it.

A. Scenario

Approach. OFDMA allows multiple nodes to transmit simultaneously without interference by assigning disjoint sets of subcarriers to each node. That is, instead of a single transmitter which uses all subcarriers to send data to a single receiver, there are m transmitters that *share* the available subcarriers to send data to n receivers. The gain comes from the assignment of subcarriers to links which experience good channel conditions, since this causes errors to become less likely. As a result, the BER in a stage using OFDMA is lower than that obtained when using Orthogonal Frequency-Division Multiplexing (OFDM) on a single link, as in routing schemes not based on corridors. Similarly to a traditional forwarding scheme, our OFDMA stage mechanism uses error correction codes and, if needed, retransmissions to obtain correct packets at each stage. In other words, errors do *not* accumulate as data flows through the corridor, but are corrected at each stage. While error correction is thus done per subcarrier instead of per frame, overhead is identical since the amount of redundancy of typical error correction codes is proportional to the amount of data.

Gains. Since OFDMA reduces the BER, it allows stages to operate at a higher modulation scheme compared to OFDM for a certain error correction capability. That is, if the BER of OFDMA for a certain modulation is similar to the BER of OFDM for a lower modulation, OFDMA can operate at the higher modulation and thus forward data significantly faster than an OFDM stage. For instance, if OFDM can only use BPSK while OFDMA can employ 4-QAM, the OFDMA stage only requires *half the time* to relay data. We use such an adaptive modulation scheme for our OFDMA stage mechanism—while all nodes within a stage use the same modulation on all subcarriers, modulations can be different at each stage. Additionally, channel quality may change throughout the corridor. Thus, if the first stage allowed for a high modulation order, subsequent stages with worse channel conditions and thus constrained to lower modulations may need to split data into multiple transmissions, incurring additional overhead. Here again, OFDMA achieves gains w.r.t. OFDM, as it typically needs less transmissions due to the use of higher modulations.

B. Forwarding scheme

We assume a stage with the same number of transmitters and senders, i.e., $m = n$. Our stage mechanism forwards data homogeneously, that is, it requires each of the m transmitters to have $1/m$ of the data and delivers $1/m$ of the data to each receiver. Alternatively, data could be distributed heterogeneously to nodes, but we choose the homogeneous variant because it ensures that at each stage all nodes need the same number of transmissions to forward data, thus simplifying scheduling and reducing coordination overhead. Our mechanism's goal is to distribute the available N_c subcarriers to the m^2 links of each stage. Note that subcarriers are allocated not just to transmitters but to *links*, since each outgoing link of a transmitter may have different quality. For example, while a certain subcarrier on the link from transmitter t_1 to receiver r_1 might be good, the same subcarrier from the same sender to r_2 might be very poor. Transmitters and receivers have m outgoing and m incoming links, respectively. Our mechanism assigns to each link a $1/m^2$ fraction of the available subcarriers, i.e., each link gets the same share of resources. Thus, each transmitter gets a total of $m \times N_c/m^2 = N_c/m$ subcarriers and uses N_c/m^2 of them for each receiver. Conversely, each receiver receives N_c/m^2 subcarriers from each transmitter and thus gets overall the aforementioned $1/m$ fraction of the data. In other words, each transmitter sends to each receiver the same amount of data. Note that at each stage, data is shifted between subcarriers and thus becomes disordered. For example, data transmitted using subcarrier s_1 in stage i may be shifted to subcarrier s_2 in stage $i + 1$ because the node transmitting the data in stage $i + 1$ does not get subcarrier s_1 . Thus, each stage must tell the next stage the current order of data to allow the destination to reorder it correctly. This control data is our inter-stage coordination overhead. Although we split frames, nodes are aware of the corridor they are part of and thus know how to forward data.

C. Subcarrier allocation

To allocate N_c/m^2 subcarriers to each link, we use an allocation strategy proposed in [10] and identified as best out of multiple allocation approaches. The strategy allocates the same number of subcarriers to each link, as required by our OFDMA scheme. We briefly summarize its operation. Essentially, the strategy follows an iterative approach. In each iteration, the strategy assigns one subcarrier to one link. The process is repeated until all subcarriers are allocated. Each iteration is divided into two steps. In a first step, the strategy chooses a *link* out of the m^2 available ones, excluding those links which already have their full share of subcarriers. More precisely, the strategy chooses the link which has the subcarrier with the *lowest* SNR. In a second step, the strategy assigns to the chosen link the subcarrier on which it experiences its *highest* SNR. The rationale behind this somewhat counter-intuitive approach is that the strategy tries to ensure that links with very bad SNR on some subcarriers get at least the N_c/m^2 subcarriers on which they perform best. Hence, the criteria used in the first step to choose a link defines which links are prioritized in the first

iterations of the algorithm and thus can choose out of more still available subcarriers. If links with high SNR are prioritized, it might happen that in the last iterations the strategy is forced to assign subcarriers with very bad channel conditions to the links with low SNR. In [10], this approach clearly outperforms strategies which prioritize links with high SNR, specially when interference is present.

D. Operation

Our OFDMA scheme is a stage mechanism and thus does not deal with the construction of the corridor. Still, it requires stage maintenance and coordination in order to allocate subcarriers according to the aforementioned strategy. Figure 2 shows the frame format of our OFDMA mechanism, which can be divided into three main parts, namely (a) CSI measurement, (b) CSI and subcarrier distribution sharing, and (c) data transmission. We assume channels to be reciprocal, i.e., channels are equal in both directions. This is valid when both directions operate at the same frequency, which is our case. Moreover, measurements in our testbed environment confirm this. Hence, for the CSI measurement in (a) the *receivers* send pilot symbols to the *transmitters* one at a time. After this first step, each transmitter knows its m outgoing links, but does not know how the remaining $m^2 - m$ links are. The transmission order is defined during corridor construction, but can be adapted during stage maintenance.

The second step (b) deals with the intra- and inter-stage coordination. First, each transmitter shares its CSI with all other transmitters. In order to do this efficiently, we use a codebook approach, similarly to other technologies using OFDMA, such as LTE. Basically, a codebook is a list of quantized CSI values shared by all nodes of a stage. Hence, instead of encoding and sending a full CSI value, transmitters only need to share the index of a similar value of the codebook, which results in much less overhead. In Section IV, we discuss multiple codebook sizes and choose a suitable one for our purposes. In particular, we share CSI in terms of SNR on each subcarrier, since we use the SNR as a metric for allocation. Once all transmitters know the SNR on each subcarrier of all m^2 links, each transmitter can independently determine the subcarrier allocation according to the aforementioned strategy. This is the **intra-stage** coordination required by our OFDMA mechanism. Regarding the **inter-stage** coordination, the previous stage needs to tell the next stage how subcarriers are ordered, as

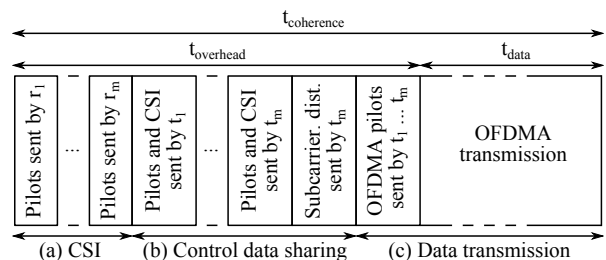


Fig. 2. OFDMA frame structure.

discussed in Section III-B. To that end, after sharing the SNR values, the last transmitter broadcasts the current order to all receivers. Concretely, it sends on each subcarrier a sequence of bits representing the index number of the subcarrier on which the subsequent data on that subcarrier was originally located. For example, if subcarrier s_2 at the current stage contains the data which originally was sent over subcarrier s_1 , the data on s_2 would be preceded by a binary representation of the index number s_1 . The number of required bits is directly related to the number of subcarriers, i.e., it is $\lceil \log_2 N_c \rceil$, where $\lceil \cdot \rceil$ denotes the ceiling function.

Finally, in (c) all transmitters send data at the same time using OFDMA. We count as overhead all transmitted symbols which are not part of actual data, including pilot symbols. We send pilots prior to each transmission even if nodes might already know the channel to the transmitter from previous transmissions, since each transmission might be affected by a different phase offset in the frequency domain due to different symbol time offsets (STO) in the preamble detection.

IV. IMPLEMENTATION

A. Testbed setup

Hardware platform. We use the Wireless Open-Access Research Platform (WARP), which is an FPGA-based Software Defined Radio (SDR) developed at Rice University [1]. It enables experiments in settings similar to an 802.11 network, but with full control regarding the lower layers. We use WARPLab [2], which is a framework that allows for rapid prototyping based on Matlab. First, we calculate in Matlab the samples to be transmitted. These samples are then transferred via Ethernet to the sending WARP board, which transmits them over the wireless medium. The receiving WARP board samples the signal and sends it back to Matlab. Note that in between frame parts (a), (b), and (c), depicted in Figure 2, data is processed in Matlab, i.e., while not fully real-time due to delays for transferring signals to and from Matlab, we do *not* process data offline, but online and *interactively*. This approach only relocates processing from the WARP board to Matlab.

Experiment setup. We carry out our experiments on ten WARP boards. Due to the limited testbed size, we cannot realize reasonable corridor construction, since we need that all nodes form part of the corridor to achieve a meaningful hop count. For simulative insights on corridor construction, we refer the reader to [11]. Here, we focus on stage maintenance and coordination. We consider corridors with stage widths $m = [2, 4]$ but without start and end stages (c.f. Figure 1), as both are variants of a generic stage with fewer links. Figure 3 shows both setups. In the $m = 2$ case, each stage consists of two nodes. Hence, with 10 boards the corridor would be limited to four stages. To look also into longer corridors, we take advantage of the two radios available on each board. We use each radio as if it were an individual node and thus only need one board per additional stage. All data sent and received is treated independently. In the $m = 4$ case, we follow a similar approach. We use nine boards for the corridor and one as an artificial interferer (c.f.

Section V-E). We place nodes in a regular pattern and in one room to better understand the results. We achieve typical indoor SNRs (20 to 30 dB) by using low transmit gains.

Synchronization. OFDMA requires transmitters to be synchronized. We achieve this via wired synchronization—while we abstract from this issue to focus on OFDMA performance, *wireless* synchronization can be accomplished using techniques from single-hop systems that also build on OFDMA, since all nodes in a stage are direct neighbors. Additionally, receivers need to be synchronized to transmitters in order to (a) find out when to start receiving data and (b) avoid carrier-frequency offset (CFO). For (a), we prefix the signal with a preamble as in 802.11a. Receivers can determine the beginning by correlating the incoming signal with the preamble. To address (b), we use a pilot-aided technique to determine and compensate CFO.

B. Practical considerations

Coherence time. Our testbed is static and thus channels are stable, i.e., the coherence time is long. We exploit this to overcome the delays for transferring signals to/from Matlab. While the delays are in the order of *milliseconds*, in our testbed channels remain constant over *minutes*. Thus, CSI obtained in frame part (a) (Figure 2) is still up-to-date in part (c). If realized in real-time, our scheme does not require long coherence times.

Acceptable BER. We use adaptive modulation at each stage according to CSI (c.f. Section III-A). Similarly to a real-world system, we aim at choosing the highest modulation which still achieves a certain acceptable BER. Typically, the acceptable BER is the error correction capability of the channel code in use. We do not restrict our results to certain codes, but analyze performance for a range of acceptable BER values. That is, we do not implement specific error correction schemes, but obtain how gains using *any* code with an error correction capability within the aforementioned range would be.

Throughput. The delays incurred by WARPLab prevent us from measuring throughput directly, since they would strongly

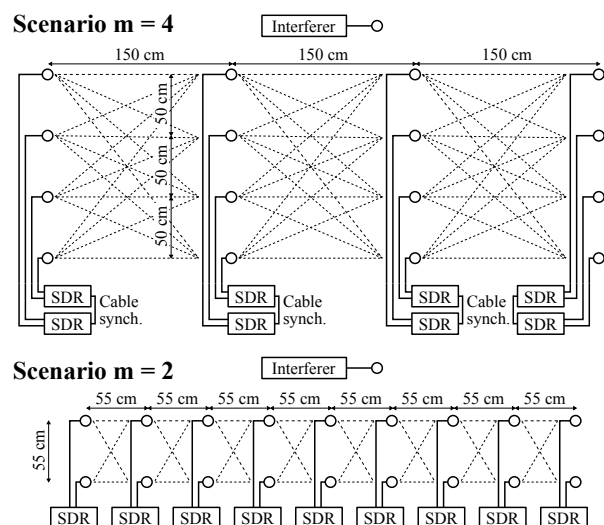


Fig. 3. Setup. The interferer is placed far enough to affect all stages similarly.

affect the result. Moreover, the large coherence times in our testbed would lead to CSI measurements at much larger intervals than in a real-world scenario. To circumvent these limitations, we obtain throughput by extrapolating our measurements. We consider an indoor scenario and assume a realistic coherence time for such a setting, namely, $t_{\text{coherence}} \approx 45$ ms [16]. For calculations, we assume that the first stage of the corridor sends a frame (Figure 2) as long as the coherence time before transmission continues in the next stage, but in practice the frame can be divided into multiple smaller packets. In subsequent stages, the transmission may take less time if the stage can use a higher modulation order than the first stage. Conversely, it also may take longer if only a lower modulation order is supported. In that case, multiple frames are needed, since each frame must not be longer than the coherence time. We compute the end-to-end corridor throughput “thp” as the transported data divided by the sum of all stage transmission durations, i.e., $\text{thp} = t_{\text{xdata}}/\text{sum}_{\text{time}}$. We calculate how much data is transmitted in the first stage based on CSI, acceptable BER and coherence time as follows.

$$t_{\text{xdata}} = \text{bits}_{S1} \frac{t_{\text{coherence}} - t_{\text{overhead}}}{t_{\text{measure}}} \quad (1)$$

where “ bits_{S1} ” is the number of bits sent in the first stage using the highest modulation order possible according to the acceptable BER during the measurement duration t_{measure} . The transmit buffers of WARPLab are not large enough to send data during the whole coherence time, i.e., $t_{\text{measure}} < t_{\text{coherence}}$. Thus, we extrapolate our measurement as shown in Equation 1 by calculating how many times t_{measure} fits into $t_{\text{coherence}}$, after subtracting the time required for overhead t_{overhead} . Next, we compute the time required to transport data through the corridor. Essentially, at each stage we calculate the number of transmissions f_m required according to the highest modulation order the stage supports. f_m may be smaller than one if the current modulation order is larger than in the first stage. Moreover, for each transmission in the stage we add the time required for overhead. To account for the number of times the overhead is incurred at a stage, we define $f_o = \max[1, f_m]$. We compute the sum of all stage transmission times as follows.

$$\text{sum}_{\text{time}} = \sum_{\forall \text{stages}} f_o \cdot t_{\text{overhead}} + f_m \cdot (t_{\text{coherence}} - t_{\text{overhead}}) \quad (2)$$

Gain control. Gain control in OFDMA is challenging. The complexity is due to the overlapping at the receiver of multiple signals *in time*, which can be decomposed *after* quantization using the Fourier Fast Transform (FFT). Still, *before* quantization the receiver can only operate on the sum. If one signal arrives with more power than others, the smaller ones suffer from higher quantization noise. The key problem is that the receiver can only adjust the largest signal to the input range of the quantizer, while all others are sampled with less accuracy. The impact of this issue can be observed in Figure 4, which depicts the BER for 64-QAM and $m = 2$ at subsequent stages for our OFDMA mechanism as well as for an OFDM baseline, which forwards data in a traditional

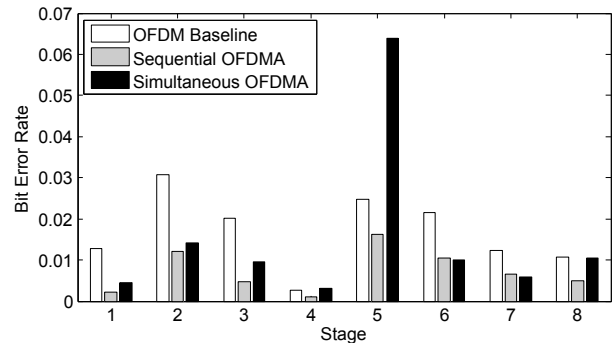


Fig. 4. Gain misadjustments. BER for 64-QAM at each corridor stage.

TABLE I
BER FOR 64-QAM WITH INCREASING CODEBOOK SIZE.

Codebook size	16 codes	64 codes	512 codes	8192 codes
OFDMA BER	0.0179	0.0170	0.0146	0.0139

hop-by-hop manner (c.f. Section V-A). Additionally, we show the performance of a *sequential* OFDMA variant, which allows nodes to send in sequence on the subcarriers allocated to them. Hence, signals do not overlap in time and thus the gain control issue is circumvented. This is not how we envision the scheme to operate once deployed, but it allows us to illustrate the impact of gain control. As shown in Figure 4, the impact of gain misadjustments varies for each stage, since it is directly dependent on the physical environment surrounding the stage. We observe that simultaneous OFDMA performs worse than sequential OFDMA, specially at stage 5. To solve this problem, transmitter gains must be adjusted to ensure that all signals are received with similar power at the receivers. This is intrinsic to OFDMA and orthogonal to the gains achievable by subcarrier allocation. Hence, we do not tackle it in our implementation. To obtain the actual subcarrier allocation gain, for the bulk of our experiments we show the sequential OFDMA results and compute throughput as if transmissions were simultaneous.

Feedback. We use quantized CSI feedback and account for the resulting overhead. To find a suitable codebook size, we measure how many bits per CSI value are needed to obtain the same subcarrier allocation than with full CSI. Figure 5 depicts the result for two stages of a $m = 2$ corridor. Both behave similarly, which means that the required codebook size does not depend on the specific channels of a stage. We choose a default value of 13 bits per code—8192 codebook entries—to achieve virtually identical allocations compared to full CSI. However, Table I shows that the BER achieved with much smaller codebooks is similar. While allocations using smaller codebooks are different than with full CSI, subcarriers allocated differently have similar performance. Hence, larger codebooks only provide marginal improvement. Still, we stick to 13 bits per code to show that overhead is reasonable even in that case. For smaller codebooks, the gained extra bits can be used to e.g. protect feedback against interference.

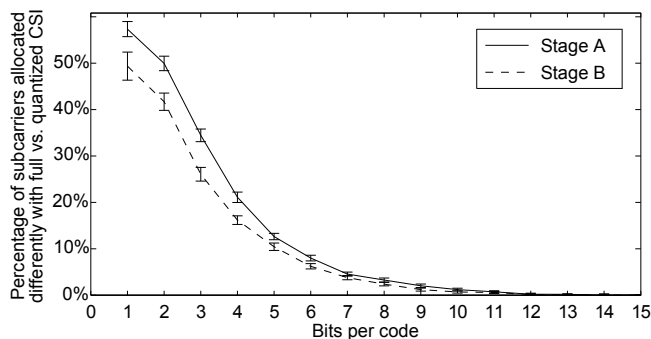


Fig. 5. Impact of quantized CSI on subcarrier allocation for two stages A/B.

TABLE II
EXPERIMENT PARAMETERS

FFT size	256	Subcarrier spacing	256.25 kHz
Usable subcarriers	112	Passband bandwidth	17.5 MHz
Symbol duration	6.4 μ s	Pilot symbols	3
Guard space	0.8 μ s	Data symbols	10

V. EVALUATION

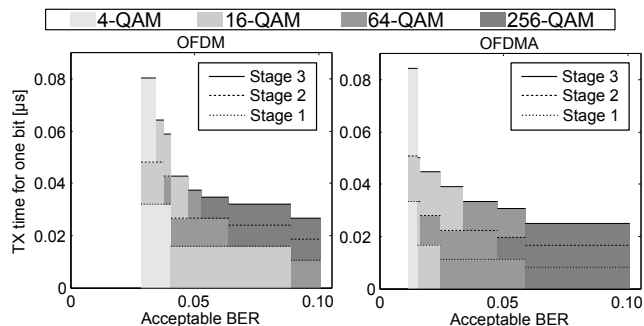
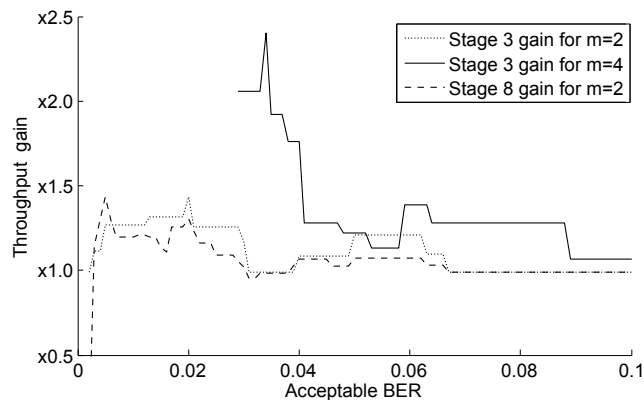
In this section we evaluate our OFDMA stage mechanism for Corridor-based Routing. Table II shows the parameters of our experiments and Table III gives an overview of our results.

A. Baseline mechanism

We compare OFDMA with traditional hop-by-hop forwarding based on OFDM. We use the same scenario than OFDMA, but choose randomly a node of each stage as a forwarder. Hence, data is relayed from node to node instead of from stage to stage. While pilot symbols are still needed to equalize the channel at the receiver, coordination and feedback are not required, which translates into smaller overhead.

B. OFDMA corridor gain

Our first experiment aims at showing the throughput gain in an OFDMA corridor. We expect the gain to stem from OFDMA being able to choose higher modulations than OFDM for a certain error correction capability. In Figure 6 we depict the end-to-end delay incurred when transporting data through our $m = 4$ corridor for any acceptable BER up to 10%. We “normalize” the result dividing the time by the amount of sent data to highlight that higher modulations transport each single bit faster—this is not apparent in the non-normalized results, since with higher modulations we send more data. The gray tones indicate the modulation used in each stage. For example, for OFDM and 10% acceptable BER, the first stage uses 64-QAM, while the second and the third use 256-QAM. The transmission time decreases as expected with increasing acceptable BER, since the more errors can be corrected, the higher the modulations that become possible and thus the faster the data is transported. For any acceptable BER, OFDMA can use higher modulations and thus requires less time than OFDM to transport data, which directly translates into throughput gain.

Fig. 6. Normalized end-to-end delay through the corridor for $m = 4$.Fig. 7. End-to-end throughput gain for corridors of widths $m = 2$ and $m = 4$.

For small acceptable BER values, both OFDM and OFDMA cannot operate, since the BER is too high even for the lowest modulation scheme in at least one of the stages. This is shown by the left white areas in Figure 6. However, note that OFDMA can already operate at about 0.012 acceptable BER, while OFDM requires at least 0.029 error correction capability to become feasible. For our $m = 2$ corridor results are equivalent, but we do not reproduce them here due to space constraints.

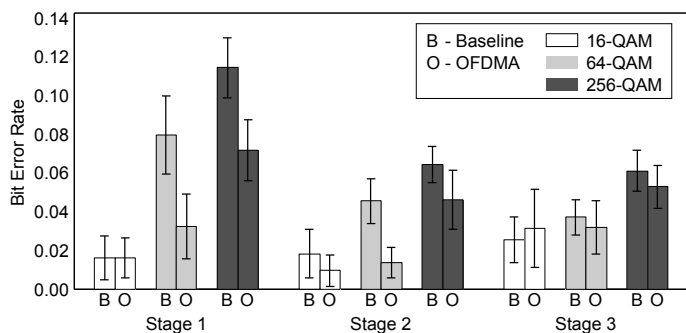
In Figure 7 we show the end-to-end throughput gains resulting from our observations in Figure 6. The $m = 4$ corridor *doubles* throughput for certain acceptable BER values and the $m = 2$ corridor achieves up to 1.4x gain. We conclude that gains increase with corridor width—the wider the corridor, the more links there are and thus the higher is the probability that OFDMA can allocate links with good channel conditions to each subcarrier. The curve for $m = 4$ starts at 0.029 acceptable BER since OFDM cannot operate for lower values and thus no gain can be computed. That is, gain would be *infinite* in the range from 0.012 to 0.029 acceptable BER. For $m = 2$, we depict the throughput gain at stage 3—to make it comparable to $m = 4$ —and at stage 8. Both curves behave similarly, which means that longer corridors do not strongly affect gains.

C. Per stage BERs

Since gains stem from adaptive modulation being able to choose higher modulations when using OFDMA due to lower BERs, we next analyze BERs for multiple modulations at each

TABLE III
EXPERIMENT OVERVIEW

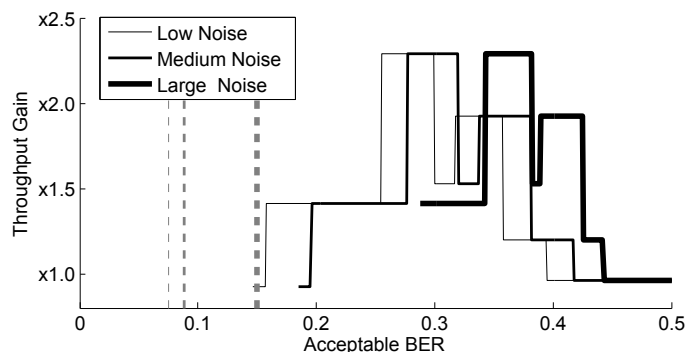
Experiment	Results	Section
OFDMA corridor gain	We achieve a throughput gain of 1.4x for a corridor width of $m = 2$. Increasing the corridor width to $m = 4$ results in a 2x gain. That is, throughput gains increase with corridor width.	V-B
Per stage BERs	OFDMA reduces the BER of a stage differently depending on the SNR requirements of the modulation rate in use and the physical environment of each stage.	V-C
Low SNRs	At low SNRs, we achieve up to 2.3x throughput gain. OFDMA can operate at lower error correction capabilities than OFDM, potentially enabling communication at all if the channel code cannot cope with large BERs.	V-D
Narrowband interference	OFDMA avoids narrowband interference by allocating each subcarrier to the link of the current stage less affected by noise. As a result, the BER of OFDMA degrades less compared to OFDM.	V-E

Fig. 8. BERs at each stage of our $m = 4$ corridor for multiple modulations.

stage of our $m = 4$ corridor. Figure 8 shows our results. As expected, OFDMA generally achieves lower BERs for a certain modulation scheme than our OFDM baseline. Still, the behavior depends on (a) the modulation scheme and (b) the stage. Regarding (a), we observe that the BER improvement for 16-QAM is limited or even non-existent. The reason for this is that in our testbed the SNR requirements for 16-QAM are low enough for OFDM to operate without incurring large BERs, i.e., channels are good enough for OFDM to work correctly and thus OFDMA does not provide significant improvements. Results for 256-QAM are similar but for the opposite reason—in this case SNR requirements are very high and thus OFDMA can also only provide marginal improvement. The largest gains are achieved for modulation schemes which are at none of the extremes regarding SNR requirements, which in this case is 64-QAM. As to our aforementioned observation (b), the specific stage also influences the achieved improvement. For instance, in Figure 8, BER improvements at stage 3 become marginal compared to the previous stages. The reason lies with the specific channels at that stage—if channel conditions are strongly impaired for all subcarriers, subcarrier selection becomes less effective. Moreover, our allocation mechanism assigns the same number of subcarriers to each link in a stage (c.f. Section III-C) and thus is forced to assign resources to a link even if it has bad quality, which results in high BERs.

D. Low SNRs

In the following, we investigate the behavior of our OFDMA stage mechanism for low SNRs. However, the close positioning of antennas in our testbed impedes us to lower SNRs below ≈ 20

Fig. 9. Throughput gain with increasing noise for $m = 4$. The vertical dashed lines indicate the acceptable BER from which on OFDMA is operable.

dB by adjusting transmit gains. Hence, we use the interferer depicted in Figure 3 to generate a small amount of white noise on all subcarriers and thus artificially achieve a lower SNR. Figure 9 depicts our results for three transmit gains at the interferer. As expected, for larger noise values—that is, lower SNRs—the acceptable BER required to achieve throughput gains increases. Still, the gains themselves are similar, reaching up to 2.3x, and follow virtually the same pattern, i.e., in Figure 9 the curve is just shifted to the right. Note that the acceptable BER at which each curve starts is the minimum BER at which OFDM can operate, but OFDMA works already at significantly lower BERs represented by the vertical dashed lines. Hence, while the 2.3x throughput gain only becomes possible at large BERs, a key advantage of OFDMA at low SNRs is that it can operate at significantly lower BERs than OFDM. Therefore, OFDMA may enable communication entirely if the channel code in use cannot cope with large BERs, while OFDM would not be able to operate.

E. Narrowband interference

Finally, our last experiment deals with narrowband interference. In contrast to Section V-D, we now use the interferer to generate noise only on a certain fraction of subcarriers. Our goal is to analyze whether subcarrier selection allows stages to *avoid* subcarriers affected by narrowband noise and thus achieve a better robustness against external interference, which is likely to occur in ISM bands. We set low transmit gains at the interferer to avoid jamming completely the affected subcarriers. As a

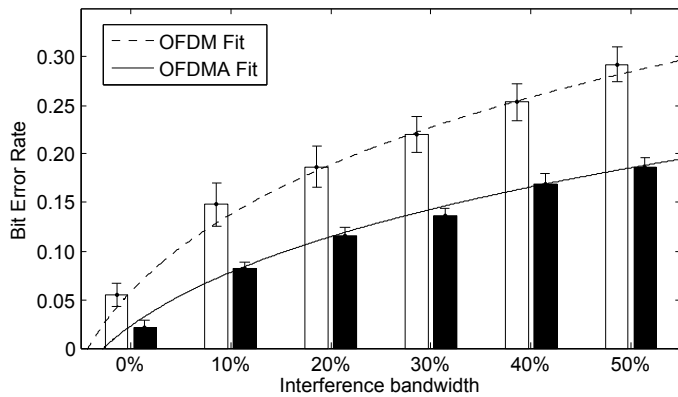


Fig. 10. BER for 64-QAM and increasing noise bandwidth (stage 1; $m = 4$).

result, nodes of a stage closer to the interferer are more affected by noise than nodes further away. In each stage, we expect our OFDMA mechanism to assign the subcarriers impacted by noise to the links which are less affected and thus degrade less for increasing noise bandwidth than OFDM. In Figure 10, we focus on the BER for 64-QAM at the first stage of our $m = 4$ corridor to investigate this effect. We observe that the behavior matches our expectations—the curves fitted on top of the results highlight that the OFDMA BER degrades at a lower rate than the OFDM BER, hence providing a better robustness against external interference.

F. Discussion

Our results show that OFDMA for Corridor-based Routing is **feasible in practice** and improves throughput significantly. The **overhead** is not critical, since we achieve large gains while accounting for stage maintenance and coordination including virtually full CSI feedback. Moreover, we observe that coarse CSI feedback provides similar improvements. That is, gains do not stem from a fine-granular classification of subcarriers according to their channel conditions, but just from coarsely identifying subcarriers with very bad channel conditions. Further, corridors using OFDMA **enable communication** at SNR values at which OFDM cannot operate at all, which shows its robustness. The **corridor shape** influences performance of our OFDMA stage mechanism regarding width but not length—gains become larger for wider corridors but are similar for increased hop counts. However, we expect a trade-off with respect to width, since from a certain width on, additional links per stage only improve diversity slightly. Finally, additional transmissions in a stage due to **adaptive modulation** choosing low modulations are not critical, since other stages are typically able to choose high modulations, what compensates for the resulting overhead.

While previous work on OFDMA for Corridor-based Routing (c.f. Section II) achieves up to 1.3x capacity improvement, we achieve up to 2x gain. As described in Section III-A, the key difference is that we acknowledge that adaptive modulation is a step-by-step process. In contrast, existing work only considers capacity and BER, which are continuous. For instance, while

the BER of OFDM might only be 10% to 30% worse than the BER of OFDMA, in our more realistic case OFDMA still achieves a much higher throughput if its BER is just small enough to use a higher modulation scheme than OFDM. In other words, at the boundary between two modulations, a small BER difference can translate into a large impact on throughput. As a result, OFDMA benefits from this practical constraint. Moreover, our evaluation considers a continuous range of acceptable BERs which includes both discrete and rateless error correction codes. Our gains come from adaptive modulation, which is inherently discrete in digital communications.

We consider a single unicast transmission. In case of multiple parallel unicast sessions, Corridor-based Routing constructs an individual corridor for each pair of communicating nodes. As a result, corridors may intersect and overlap, posing further challenges in terms of flow control and synchronization among corridors. For instance, joining two or more parallel corridors may provide better performance than operating them individually depending on, e.g., the average packet size and the duration of each flow. The throughput of each flow varies according to how resources are shared among flows. However, the overall OFDMA throughput gain does not depend on the flow the data belongs to. Hence, the main insights of our evaluation can be translated to a scenario with multiple parallel transmissions. Further, synchronization among corridors becomes key to determine whether, e.g., joining multiple corridors is profitable. For example, the overhead of joining two corridors may not pay off if one of the transmissions is about to finish. Still, such synchronization takes place at the network layer and thus occurs at a much larger timescale than the coordination at the physical layer we consider in our evaluation. Hence, we do not expect it to become critical. Additionally, the operation of intersecting and overlapping corridors raises the question whether OFDMA is the most suitable technique to support such transmissions. For instance, parallel transmissions in opposite directions could benefit more from network coding at the physical layer [9] within the corridor. However, investigating such alternative mechanisms is beyond the scope of this paper.

VI. CONCLUSION

We present a practical approach to enable OFDMA in Wireless Multihop Networks using Corridor-based Routing, which is a routing paradigm that supports state-of-the-art physical layer techniques. It widens traditional hop-by-hop paths in order to span a group of nodes at each hop and thus provide spatial diversity within an end-to-end path. Our OFDMA mechanism achieves performance gains in terms of throughput by allocating available subcarriers to those links providing good channel conditions. In contrast to previous work, we consider practical constraints, such as modulation and coding schemes. We implement our mechanism on software-defined radios and evaluate it in a multihop testbed. We observe that gains increase with stage width and that OFDMA can efficiently avoid subcarriers affected by interference. We achieve up to 2x throughput gain compared to traditional hop-by-hop forwarding and more than 1.5x improvement compared to previous work

using OFDMA corridors. The key feature of our approach is that we take into account the step-by-step nature of adaptive modulation. Future work includes studying further strategies for allocating subcarriers to links, investigating the performance of our scheme on corridors of variable width, and designing flow control mechanisms for multiple parallel transmissions.

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