Opportunistic forwarding in multi-hop OFDMA networks with local CSI

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Abstract— **In multi-hop networks, conventional unipath routing approaches force the data transmission to follow a fixed sequence of nodes. In this paper, we widen this path to create a corridor of forwarding nodes. Within this corridor, data can be split and joined at different nodes as the data travels through the corridor towards the destination node. To split data, decode-and-forward OFDMA is used since with OFDMA, one can exploit the benefits of opportunistically allocating different subcarriers to different nodes according to their channel conditions. To avoid interference, each subcarrier is only allocated once per hop. It is assumed that only local channel state information (CSI) for the next hop towards the destination is available at the nodes, i.e. it can not be guaranteed that a certain node is able to forward its received data in the next hop. This leads to additional transmission phases decreasing the overall network throughput. In this paper, different opportunistic forwarding algorithms are presented which differ in the resource allocation strategy and in the amount of cooperation required between the nodes. Simulations show that in multi-hop networks, corridor-based routing using opportunistic forwarding with a proper resource allocation strategy outperforms conventional unipath routing approaches in terms of achievable throughput, especially in case of a node drop out.**

Index Terms— **OFDMA, routing, local CSI.**

I. INTRODUCTION

In mobile ad hoc networks (MANETs), mobile wireless nodes exchange data among each other without using a fixed base station or a wired backbone network. Due to the limited transmission ranges of the nodes, a transmission over multiple hops is needed requiring routing to exchange data with any node in the network.

Unipath routing from a source to a destination node has been considered e.g. in [1] and [2]. Multipath routing can be applied to balance the load, to increase the fault tolerance and to increase the aggregated bandwidth [3] compared to unipath routing which suffers from problems such as congestions and bottlenecks due to the dynamic nature of wireless ad hoc networks.

In this paper, we present an alternative approach assuming that a unipath route has already been determined from a network layer perspective. This path is expanded to a corridor consisting of a certain number of forwarding nodes along the route in order to introduce some flexibility. Within this corridor, data can be split and joined as it travels towards the destination node. For the splitting of the data, Orthogonal Frequency Division Multiple Access (OFDMA) is used since it allows to opportunistically allocate different subcarriers to different nodes according to their channel conditions, i.e., information from the physical layer can be incorporated into the network layer unipath route in a cross-layer manner. Allocating each subcarrier only once per hop, interference can be avoided. With the proposed scheme, the reliability and aggregated throughput of the unipath route can be increased without having to compute a new route. In [4]-[7], multi-hop OFDM based networks have already been investigated. However, in all mentioned works the problem of resource and power allocation in multi-hop OFDM networks is only considered for unipath routing without splitting the data. Furthermore, these works always assume end-to-end Channel State Information (CSI) for all hops from the source to the destination. In our previous work [9], we analyzed the available throughput of corridor-based routing OFDMA multi-hop networks assuming end-to-end CSI. In this work, we assume only local CSI for the next hop towards the destination which is a much more reasonable assumption in practical applications.

The remainder of this paper is organized as follows. In Section II, the system model is presented. In Section III, corridor-based routing using opportunistic forwarding with local CSI is introduced. In Section IV, two opportunistic forwarding schemes which require full cooperation in the resource allocation between the forwarding nodes of a given hop are presented. In Section V, an opportunistic forwarding scheme which requires only limited cooperation between the forwarding nodes of a given hop is introduced. In Section VI, the performance of the different forwarding algorithms is discussed and compared to an OFDMA unipath approach. Furthermore, the impact of a node drop out on the performance of the different forwarding schemes is analyzed. Finally, conclusions are drawn in Section VII.

II. SYSTEM MODEL

In this work, a multi-hop transmission with h hops assuming one source node S, one destination node D and d possible forwarding nodes in each of the intermediate $h-2$ hops is considered as shown in Fig. 1. The nodes apply the decode-and-forward protocol, i.e., in each hop, each node decodes the received message and forwards a re-encoded version of the message. Furthermore, perfect time and frequency synchronisation between the forwarding nodes is assumed.

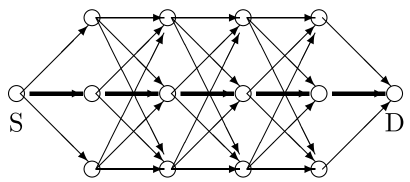

Fig. 1. Multi-hop transmission ($h = 5$) with one source (S), one destination (D) and $d = 3$ forwarding nodes per hop

OFDMA is applied as multiple access scheme where the bandwidth is subdivided into N orthogonal subcarriers. Rayleigh fading for the channels between the nodes is assumed, i.e., the fast fading on the n-th subcarrier with $n = 1, .., N$ from node i to node j with $i, j = 1, .., d$ in hop k described by the transfer factor $H_{i,j,n}^{(k)}$ is modeled as a complex Gaussian distributed random process with variance one. The average noise power per subcarrier for the link from node i to node j in the k-th hop is denoted by $P_{\mathrm{N},i,j,n}^{(k)}$. From each node i on each subcarrier n in each hop k, data is transmitted with power $p_{i,n}^{(k)}$ where the total transmit power per hop is normalized to $P_{\mathrm{T}} = \sum_{n=1}^{N} \sum_{i=1}^{d} p_{i,n}^{(k)} = N$.

Let $\lambda_{i,j,n}^{(k)}$ denote the normalized Signal-to-Noise Ratio (SNR) of the channel from node i to node j on the n-th subcarrier in hop k assuming $p_{i,n}^{(k)} = 1$ for all k, i and n given by

$$\lambda_{i,j,n}^{(k)} = \frac{1}{P_{\mathrm{N},i,j,n}^{(k)}} \cdot \left| H_{i,j,n}^{(k)} \right|^2 . \tag{1}$$

III. Corridor-based routing with local CSI

In this section, the idea of corridor-based routing using opportunistic forwarding in multi-hop OFDMA networks with local CSI and the involved additional transmissions are introduced.

A. Opportunistic forwarding

Applying corridor-based routing, data is split and joined using OFDMA as it travels through the corridor thereby exploiting diversity of the different forwarding nodes. Finally, the data merges at the destination node. To avoid interference it is assumed that each subcarrier is only allocated once per hop.

In the following, it is assumed that the end-to-end path defining the corridor has been determined (direct path from node S to node D in Fig. 1). The corridor size is denoted by d, the number of potential forwarding nodes in each hop which are in a reachable distance. Note that in a real network, the number of potential forwarding nodes per hop can be different. However, to simplify the analysis, we assume a constant number d of forwarding nodes per hop. Nevertheless, the proposed algorithms presented in the next sections are applicable in any directed network graph with one source and one destination.

B. Additional transmissions due to local CSI

Concerning CSI, we assume that only CSI of the channels of the next hop is available. We refer to it as local CSI. This is a realistic assumption especially for larger networks. Furthermore, by restricting ourselves to local CSI, the overhead which has to be spent to acquire CSI can be greatly reduced compared to the case requiring global CSI for all hops. Moreover, there is no need for a central unit to collect the CSI and to perform the resource and power allocation as this is done by the nodes themselves in each hop in a distributed manner.

Let N_{T} denote the number of transmission phases required to complete the data transmission from node S to node D. Furthermore, let R_1 denote the throughput of the first hop. Then, the network throughput is defined as

$$R_{\mathrm{net}} = \frac{R_1}{N_{\mathrm{T}}} . \tag{2}$$

From this it follows that the source waits until the arrival of the data at the destination before transmitting new data in order not to introduce interference to the system. In case that each node is always able to forward all data which has been transmitted to the node in the previous hop, N_{T} equals the number h of hops ($N_{\mathrm{T}} = h$). However, as the resource allocation is done without knowledge of the channel conditions of the next hops, it is possible that a certain node is not able to forward all its buffered data within one transmission phase. In this case, additional transmissions are required leading to $N_{\mathrm{T}} > h$. Note that $N_{\mathrm{T}} \in \mathbb{R}_{+}$, i.e., for a required additional transmission phase, it is possible that only a fraction of the resources of the primary transmission phase is needed to successfully transmit the remaining data buffered.

IV. Opportunistic forwarding with full cooperation

In this section, two opportunistic forwarding algorithms are presented which require full cooperation between the nodes of a given hop as the complete local CSI of all possible links within this hop has to be exchanged between the nodes and a common decision on the resource allocation has to be made and communicated. Note that the overhead associated with this cooperation is not considered in this paper.

A. Iterative Greedy Algorithm

The first approach is to use only the best subcarriers when opportunistically forwarding the data. In the first hop, i.e. from the source to the forwarding nodes of the second stage, data is only sent to forwarding nodes using subcarriers which provide the highest SNR. After resource allocation for the first hop, water-filling [11] is applied for power allocation assuming a maximum transmit power P_{T} per hop. In the consecutive hops towards the destination, the subcarriers are allocated iteratively. In each iteration, the subcarrier and the corresponding forwarding and receiving node which provide the highest

SNR are selected for data transmission. The allocated subcarrier is then taken out of consideration. If the buffer of the corresponding forwarding node is empty, this node is taken out of consideration in the next iterations as well. This procedure is repeated for all nodes under consideration until all buffers are empty or all subcarriers are allocated. In case that some nodes still have data to forward, additional transmission phases are carried out until all nodes have forwarded their data. Note that due to the iterative nature of the algorithm, an equal power allocation over the different allocated subcarriers is assumed for the intermediate hops towards the destination as it is not possible to know the SNR values of the allocated subcarriers in advance to apply water-filling for power allocation.

To determine the amount of data transmitted to the d different forwarding nodes in the first hop, let us introduce the $d \times N$ Greedy allocation matrix $\mathbf{Z}_{\mathrm{G}}{}^{(1)}$. The i, n-th element of $\mathbf{Z}_{\mathrm{G}}{}^{(k)}$ equals $z^{(1)}_{\mathrm{G},i,n} = 1$ if node i transmits on the n-th subcarrier, i.e., for the n-th subcarrier, the i-th forwarding node provides the highest SNR. If node i does not transmit data on the n-th subcarrier, $z^{(1)}_{\mathrm{G},i,n} = 0$. Furthermore, let us introduce a $1 \times N$ index vector $\mathbf{y}^{(1)}$. The n-th element $y^{(1)}_n$ of $\mathbf{y}^{(1)}$ denotes the index of the node to whom the data on this subcarrier is transmitted. With the function $r(w, \mathbf{a})$ returning the positions of the entry w in a vector $\mathbf{a}$, the n-th element of $\mathbf{y}^{(1)}$ is given by

$$y^{(1)}_n = r(1, \mathbf{Z}_{\mathrm{G}}{}^{(1)}(:, n)) \quad (3)$$

where $\mathbf{Z}_{\mathrm{G}}{}^{(1)}(:, n)$ denotes the n-th column of matrix $\mathbf{Z}_{\mathrm{G}}{}^{(1)}$.

From matrix $\mathbf{Z}_{\mathrm{G}}{}^{(1)}$ one can extract an SNR vector $\lambda^{(1)}_{\mathrm{sc}}$ with length N containing the SNRs of the allocated subcarriers. The n-th element of $\lambda^{(1)}_{\mathrm{sc}}$ is given by

$$\lambda^{(1)}_{\mathrm{sc},n} = \lambda^{(1)}_{1,y^{(1)}_n,n}. \quad (4)$$

Applying water-filling, the power allocation in the first hop leads to

$$p^{(1)}_n = \max\{0, P_{\mathrm{W}} - \frac{1}{\lambda^{(1)}_{\mathrm{sc},n}}\} \quad (5)$$

with $n = 1, .., N$ and $P_{\mathrm{W}} = \frac{1}{N}\sum_{v=1}^{N} p^{(1)}_v + \frac{1}{\lambda^{(1)}_{\mathrm{sc},n}}$ denoting the water level. The achievable amount of data $b^{(1)}_{1,j}$ to transmit from the source to forwarding node j is then given by

$$b^{(1)}_{1,j} = \sum_{v=r(1,\mathbf{Z}_{\mathrm{G}}{}^{(1)})} \log_2(1 + p^{(1)}_v \lambda^{(1)}_{\mathrm{sc},v}). \quad (6)$$

In the following, the pseudo code of the iterative Greedy algorithm for the remaining hops towards the destination is presented:

1) Set all buffer levels $b^{(k)}_j$ for the forwarding nodes to zero ($b^{(k)}_j = 0$) for $k = 3, .., h - 1$
2) Set $k = 2$ (second hop)
3) Set set $\mathcal{S} = \{1, 2, .., d\}$
4) Check for nodes with empty buffer $b^{(k)}_j = 0$ $j \in \mathcal{S}$ and exclude them from set $\mathcal{S}$
5) Set set $\mathcal{S}_{\mathrm{sc}} = \{1, 2, .., N\}$
6) Considering all forwarding nodes of set $\mathcal{S}$ and all subcarriers of set $\mathcal{S}_{\mathrm{sc}}$, determine subcarrier n^*, forwarding node i^* and receiving node j^* which provide the highest SNR ($n^*, i^*, j^* = \arg\max_{n,i,j} \lambda^{(k)}_{i,j,n}$)
7) Take subcarrier n^* out of consideration ($\mathcal{S}_{\mathrm{sc}} = \mathcal{S}_{\mathrm{sc}} \setminus n^*$)
7) Determine achievable amount of data b to transmit from node i^* to node j^* using subcarrier n^* assuming equal power allocation with $p^{(k)}_{n^*} = 1$ ($b = \log_2(1 + \lambda^{(k)}_{i^*,j^*,n^*})$)
8) Subtract b from current buffer level of node i^* ($b^{(k)}_{i^*} = b^{(k)}_{i^*} - b$)
9) If $b^{(k)}_{i^*} < 0$, the data transmitted from node i^* to node j^* is set to $b_{i^*,j^*} = b + b^{(k)}_{i^*}$ and $\mathcal{S} = \mathcal{S} \setminus i^*$, else $b_{i^*,j^*} = b$
10) Update buffer level of receiving node j^* ($b^{(k+1)}_{j^*} = b^{(k+1)}_{j^*} + b_{i^*,j^*}$)
11) If $\mathcal{S} = \{\}$ and $k = h$, transmission finished
12) If $\mathcal{S} = \{\}$ and $k < h$, $k = k + 1$ and go to 3) (hop completed, start new hop)
13) If $|\mathcal{S}_{\mathrm{sc}}| > 0$, go to 6) (hop not finished yet), else go to 5) (no subcarriers left, additional transmission phase required)

B. Iterative Hungarian Method

Another approach is to apply a Fair Resource Scheduling (FRS) using the Hungarian Method [10]. In the first hop, the data is transmitted from the source node to the d forwarding nodes of the second stage where the same number of disjoint subcarriers is allocated to each forwarding node following the Hungarian Method which maximizes the sum of the channel gains of these allocated subcarriers. By doing so, the diversity of all d forwarding nodes can be exploited in the next hop. Like with the iterative Greedy algorithm, water-filling is applied over the allocated subcarriers of the first hop. Hence, the same steps which lead to (6) can be used to determine the amount of data transmitted in the first hop. Only allocation matrix $\mathbf{Z}_{\mathrm{G}}{}^{(1)}$ must be replaced by allocation matrix $\mathbf{Z}_{\mathrm{HM}}{}^{(1)}$ representing the resource allocation with respect to the Hungarian Method. In the next hops towards the destination node, the subcarriers are iteratively allocated applying the Hungarian Method. In each iteration, each forwarding node chooses its best subcarrier out of all its allocated subcarriers, i.e., in contrast to the Greedy algorithm, it is always guaranteed that due to the FRS policy each forwarding node gets access to a subcarrier in each iteration.

These chosen subcarriers are then taken out of consideration for the next iterations. Next, each node determines the amount of data which can be transmitted and checks whether there is still data left in its buffer. For the case that the buffer of a certain node is empty, this node will no longer be considered in the next iterations. This procedure is repeated for all nodes under consideration until all buffers are empty or all subcarriers are allocated. Like with the iterative Greedy algorithms, additional transmission phases are carried out if necessary.

In the following, the pseudo code of the algorithm for the remaining hops towards the destination is presented:

1) Set all buffer levels $b_j^{(k)}$ for the forwarding nodes to zero ($b_j^{(k)} = 0$) for $k = 3, .., h-1$
2) Set $k = 2$ (second hop)
3) Set set $\mathcal{S} = \{1, 2, .., d\}$
4) Check for nodes with empty buffer $b_j^{(k)} = 0 \; j \in \mathcal{S}$ and exclude them from set $\mathcal{S}$
5) Set set $\mathcal{S}_{\text{sc}} = \{1, 2, .., N\}$
6) For all forwarding nodes of set $\mathcal{S}$ and all subcarriers of set $\mathcal{S}_{\text{sc}}$, consider only receiving node $j^\star(i, n, k) = \arg\max_j \{\lambda^{(k)}_{i,1,n}), .., \lambda^{(k)}_{i,d,n})\}$ which provides the highest SNR
7) Apply Hungarian Method resulting in $d \times N$ allocation matrix $\mathbf{Z}_{\text{HM}}{}^{(k)}$ and $1 \times N$ index vector $\mathbf{y}^{(k)}$ denoting the index of the node to whom the data on a given subcarrier is transmitted
8) Calculate SNR vector $\lambda^{(k)}_{\text{sc}}$ with length N containing the SNRs of the allocated subcarriers: $\lambda^{(k)}_{\text{sc},n} = \lambda^{(k)}_{r(1,\hat{\mathbf{Z}}^{(k)}(:,n)),y^{(k)}_n,n}$
9) Choose for each forwarding node i under consideration the subcarrier index $n(i)$ of the subcarrier allocated to node i which provides the highest SNR
10) Take these subcarriers out of consideration ($\mathcal{S}_{\text{sc}} = \mathcal{S}_{\text{sc}} \setminus n(i)$)
11) Put the SNR values of the chosen subcarriers into an vector $\lambda^{(k)}_{\text{sc},\max}$ with length $|\mathcal{S}|$
12) Use $\lambda^{(k)}_{\text{sc},\max}$ to calculate power allocation $p_m^{(k)}$ according to (5) with $m = 1, .., |\mathcal{S}|$
13) For each forwarding node i under consideration, determine achievable amount of data b to transmit from node i to node $y^{(k)}(n(i))$ using subcarrier $n(i)$ ($b_i = \log_2(1 + p_m^{(k)} \cdot \lambda^{(k)}_{\text{sc},\max}(m))$)
14) For each forwarding node i under consideration, subtract b from its current buffer level ($b_i^{(k)} = b_i^{(k)} - b$)
15) If $b_i^{(k)} < 0$, the data transmitted from node i to node $j(i) = y^{(k)}(n(i))$ is set to $b_{i,j(i)} = b + b_i^{(k)}$ and $\mathcal{S} = \mathcal{S} \setminus i$,
    else $b_{i,j(i)} = b$
16) Update buffer level of receiving node $j(i)$ of all receiving nodes ($b^{(k+1)}_{j(i)} = b^{(k+1)}_{j(i)} + b_{i,j(i)}$)
17) If $\mathcal{S} = \{\}$ and $k = h$, transmission finished
18) If $\mathcal{S} = \{\}$ and $k < h$, $k = k + 1$ and go to 3) (hop completed, start new hop)
19) If $|\mathcal{S}_{\text{sc}}| > 0$, go to 6) (hop not finished yet),
    else go to 5) (no subcarriers left, additional transmission phase required)

V. Opportunistic forwarding with limited cooperation

In this section, an opportunistic forwarding algorithm is presented which only requires limited cooperation between the nodes of a given hop as not the complete local CSI has to be exchanged but only information concerning the buffer level of the different forwarding nodes. The first hop is performed identically as with the iterative Greedy algorithm. For the next hops, blocks of subcarriers are assigned to the different forwarding nodes based on the buffer levels of the forwarding nodes. Within each block, the resource allocation is then performed independently in a distributed manner without having a central unit. Here, a greedy allocation strategy is applied where each subcarrier is allocated exclusively. In case that some nodes are not able to forward all its buffered data, additional transmission phases are carried out until all nodes have forwarded their data. Due to the similar procedure of this algorithm compared to the iterative Greedy algorithm, the pseudo code of Section IV-A can be used again only with two small modifications. Between step 4) and 5), an intermediate step 4a) has to be introduced to calculate the block size N_j of the subcarriers assigned to forwarding node $j \in \mathcal{S}$ based on the current buffer levels $b_j^{(k)}$ given by

$$N_j = \left[\frac{N \cdot b_j^{(k)}}{\sum_j b_j^{(k)}} \right]_{\mathcal{N}^+} \tag{7}$$

where $[x]_{\mathcal{N}^+}$ returns the rounding of x to the nearest positive integer. In case that $\sum_j N_j < N$, $\Delta = \sum_j N_j - N$ is added to the smallest of the block size values N_v with $v = \arg\min_v \{N_v\}$. In case that $\sum_j N_j > N$, $\Delta = N - \sum_j N_j$ is subtracted from the largest of the block size values N_v with $v = \arg\max_v \{N_v\}$. In step 6) and 8), the $d \times N$ SNR matrix $\Lambda_i^{(k)}$ of each forwarding node i in hop k given by the elements $\lambda^{(k)}_{i,j,n}$ has to be modified. To incorporate the fact that the greedy resource allocation is performed only inside the assigned resource blocks in a distributed manner, matrix $\Lambda_i^{(k)}$ has to be multiplied component-wise with a $d \times N$ block matrix $\mathbf{M}_{\text{B},i}$ given by

$$\mathbf{M}_{\text{B},i} = \begin{bmatrix} \mathbf{0}_{d \times \sum_{\mu=1}^{i-1} N_\mu} & \mathbf{1}_{d \times N_i} & \mathbf{0}_{d \times \left(N - \sum_{\mu=1}^{i} N_\mu\right)} \end{bmatrix} \tag{8}$$

where $\mathbf{0}_{p \times q}$ and $\mathbf{1}_{p \times q}$ denote a $p \times q$ zero matrix and a $p \times q$ one matrix, respectively. Hence,

$$\tilde{\Lambda}_i^{(k)} = \Lambda_i^{(k)} \odot \mathbf{M}_{\text{B},i} \tag{9}$$

with elements $\tilde{\lambda}^{(k)}_{i,j,n}$ and $\odot$ denoting a component-wise multiplication. From this it follows that in step 6) and 8), $\lambda^{(k)}_{i,j,n}$ must be replaced by $\tilde{\lambda}^{(k)}_{i,j,n}$.

VI. Numerical results

To evaluate the performance of the proposed opportunistic forwarding schemes, we assume an OFDMA network with $N = 64$ subcarriers, $h = 4$ hops and $d = 1, 2, 4, 8$ forwarding nodes per hop. For simplicity, the average SNR $\bar{\gamma}^{(k)}_{i,j,n} = \frac{1}{P^{(k)}_{\text{N},i,j,n}}$ per subcarrier is assumed to be equal for all links within one hop and the same for all hops ($\bar{\gamma}^{(k)}_{i,j,n} = \bar{\gamma} \; \forall \; i, j, k$). For comparison, an

OFDMA multi-hop scenario with the same network is considered where the data transmission follows only one path without splitting the data to different nodes. Here, all subcarriers are allocated to one given node followed by a power allocation using water-filling. For this scenario, two unipath schemes are considered. With the first scheme referred to as random forwarding along unicast route, the forwarding node for the next hop is chosen randomly. With the second scheme referred to as opportunistic forwarding along unicast route, the node selection is based on the achievable throughput, i.e., the node which provides the highest throughput is chosen as forwarding node for the next hop.

In Fig. 2, the throughput of the two unipath schemes is depicted as a function of the average SNR. The throughput is averaged over 1000 independent Monte Carlo simulations. It can be seen that for an increasing number d of forwarding nodes, the throughput performance slightly increases due to the higher node diversity. However, the gain is rather small as the variance of the throughput applying water-filling over $N = 64$ subcarriers is rather small, i.e., choosing a node out of several nodes with similar throughput performance does not bring so much gain. Note that for each number d of forwarding nodes, the performance of the random forwarding scheme is equal to the performance of the opportunistic forwarding along unicast route with $d = 1$ forwarding node as in both cases no selection takes place.

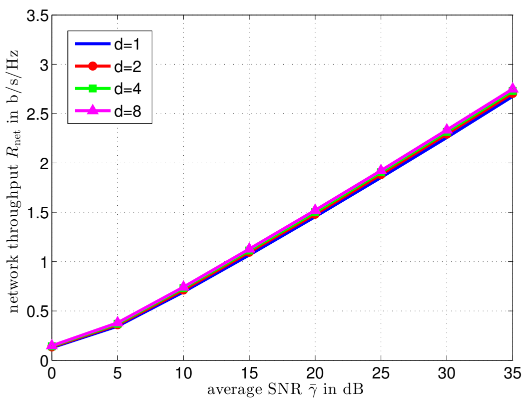

Fig. 2. Network throughput applying unipath routing versus average SNR

In Fig. 3, the analysis is shown for the iterative Greedy algorithm. Although only the best subcarriers are used for transmission, the performance decreases when increasing the number d of forwarding nodes. The reason for that is originated in the greedy resource allocation policy. In the first hop, this policy leads to a maximum network throughput. However, in the consecutive hops, this policy increases the number of additional transmission phases decreasing the throughput. As only the forwarding nodes with the best subcarriers are allowed to forward their data without considering the other forwarding nodes which also have data to transmit, it is possible that these forwarding not are not able to forward their data causing additional transmissions. For an increasing number of forwarding nodes, this problem caused by the unbalanced resource allocation becomes even more severe.

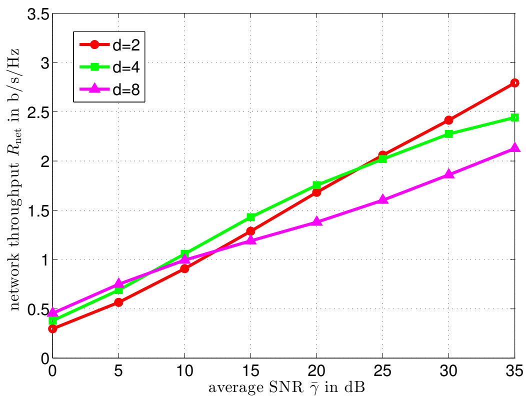

Fig. 3. Network throughput applying opportunistic forwarding with iterative Greedy algorithm versus average SNR

In Fig. 4, the network throughput is depicted applying the iterative Hungarian Method. It can be seen that with increasing number d of forwarding nodes, the throughput increases due to a higher diversity. The reason for that is that due to the FRS policy, each forwarding node gets access to the same amount of subcarriers to forward its data without causing too much additional transmission phases which would undo the diversity gains.

In Fig. 5, the network throughput is depicted applying the scheme with limited cooperation. For increasing d, the network throughput also increases up to $d = 4$ forwarding nodes. For $d = 8$, the network throughput becomes worse again. For larger number d of forwarding node, the simple resource block assignment cannot guarantee each forwarding node to forward its data without additional transmission phases. However, compared to the iterative Greedy algorithm, the decrease is much less severe. The reason for that lies in the resource block assignment which in contrast to the iterative Greedy algorithm concedes access to the same amount of subcarriers to each forwarding node to forward its data similar to the Hungarian Method.

In Fig. 6, the performances of the different schemes is compared for $d = 4$ forwarding nodes. It can be seen that for this scenario, all proposed opportunistic forwarding schemes outperform the conventional unipath routing scheme. It can further be seen that the algorithm with limited cooperation is only slightly worse compared to the two schemes requiring full cooperation, i.e., for practical applications this scheme could be especially interesting. Regarding the iterative Greedy and the iterative Hungarian, it can be seen that for average SNRs below 15 dB, the iterative Greedy performs better than the iterative Hungarian. For SNRs above 15 dB it is vice-versa. Obviously, for this parameter setting the negative effect of unbalanced resource allocation becomes dominant at this SNR value.

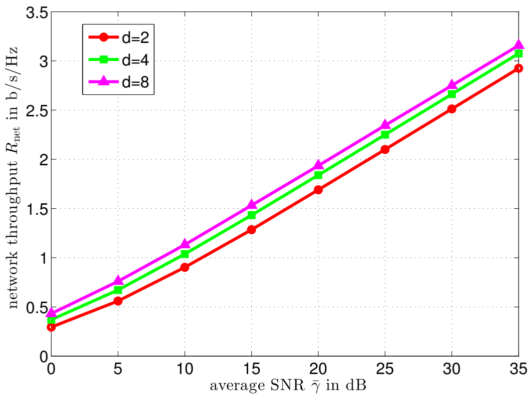

Fig. 4. Network throughput applying opportunistic forwarding with iterative Hungarian method versus average SNR

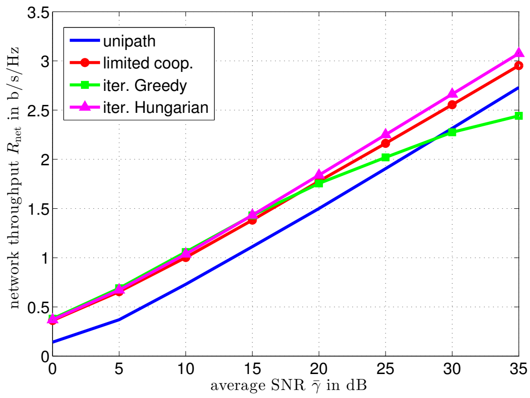

Fig. 6. Comparison of the different forwarding schemes for $d = 4$ forwarding nodes per hop and $h = 4$ hops

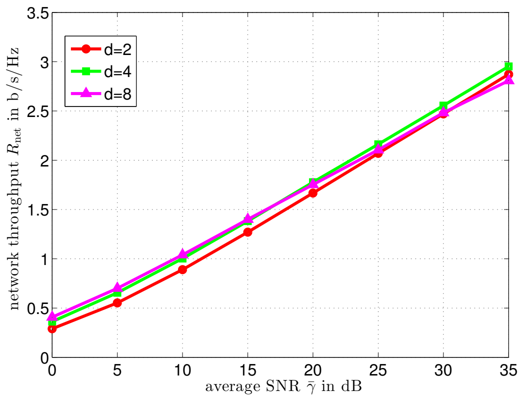

Fig. 5. Network throughput applying opportunistic forwarding with limited cooperation versus average SNR

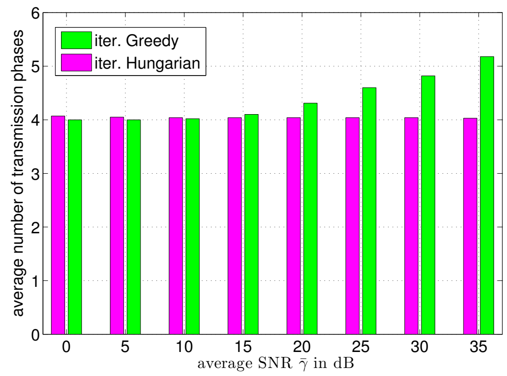

Fig. 7. Average number of required transmission phases versus average SNR for $d = 4$ forwarding nodes per hop and $h = 4$ hops

Fig. 7 shows the average number of required transmission phases as a function of the average SNR. It can be seen that for low SNRs, the iterative Greedy hardly requires more transmission phases than hops (in this case $h = 4$). For SNRs above 15 dB, the number of required transmission phases increases of the iterative Greedy, while for the iterative Hungarian, the number of transmission phases remains almost constant.

To further investigate this, also the impact of the number of available subcarriers have to be taken into account. In Fig. 8, the average SNR threshold above which the iterative Hungarian Method outperforms the iterative Greedy is depicted as a function of the number N of available subcarriers for different d. For example, having $N = 50$ subcarriers in the system with $d = 2$ forwarding nodes (solid curve), one should use the iterative Hungarian for average SNR values above 10 dB. From the figure, it can be seen that the more subcarriers are available in the system, the less dominant is the negative effect of the unbalanced resource allocation of the Greedy algorithm. However, increasing the number of forwarding nodes, the performance of the Greedy algorithm decreases as already seen before.

To complete the analysis of the schemes, also the impact of the number h of hops is discussed. In Fig. 9 and Fig. 10, the performance of the different schemes is depicted for $d = 4$ forwarding nodes and $h = 3$ and $h = 5$ hops in the system, respectively. In all cases, the iterative Hungarian Method outperforms the other two opportunistic forwarding schemes providing significant throughput gains compared to the conventional unipath scheme. However, it has to be noted that increasing the number of hops, the network throughput decreases. This has two reasons. First, the throughput decreases due to the increased number h of hops and the corresponding transmission phases. Second, due to the fact that increasing the number of hops, also the probability for a bad hop with rather poor channel gains increases which causes additional transmission phases.

Finally, the impact of a node drop out is analyzed for the different forwarding schemes for a scenario with $h = 4$ hops. In the following, we assume that the middle node in the third stage of the network suffers from bad channel conditions, i.e., all links to this node have poor channel gains. This is expressed by SNR $\bar{\gamma}_{\text{bad}}$ for this node. In Fig. VI, the network throughput assuming an average SNR of $\bar{\gamma} = 15$ dB for the unaffected nodes is depicted as a function of $\bar{\gamma}_{\text{bad}}$ for the different schemes with

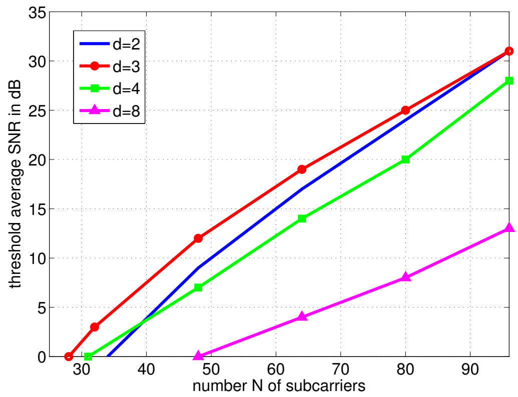

Fig. 8. Threshold SNR values for switching from Greedy algorithm to Hungarian method applying opportunistic forwarding

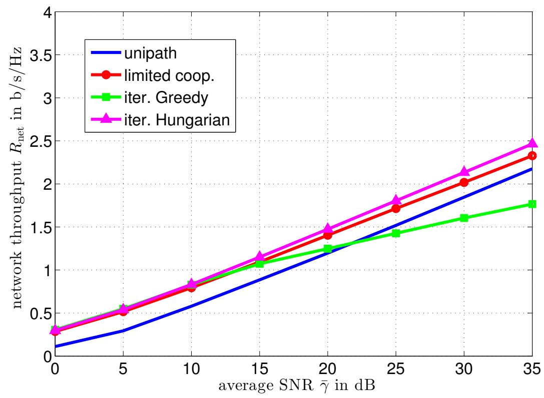

Fig. 10. Comparison of the different forwarding schemes for $d = 4$ forwarding nodes per hop and $h = 5$ hops

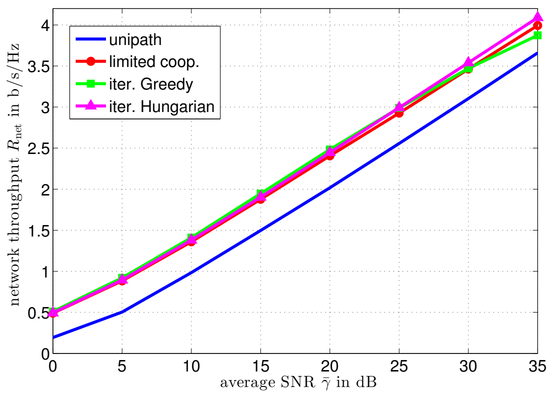

Fig. 9. Comparison of the different forwarding schemes for $d = 4$ forwarding nodes per hop and $h = 3$ hops

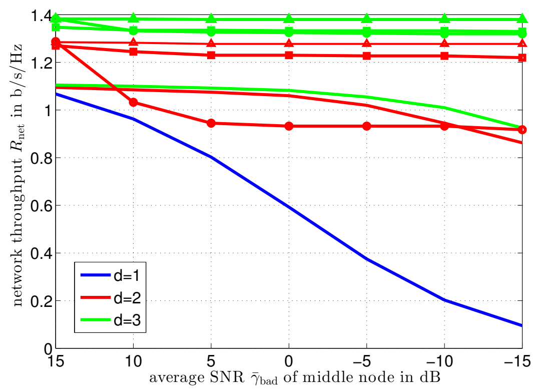

Fig. 11. Network throughput vs. average SNR $\bar{\gamma}_{\mathrm{bad}}$ of middle node with $\bar{\gamma} = 15$ dB and $h = 4$ hops (solid - unipath, circle - iterative Greedy, square - limited cooperation, triangle - iterative Hungarian)

different numbers d of forwarding nodes. It can be seen that applying unipath routing, the throughput decreases for decreasing $\bar{\gamma}_{\mathrm{bad}}$ especially for the case $d = 1$ as the drop out node forms a bottleneck causing multiple additional transmission phases. However, applying corridor-based routing, this bottleneck can be bypassed. For the iterative Hungarian and the limited cooperation scheme, this bypassing causes hardly any loss in throughput especially when increasing the number d of forwarding nodes per hop. For the iterative Greedy however, the node drop out causes significant throughput loss as the problem of unbalanced resource allocation becomes even severe losing a potential forwarding node. In case of $d = 2$ forwarding nodes, the performance becomes even worse than unipath routing.

Consequentially, applying corridor-based routing with the proper resource allocation policy, it is possible to compensate a node drop out without having to re-calculate a new route as with conventional unipath routing. Thereby, the network becomes more robust to disturbances.

VII. Conclusions

In this work, we presented the concept of corridor-based routing using opportunistic forwarding in multi-hop OFDMA networks with local CSI. In contrast to forwarding along a unicast route where the data transmission follows one particular path through the network, the data is allowed to be split and joined within a forwarding node corridor to exploit diversity applying opportunistic forwarding using OFDMA. We presented three different algorithms which differ in the resource allocation policy and the amount of required cooperation between the nodes. Compared to an conventional OFDMA unipath forwarding scheme, the proposed schemes provide significant gains in network throughput where the scheme requiring limited cooperation only slightly performs worse than the ones with full cooperation. Furthermore, two of the proposed schemes can compensate a node drop out without having to re-calculate a new route as with conventional unipath routing increasing the robustness of the network.

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