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Cooperative Forwarding using Distributed MISO in OFDMA Multihop Networks

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***Abstract*—In this work, we investigate cooperative multihop communications based on OFDMA and fountain codes. Data packets are forwarded between clusters of simultaneously transmitting nodes which exploit the diversity of links by sharing the available subcarriers based on local channel conditions. Furthermore, to enable distributed MISO transmissions between clusters, we investigate the potential of distributing data packets within the cluster by single node transmissions prior to the common transmissions aiming to increase the achievable throughput. We present two novel forwarding schemes that utilize distributed MISO transmissions while taking advantage of the properties of fountain codes. The first scheme relies on a full distribution of all data packets within each cluster while the second scheme adapts the extent to which data packets are distributed within the cluster according to local channel conditions. The proposed schemes are compared to an exclusive SISO forwarding scheme in which no additional distribution within each cluster is used.**

I. Introduction

Cooperation between forwarding nodes in a multi-hop network can be used to exploit the diversity of links within the network and increase the achievable throughput. In [1] and [2], Corridor-based Routing is proposed in which intermediate hops between source and destination consist of multiple cooperating forwarding nodes in order to utilize Orthogonal Frequency Division Multiple Access (OFDMA) in a distributed manner. This network structure provides spatial diversity in form of several links between the different transmitters and receivers in each hop. By an adaptive resource allocation among the transmitters in each hop, throughput gains are realized compared to forwarding data along a path of single nodes. In [2], Corridor-based Routing is also implemented on software-defined radios to evaluate the performance in a wireless test-bed.

Beside OFDMA, multiple antenna techniques proved to be a very successful method to increase data throughput in many state-of-the-art wireless systems. In a network consisting of single antenna nodes, multiple-input single-output (MISO) transmissions can be realized in a distributed manner by using multiple transmitters simultaneously. The feasibility of simultaneous transmissions in a MISO fashion is investigated in [3]. In [4], a cross-layer framework is presented that exploits the increased transmission range due to achievable diversity gains based on distributed MISO transmissions. A routing protocol that adaptively decides on the number of cooperating nodes and the used cooperation strategy is proposed in [5]. However, to enable distributed MISO transmissions, the same data packet has to be available at the corresponding transmitters. To achieve this, a source node can adapt its transmission rate according to the node with the worst channel conditions out of the cluster of desired next hop forwarders which can lead to a significant rate loss compared to a point-to-point transmission to the receiver with the strongest channel.

In this work, we propose a strategy to reduce this rate loss by utilizing the properties of fountain codes which are offering a promising alternative to fixed rate transmissions. Using fountain codes, data packets are transmitted by a theoretically infinitely long code stream and each receiver accumulates mutual information according to its respective channel capacity until it is able to decode the data packet. The performance of fountain codes in collaborative relay networks is investigated in [6] and [7]. In [6], it is shown that they are superior to energy accumulation approaches. Applying fountain codes, the transmission of data packets to a cluster of nodes can then be done step-wise. First, the source transmits until at least one node out of the cluster is able to decode each packet. Second, each node within the cluster can interchange its decoded data packets with the other nodes to fill the remaining gaps in terms of mutual-information. This step-wise distribution will be beneficial in case that the channel conditions within the cluster are better than the channel conditions from the source to the nodes within the cluster. The application of fountain codes for OFDMA multi-hop networks using only single-input single-output (SISO) transmissions is considered in [8].

In this work, we propose a novel strategy that considers adaptive OFDMA subcarrier allocation for multihop networks and integrates distributed MISO transmissions while taking advantage of the properties of fountain codes. We propose two novel forwarding schemes which enable distributed MISO transmissions by an intra-cluster exchange of data packets. The first scheme is based on a full distribution of all data packets within the cluster while the second scheme adapts the extent to which data packets are distributed within the cluster according to local channel conditions. Furthermore, for the common transmission phase in which all nodes within a cluster transmit simultaneously, we present a suitable strategy to determine beam weights for the MISO transmissions as well as a strategy for subcarrier allocation.

The rest of the paper is organized as follows. The system model is given in Section II. Section III considers the transmission strategy in the first hop of the network. Potential gains of using distributed MISO transmissions are analyzed in

Section IV. Two elementary cluster transmission phases and two proposed forwarding schemes are introduced in Section V and VI, respectively. Their performance is evaluated in Section VII and Section VIII concludes the paper.

II. System model

We consider a multihop network consisting of one source node, one destination node and N_{c} intermediate clusters each consisting of N_{f} potential forwarding nodes as shown in Figure 1. We assume that all nodes are single antenna, half-duplex nodes which are not able to transmit and receive at the same time. The transmission is based on OFDMA as multiple access scheme with N_{sc} orthogonal subcarriers. We assume a log distance path loss between a transmitter i and receiver j with path loss exponent α which leads to the average link SNR $\bar{\gamma}_{i,j}$. In addition, we assume Rayleigh fading on each subcarrier. The channel transfer factor $h_{i,j,n}^{(t)}$ of subcarrier n between transmitter i and receiver j in time slot t is independent of the other subcarriers and assumed to be constant for time slot t of duration T. We assume local channel knowledge which means that nodes within a cluster have current channel information about all channels to the nodes of the next cluster. This requires channel estimation and 1-hop feedback at the beginning of each time slot.

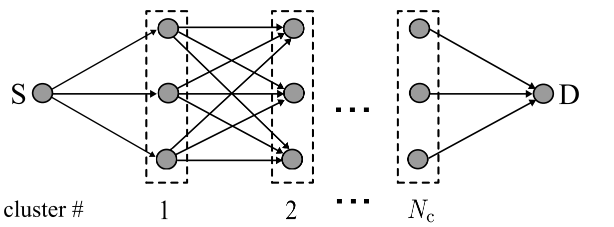


Fig. 1. Multi-hop network with $N_{\mathrm{f}} = 3$ forwarding nodes within each cluster

The use of ideal fountain codes is assumed which achieve Shannon capacity at any rate. A data packet is decodable at a receiver if the accumulated mutual information reaches the entropy H_{data} of a data packet, i.e.

$$\sum_{t}\sum_{n} T \cdot \log_2(1+\gamma_{j,n}^{(t)}) \geq H_{\mathrm{data}}, \tag{1}$$

where $\gamma_{j,n}^{(t)}$ denotes the SNR at receiver j concerning subcarrier n in time slot t. Equation (1) is justified by the assumption that different codes are transmitted which all represent the same data packet. The receiver accumulates mutual information by each different code instead of accumulating energy if the same code is used for multiple transmissions. We consider a step-by-step transmission where only the source node or nodes belonging to the same cluster transmit at a time. Instantaneous acknowledgments by the receiver after each time slot are assumed.

III. First hop transmission strategy

In this section, the transmission strategy used at the source node is introduced which is the basis for all considered transmission schemes in the following. In the first hop, the data transmission is based on a simple principle: For each of the N_{sc} available subcarriers, one data packet is selected in each time slot according to Algorithm 1. In the beginning, all data packets that have to be transmitted are stored in set $\mathcal{S}_{\mathrm{packets}}$. The N_{sc} data packets to transmit are selected such that multiple different data packets are transmitted in parallel on the different subcarriers in each time slot. In case that a data packet has been successfully decoded by a node of the next cluster, the node sends an acknowledgment and the corresponding data packet is removed from set $\mathcal{S}_{\mathrm{packets}}$ and not considered for the scheduling in the next time slot. In case that the number of remaining undecoded data packets in set $\mathcal{S}_{\mathrm{packets}}$ is less than N_{sc}, the elements within $\mathcal{S}_{\mathrm{packets}}$ are reused until the number of elements matches the number of subcarriers. This procedure ensures that each data packet is available at least at one node of the next cluster and leads to a distribution of the data packets among the nodes depending on the individual channel conditions of the receiving nodes concerning the different subcarriers. We assume that the nodes within a cluster can overhear each others acknowledgments such that the nodes know which data packets are available at which node in the cluster.

Algorithm 1 Data packet to subcarrier scheduling

```
Require: set S_packets of all undecoded data packets
    set S*_packets = S_packets (temporary copy)
    for n = 1 to N_sc do
        1) allocate first element of S*_packets to subcarrier n
        2) cancel selected packet out of set S*_packets
        if S*_packets = {} (empty) then
            3) set S*_packets = S_packets
        end if
    end for
    cancel acknowledged packets out of S_packets
```

IV. Analyzing potential gains of using distributed MISO

To apply distributed MISO transmissions, the same data packet needs to be available at all desired transmitters. Since the source node stops transmitting a data packet once at least one node of the first cluster has decoded it, additional effort needs to be spent to enable distributed MISO. How this distribution takes place is considered in the next section. In this section, we first want to analyze the potential gains of distributed MISO transmissions to figure out if the additional effort is worth to be spent. If this effort is not spent and each data packet is only available at one node of the cluster, the achievable throughput can be increased by allocating each subcarrier to a transmit node according to the current channel conditions. In other words, we can select the best out of multiple links for each subcarrier. Therefore, we investigate the achievable capacity of distributed MISO transmissions and compare it with the capacity achievable by an exclusive allocation of a subcarrier to the best out of multiple transmitters. For simplicity reasons, we consider a scenario with N_f transmitters, only one receiver and only one subcarrier.

A. Best-of-Selection

The probability density function (pdf) of the envelope of the channel response $|h_i| = x$ corresponding to transmitter i assuming Rayleigh fading is given by

$$P(|h_i| = x) = \frac{2x}{\bar{\gamma}_i} e^{-\frac{x^2}{\bar{\gamma}_i}}, \quad \text{for } x \geq 0, \tag{2}$$

where $\bar{\gamma}_i$ denotes the average SNR of this channel. The corresponding cumulative distribution function (cdf) is given by

$$P(|h_i| \leq x) = 1 - e^{-\frac{x^2}{\bar{\gamma}_i}}, \quad \text{for } x \geq 0. \tag{3}$$

In case that we can select the best channel out of N_f links, the resulting pdf of the best-of-N_f selection is given by

$$\begin{aligned} P(|h_\mathrm{max}| = x) &= \sum_{i_1=1}^{N_\mathrm{f}} P(|h_{i_1}| = x) \prod_{i_2=1, i_2 \neq i_1}^{N_\mathrm{f}} P(|h_{i_2}| \leq x) \\ &= \sum_{i_1=1}^{N_\mathrm{f}} \frac{2x}{\bar{\gamma}_{i_1}} e^{-\frac{x^2}{\bar{\gamma}_{i_1}}} \prod_{i_2=1, i_2 \neq i_1}^{N_\mathrm{f}} \left(1 - e^{-\frac{x^2}{\bar{\gamma}_{i_2}}}\right), \end{aligned} \tag{4}$$

where $|h_\mathrm{max}| = \max_i(|h_i|)$. The pdf of $|h_\mathrm{max}|$ for different numbers N_f of transmitters is shown in Figure 2a). Assuming a normalized transmit and noise power equal to one, the average channel capacity of the best-of-N_f selection can be determined by

$$\bar{C}_\text{best-of} = \int_0^\infty P(|h_\mathrm{max}| = x) \cdot \log_2\left(1 + x^2\right) \mathrm{d}x. \tag{5}$$

B. MISO transmission

Instead of selecting the best transmitter out of N_f, nodes can also transmit simultaneously in a MISO fashion if the corresponding data is available at all nodes. The optimal strategy in terms of channel capacity is to adjust the phase of each signal such that they add up constructively at the receiver [9]. To achieve this, transmitter i uses a beam weight $\alpha_i = \frac{h_i^*}{|h_i|\sqrt{N_\mathrm{f}}}$. In this case, the resulting SNR at the receiver assuming noise power equal to one and assuming that the overall transmit power is equal to one and equally distributed among the transmitters is given by

$$\gamma_\mathrm{miso} = |h_\mathrm{miso}|^2 = \left(\sum_i^{N_f} \frac{|h_i|}{\sqrt{N_\mathrm{f}}}\right)^2. \tag{6}$$

The pdf of $|h_\mathrm{miso}|$ for different number of transmitters N is shown in Figure 2b). The average channel capacity using distributed MISO transmission is given by

$$\bar{C}_\mathrm{miso} = \int_0^\infty P\left(|h_\mathrm{miso}| = x\right) \cdot \log_2\left(1 + x^2\right) \mathrm{d}x. \tag{7}$$

In Figure 2c), the average capacities for best-of-selection and for MISO transmissions are shown over the number N_f of potential transmitters, in which each link has an average SNR of 15 dB (assuming transmit power equal to one). It can be seen that MISO transmissions provide significantly higher capacity gains compared to a best-of-selection especially for a high number of transmitters. For instance, for $N_\mathrm{f} = 4$ transmitters, distributed MISO achieves approximately 69.5 % gain while the best-of-selection only achieves approximately 46 % gain compared to the single transmitter case. However, as mentioned before, to utilize distributed MISO, each transmitter has to have the corresponding data packet. How data packets can be distributed among the desired forwarders within each cluster is considered in the next section.

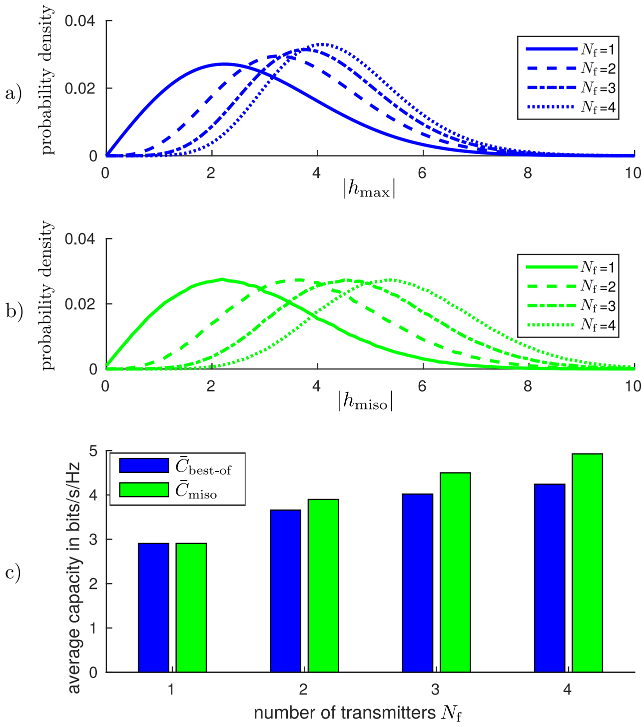
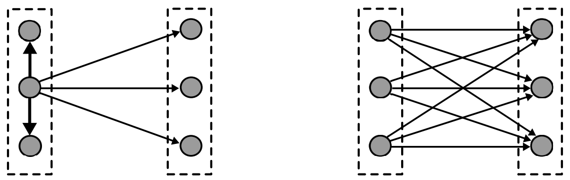


Fig. 2. Comparison between best-of selection and MISO transmissions for different numbers N_f of transmitters.

V. Enabling distributed MISO transmissions - Cluster transmission phases

To provide data packets to multiple nodes of a cluster, the source node could continue to send coded versions of each packet until all desired nodes have successfully decoded the packets. However, in case that the cluster nodes are placed closer to each other compared to the distance to the source or to the nodes of consecutive clusters, the SNRs of the links within the cluster are probably much higher. Therefore, it is beneficial to exchange data packets within each cluster. By using of fountain codes, all nodes within the cluster have already accumulated mutual information concerning all transmitted data packets. This means that the additional exchange within the cluster only needs to close the remaining gap in terms of mutual information to enable the other nodes to decode a certain packet. In the following, two elementary transmission



a) intra-cluster distribution phase b) inter-cluster forwarding phase

Fig. 3. Possible transmission phases. a) Only a single node within a cluster is transmitting at a time such that other nodes within the cluster can overhear. b) All nodes within the cluster are transmitting simultaneously.

phases, the intra-cluster distribution phase and the inter-cluster forwarding phase, are introduced which are considered within each cluster.

A. Intra-cluster distribution phase - Single node transmission

In the first transmission phase shown in Figure 3a), only one node of a cluster is transmitting at a time using all subcarriers. Since we assume that nodes cannot transmit and receive simultaneously, this is the only way to distribute data packets within the cluster. The nodes can successively claim this transmission phase in a round robin fashion. Each node is aiming at distributing data packets within the cluster which could not be decoded so far by the other nodes to enable distributed MISO transmissions in the following inter-cluster forwarding phase. Of course, also the nodes of the next cluster can overhear the transmissions and already start to accumulate mutual information about the distributed data packets. For how many time slots the nodes utilize the intra-cluster distribution phase depends on the used forwarding schemes which are introduced in the next section.

Since there is only one node transmitting at a time in the intra-cluster distribution phase, the possible gain achieved by a subcarrier allocation or by distributed MISO transmissions cannot be achieved during this phase. This means that enabling MISO transmissions to achieve higher throughput gains in the inter-cluster forwarding phase comes at the cost of temporarily reduced throughput to the next cluster during intra-cluster distribution.

B. Inter-cluster forwarding phase - Common and simultaneous node transmission

In the second phase, named inter-cluster forwarding phase, all nodes within the current cluster are transmitting simultaneously as shown in Figure 3b). The aim is to forward each data packet to at least one node of the next cluster as fast as possible. Nodes stop transmitting a certain data packet once at least one receiver of the next cluster has successfully decoded the packet. The nodes can share the available subcarriers based on the local channel knowledge. The diversity of links between the clusters can be exploited by an adaptive subcarrier allocation. In addition, multiple nodes can transmit on the same subcarrier if they transmit the same data packet. In this case, the nodes have to use the same code to represent the data packet. Therefore, no interference between different signals takes place, but an amplification of the same signals is achieved. To enable a fair comparison in terms of transmit power between different forwarding schemes, we limit the transmit power per subcarrier. In case that multiple nodes transmit on the same subcarrier, we assume the transmit power used on this subcarrier is equally distributed among the nodes.

VI. Forwarding schemes utilizing distributed MISO

In this section, two forwarding schemes are presented which are aiming to minimize the number of required time slots until each data packet has been decoded by one node of the next cluster. The first scheme relies on a full distribution of all data packets within each cluster. The second scheme adapts the extent to which data packets are distributed within the cluster according to the local channel conditions.

A. Cooperative forwarding based on full intra-cluster distribution

As mentioned before, each node within a cluster is aware of the availability of the data packets at the other nodes within the cluster by overhearing the transmitted acknowledgments. In order to provide each data packet to each node within the cluster, nodes can successively utilize the intra-cluster distribution phase. Within this phase, the single node which is transmitting uses all subcarriers. To schedule the data packets to the subcarriers, Algorithm 1 is used but instead of starting with a set containing all data packets, each node i maintains a set $\mathcal{S}_{\mathrm{packets},i}$ which includes all packets which are available at node i but not at each of the other nodes within the current cluster. Data packets which are decoded by all nodes within the cluster are removed from set $\mathcal{S}_{\mathrm{packets},i}$. Each node i within the cluster demands the intra-cluster distribution phase until its set $\mathcal{S}_{\mathrm{packets},i}$ is empty which means that all data packets are available at all nodes within the cluster.

In the inter-cluster forwarding phase, each data packet is transmitted in a distributed MISO fashion by all nodes within the cluster. The corresponding N_{sc} data packets for each subcarrier in the next time slot are again selected based on Algorithm 1. This time, the scheduling is again based on set $\mathcal{S}_{\mathrm{packets}}$ which contains all data packets which are not decoded by the nodes of the next cluster so far. In order to minimize the required time slots until at least one node of the next cluster is able to decode a certain packet, the transmit nodes use a beam weight adapted to one receiver j such that the signals from the different transmitters will constructively add up at this receiver j. To find the best receiver for each subcarrier n out of the next cluster, we determine the time t_{req,j,n_k} required by each receiver j to decode data packet k by

$$t_{\mathrm{req},j,n_k} = \frac{H_{\mathrm{data}} - H_{j,k}}{C_{\mathrm{miso},j,n}}, \tag{8}$$

where $H_{j,k}$ denotes the mutual information that node j has already accumulated concerning data packet k and $C_{\mathrm{miso},j,n}$ denotes the MISO channel capacity achievable in the current time slot at receiver j using subcarrier n if the transmit nodes adapt their beam weights to this receiver. For each subcarrier

n, the transmit nodes select receiver j with the lowest t_{req,j,n_k} and then use the corresponding beam weight given by

$$\alpha_{i,n} = \frac{h^*_{i,j,n}}{|h_{i,j,n}|\sqrt{N_\mathrm{f}}}. \quad (9)$$

By using these beam weights, the different phases of the channels to receiver j are canceled out such that a beamforming takes place. The achieved channel capacity at receiver j is then given by

$$C_{\mathrm{miso},j,n} = \log_2 \left(1 + \left(\sum_i^{N_f} \frac{|h_{i,j,n}|}{\sqrt{N_\mathrm{f}}} \right)^2 \right). \quad (10)$$

B. Cooperative forwarding based on adaptive intra-cluster distribution

As explained in Section V, distributing data packets within a cluster comes at the cost of temporarily reduced throughput to the next cluster since no adaptive subcarrier allocation and no MISO transmission can be exploited in this phase. Therefore, we aim at finding an adaptive scheme in which nodes only exchange a part of the data packets depending on the local channel conditions in order to reduce the required time slots for the intra-cluster distribution.

Based on Equation (6), we can determine if an additional transmitter improves the SNR of a MISO transmission. In case there are $N_f - 1$ transmitters, adding an N_f-th transmitter only leads to a higher MISO-SNR if the following inequality holds:

$$\left(\sum_i^{N_\mathrm{f}} \frac{|h_i|}{\sqrt{N_\mathrm{f}}} \right)^2 \geq \left(\sum_i^{N_\mathrm{f}-1} \frac{|h_i|}{\sqrt{N_\mathrm{f}-1}} \right)^2 \quad (11)$$

By rearranging the inequality, we get

$$|h_{N_f}|^2 \geq \left(\sqrt{\frac{N_\mathrm{f}}{N_\mathrm{f}-1}} - 1 \right) \cdot \left(\sum_{i=1}^{N_\mathrm{f}-1} |h_i| \right)^2 . \quad (12)$$

This inequality provides a condition for an additional channel which has to be fulfilled to improve a common MISO transmission. As a consequence, we conclude that not all data packets have to be available at all nodes within the cluster to achieve the highest possible throughput in the inter-cluster forwarding phase.

However, an optimal solution on how many data packets should be available at which node cannot be found since it would require exact non-causal knowledge about the future channel conditions on all subcarriers during the upcoming time slots. Therefore, we introduce a sub-optimal heuristic based on the available channel knowledge between the nodes of consecutive clusters. The aim is to find a percentage of data packets that should be available at node i based on the current average SNR $\bar{\gamma}_i$ between node i and the nodes of the next cluster. Based on test simulations in which each data packet is available at each node in a cluster, we can determine which percentage of data packets is used by each node if Inequality (12) is applied as a condition for a node to take part of a MISO transmission. This means that first, only the node with

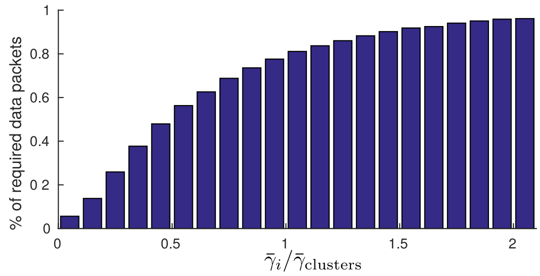


Fig. 4. Percentage of required data packets for a cluster size of $N_\mathrm{f} = 3$ nodes.

the strongest channel is selected as transmitter and the node with the next-best channel is only added if Inequality (12) is fulfilled. In Figure 4, the percentage of required data packets is shown for a cluster size $N_\mathrm{f} = 3$ over the ratio between the current average SNR $\bar{\gamma}_i$ of node i and the current average SNR $\bar{\gamma}_{\mathrm{clusters}}$ of all links between the consecutive cluster. The results depend on the number N_f of forwarding nodes in each cluster. Therefore, we determine this distribution for different cluster sizes N_f and use the results as a look-up table to decide in each individual cluster how many data packets should be exchanged within the cluster.

As a consequence, each node within the current cluster only demands the intra-cluster distribution phase as long as it still has data packets available which are not available at a node which does not fulfill the percentage of data packets according to the look-up table. For the scheduling of data packets to subcarriers in the intra-cluster distribution phase, again Algorithm 1 is used but it is based on a sorted set $\mathcal{S}^{\mathrm{sort}}_{\mathrm{packets},i}$ of the data packets. Set $\mathcal{S}^{\mathrm{sort}}_{\mathrm{packets},i}$ contains all data packets which are available at node i but not at all other nodes of the cluster, sorted by the number of nodes at which they are available in decreasing order. This means that data packets which are not available at most other nodes are selected first, which makes the distribution more efficient. Furthermore, a node i only uses the intra-cluster distribution as long as the number of data packets in set $\mathcal{S}^{\mathrm{sort}}_{\mathrm{packets},i}$ is at least equal to half the number of subcarriers N_{sc}. This prevents a wasteful use of resources for a distribution of only a very few data packets.

Since not all data packets are available at all nodes within the cluster after the intra-cluster distribution, the scheduling of data packets to subcarriers becomes important in the inter-cluster forwarding phase. Different combinations of the transmitters provide different channel capacities on the available subcarriers. Therefore, we select the N_{sc} data packets to be transmitted in the next time slot according to Algorithm 1, but we do not directly assign them to the subcarriers as explained in step 1) of the algorithm. For each possible assignment of a data packet k to a subcarrier n, we determine the time t_{req,j,n_k} required for each of the possible receiver j to decode data packet k if it is transmitted on subcarrier n. Thereby, the transmit nodes are selected step-wise, out of the nodes at which data packet k is available, only if they fulfill Inequality (12). The minimum t_{req,j,n_k} with respect to the potential receiver is stored in a $N_{\rm sc} \times N_{\rm sc}$-cost matrix $\mathbf{C}$. The k, n-th element in this matrix is then given by

$$\mathbf{C}(k,n) = \min_j (t_{\text{req},j,n_k}). \tag{13}$$

To assign the data packets to the subcarriers, the Hungarian method [10] is used. This algorithm determines the assignment with the minimum possible sum of the selected elements t_{req,j,n_k}.

VII. Performance Evaluation

In this section, the performance of the proposed forwarding schemes is evaluated based on simulations. To evaluate the utilization of distributed MISO transmissions, we compare the two schemes with a third forwarding strategy which only uses SISO transmissions. This SISO forwarding scheme is identical to the second forwarding scheme presented in Subsection VI B, which is in the following termed "MISO adaptive", except that no intra-cluster distribution takes place at all. The corresponding cost-matrix is determined based on the SISO capacities, but the subcarrier assignment is still based on the Hungarian method. The forwarding scheme proposed in Subsection VI A is termed "MISO full" in the following.

For the simulations, the parameters given in Table I are used. We generate networks with a fixed position of the source and the destination but with randomly distributed remaining nodes. Before the data transmission, only a part of the nodes is selected which form the structure introduced in Section II as follows: First, a unipath between source and destination is determined with a minimum possible number of hops under the constraint of a minimum average link SNR of 15 dB. This average SNR value is achieved for a distance of approximately 19.5 m. Each of the intermediate nodes within this unipath constitutes the starting point of a cluster. Next, each of these nodes selects the additional nodes for its cluster. The additional nodes for each cluster are selected according to the highest minimum link SNR with respect to the previous node and the next node within the unipath.

The entropy H_{data} of each data packet is normalized to 1 bit/Hz such that the results become independent of the subcarrier bandwidth. The length T of each time slot is chosen such that for an average SNR of 15 dB approximately four transmissions are required to decode a data packet. Reducing T can enable a more precise adaptation of the required time resources for each data packet. However, after each time slot, a pause is required for acknowledgments which reduces the effective throughput. This overhead introduced by the required acknowledgments is not taken into account in this work. Therefore, we have chosen T such that the required overhead keeps reasonable.

In Figure 5, the achievable end-to-end throughput is depicted as a function of the number of nodes on the map. For an increased number of nodes on the map, the number of required hops for the construction of the underlying unipath can be reduced. For 100 nodes on the map, on average 5.52 hops are required while for 200 nodes, only 5.04 hops are required. Furthermore, since more potential nodes are available

TABLE I
System Parameters

Map size $x \times y$	$100\text{m} \times 50\text{m}$
Number of nodes on the map	100-200
Position source (x, y)	$(10, 25)$
Position destination (x, y)	$(90, 25)$
Pathloss exponent α	3
Number $N_{\rm sc}$ of subcarriers	16
Number of data packets	100
Entropy of each data packet H_{data}	1 bit/Hz
Time slot length T	0.05 s

for each cluster, the channel conditions tend to be better. This leads to better conditions for all considered schemes which results in higher achievable throughput. It can be seen that the MISO full forwarding scheme is outperformed by the SISO forwarding scheme. This means that the full distribution of data packets within each cluster is too expensive in terms of the lost throughput to the next cluster within this phase. Compared with that, the SISO scheme exploits the link diversity by the adaptive subcarrier allocation among the nodes of each cluster the whole time. Furthermore, it can be seen that by increasing the number $N_{\rm f}$ of forwarding nodes in each cluster to 4 nodes, the MISO full scheme can only significantly increase the throughput in networks with a high node density. In this case, the nodes within a cluster tend to be placed closer to each other which makes the intra-cluster distribution more efficient. For only 100 nodes in the network, only a small gain is achieved by a larger cluster size. The same effect is observable for the MISO adaptive scheme which outperforms the other two considered schemes for all considered network densities. Compared to the MISO full scheme, a throughput gain of up to 7.55 % can be achieved by adapting the intra-cluster distribution for a network with 200 nodes and a cluster size $N_{\rm f} = 4$. By reducing the effort for the intra-cluster distribution to a reasonable extent, including distributed MISO transmissions leads to throughput gains.

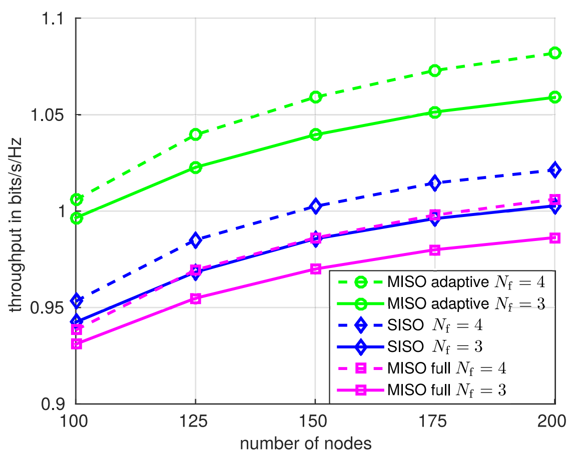


Fig. 5. Average achievable throughput for different number of nodes in the network

VIII. Conclusion

In this work, we proposed two novel cooperative forwarding strategies which integrate distributed MISO transmissions in data forwarding using clusters of cooperating nodes in OFDMA multihop networks. We compared the proposed schemes with a forwarding strategy that only considers SISO transmissions. It was shown that distributed MISO transmissions can provide high potential gains in terms of achievable throughput. However, to enable distributed MISO transmissions the distribution of the same data packet to multiple desired transmitters is required which causes rate losses during the distribution phase. By exploiting the properties of fountain codes and by adapting the extend to which data packets are distributed within each cluster, a higher throughput could be achieved by including distributed MISO transmissions compared to the pure SISO forwarding strategy.

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References

[1] A. Kuehne, A. Klein, A. Loch, and M. Hollick, "Corridor-based routing using opportunistic forwarding in OFDMA multihop networks," in *Proc. IEEE International Symposium on Personal Indoor and Mobile Radio Communications*, 2012.

[2] A. Loch, M. Hollick, A. Kuehne, and A. Klein, "OFDMA for wireless multihop networks: From theory to practice," *Pervasive and Mobile Computing*, vol. 23, pp. 104 – 121, 2015.

[3] M. Kurth, A. Zubow, and J. P. Redlich, "Cooperative opportunistic routing using transmit diversity in wireless mesh networks," in *Proc. IEEE INFOCOM 2008 - The 27th Conference on Computer Communications*, April 2008.

[4] G. Jakllari, S. V. Krishnamurthy, M. Faloutsos, P. V. Krishnamurthy, and O. Ercetin, "A cross-layer framework for exploiting virtual MISO links in mobile ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 6, no. 6, pp. 579–594, June 2007.

[5] S. Lakshmanan and R. Sivakumar, "Proteus: Multiflow diversity routing for wireless networks with cooperative transmissions," *IEEE Transactions on Mobile Computing*, vol. 12, no. 6, pp. 1146–1159, June 2013.

[6] A. Molisch, N. Mehta, J. S. Yedidia, and J. Zhang, "Performance of fountain codes in collaborative relay networks," *IEEE Transactions on Wireless Communications*, vol. 6, no. 11, pp. 4108–4119, Nov. 2007.

[7] S. C. Draper, L. Liu, A. F. Molisch, and J. S. Yedidia, "Cooperative transmission for wireless networks using mutual-information accumulation," *IEEE Transactions on Information Theory*, vol. 57, no. 8, pp. 5151–5162, Aug 2011.

[8] F. Hohmann and A. Klein, "Opportunistic forwarding using rateless codes in OFDMA multihop networks," in *Proc. of the IEEE 84th Vehicular Technology Conference*, 2016.

[9] M. Vu, "MISO capacity with per-antenna power constraint," *IEEE Transactions on Communications*, vol. 59, no. 5, pp. 1268–1274, May 2011.

[10] H. W. Kuhn, "The hungarian method for the assignment problem," *Naval Research Logistics Quarterly*, vol. 2, pp. 83 – 97, 1955.