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Corridor-based Routing using Opportunistic Forwarding in OFDMA Multihop Networks

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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. For the presented scheme, the problem of optimizing the network throughput by means of resource and power allocation is formulated and two suboptimal algorithms are proposed to solve this problem with feasible effort. Simulations show that in multi-hop networks corridor-based routing using opportunistic forwarding outperforms conventional unipath routing approaches in terms of achievable throughput.**

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 direct transmission is not always possible, i.e., a transmission over multiple hops is needed requiring routing to exchange data with any node in the network. Thus, routing is a crucial issue for this kind of networks.

Determining a single route from a source to a destination node in a MANET has been considered, e.g., in [1] and [2]. To alleviate problems such as congestions and bottlenecks which appear in unipath routing due to the dynamic nature of wireless ad hoc networks, multipath routing can be applied to balance the load, to increase the fault tolerance and the aggregated bandwidth [3]. In this paper, we present another approach assuming that a unipath route has already been determined from a network layer perspective. In order to introduce some flexibility, we widen this path to a corridor consisting of a certain number of forwarding nodes along the route. Inside this corridor, data can be split and joined as it travels towards the destination node. To split data at a given node, Orthogonal Frequency Division Multiple Access (OFDMA) is used since OFDMA offers the opportunity of allocating 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. Assuming that each subcarrier is only allocated once per hop, interference can be avoided. This approach can be interpreted as a non-disjoint multipath routing [3] within a corrdidor of a given unipath route. Hence, the reliability and aggregated throughput of the unipath route can be increased without having to compute a new route by considering the current channel conditions of the nodes using OFDMA within the corridor. OFDMA in multi-hop networks has already been investigated, e.g. in [4]-[9]. In [4], the authors assume a two-hop transmission in a multiuser scenario where the base station and the intermediate relays are connected through wired lines. In [5], multi-hop OFDM networks applying amplify-and-forward relaying are considered assuming only unipath routing without splitting the data to different forwarding nodes. In [6]-[8], the problem of resource and power allocation in multi-hop OFDM networks applying decode-and-forward is considered assuming only unipath routing as well. In [9], the power and resource allocation is discussed for the case that the transmission is not performed hop-by-hop but simultaneously, avoiding inter-hop interference by frequency sharing. However, also only unipath routing is considered. To the best of the authors' knowledge, a multi-hop OFDMA network which applies data splitting and merging through a forwarding corridor has not been considered so far.

The remainder of this paper is organized as follows. In Section II, the system model is presented. In Section III, the corridor-based routing using opportunistic forwarding is introduced together with the problem formulation of allocating resources and power. In Sections IV and V, two algorithms are presented which both solve the OFDMA resource and power allocation problem. In Section VI, the performance of the two algorithms is discussed and compared to an OFDMA unipath approach. Finally, conclusions are drawn in Section VII.

II. System model

In this work, we consider 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 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.

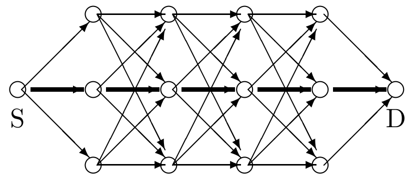


Fig. 1. Multi-hop transmission ($h = 5$) with one source (S), one destination (D) and $d = 3$ forwarding nodes per hop

OFDMA is used as multiple access scheme and 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 $H^{(k)}_{i,j,n}$ is modeled as a complex Gaussian distributed random process with variance one. The average noise power per subcarrier is denoted by σ^2. From each node i on each subcarrier n in each hop k, data is transmitted with power $p^{(k)}_{i,n}$ where the total transmit power P_T per hop is given by $P_\mathrm{T} = \sum_{n=1}^{N} \sum_{i=1}^{d} p^{(k)}_{i,n}$.

Let $\lambda^{(k)}_{i,j,n}$ 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 $p^{(k)}_{i,n} = 1$ for all k, i and n given by

$$\lambda^{(k)}_{i,j,n} = \frac{1}{\sigma^2} \cdot \left| H^{(k)}_{i,j,n} \right|^2 . \quad (1)$$

Note: The following notations are used throughout this work: $\mathbf{I}_{m\times m}$ denotes a $m \times m$ unity matrix, $\mathbf{O}_{p\times q}$ denotes a $p \times q$ zero matrix and $\mathbf{1}_{1\times m}$ denotes a column vector of ones with length m. The operator $\otimes$ denotes the Kronecker product.

III. Corridor-based routing using opportunistic forwarding in multi-hop OFDMA networks

In this section, the idea of corrdidor-based routing using opportunistic forwarding in multi-hop OFDMA networks is presented followed by the problem formulation.

A. Opportunistic forwarding

In unipath routing through a network, the transmission of the data is forced to follow a fixed sequence of nodes. The idea is to introduce some flexibility by widening this path to create a corridor. Within this corridor, data can be split and joined as it travels through the corridor thereby exploiting diversity of the different forwarding nodes. Finally, the data merges at the destination node. To split data at a given node, OFDMA is used since OFDMA offers the opportunity of allocating different subcarriers to different nodes according to their channel conditions without introducing interference assuming 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). Furthermore, perfect CSI of all links in each hop is assumed. 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 this paper, the number d of forwarding nodes in the corridor is given, i.e., the actual node selection is not considered here. Moreover, the overhead which has to be spent in order to coordinate the data transmission within the corridor is not considered. The scope of this paper is to analyze the theoretical potential of this approach. In practical MANETs, one could think of a rather static network where the channel conditions do not change significantly over time, i.e., the coordination of the nodes could be performed in rather large time intervals alleviating the impact of the coordination overhead.

B. Problem formulation

In this corridor-based routing scheme, the question arises how to allocate the subcarriers and transmit power in each hop such that the throughput of the whole network is maximized. To do so, we have to consider that the amount of data transmitted per link must not exceed the link capacity which is given by

$$C^{(k)}_{i,j,n} = \log_2(1 + p^{(k)}_{i,n} \lambda^{(k)}_{i,j,n}) \quad (2)$$

for the link from node i to node j on the n-th subcarrier in the k-th hop. From this, it follows that the amount of data which is forwarded to a given node must not be larger than the amount of data the node is able to forward in the next hop.

In the following, we define $\mathbf{Z}^{(k)}$ as a 3-dimensional $d\times d\times N$ allocation tensor in the k-th hop with $k = 1, .., h$. The i, j, n-th element $z^{(k)}_{i,j,n}$ of $\mathbf{Z}^{(k)}$ with $i, j = 1, .., d$ and $n = 1, .., N$ equals $z^{(k)}_{i,j,n} = 1$ if node i transmits on the n-th subcarrier to node j and $z^{(k)}_{i,j,n} = 0$ if node i does not transmit data on the n-th subcarrier to node j. The throughput of the network is determined by the amount of data transmitted in the first hop divided by the number h of hops. Hence, the optimization problem is given by

$$C_{\mathrm{net,max}} = \max_{\mathbf{Z}^{(k)}, p^{(k)}_{i,n}} \frac{1}{h} \sum_{n=1}^{N} \sum_{j=1}^{d} z^{(1)}_{1,j,n} \log_2(1 + p^{(1)}_{1,n} \lambda^{(1)}_{1,j,n}) \quad (3)$$

$$\begin{aligned}
s.t.& \\
a)\quad & \sum_{n=1}^{N} \sum_{i=1}^{d} p^{(k)}_{i,n} = P_\mathrm{T} \ \forall\, k \\
b)\quad & \sum_{i=1}^{d} \sum_{j=1}^{d} z^{(k)}_{i,j,n} = 1 \ \forall\, n, k \\
c)\quad & \sum_{v=1}^{d} \sum_{n=1}^{N} z^{(k-1)}_{v,j,n} \log_2(1 + p^{(k-1)}_{v,n} \lambda^{(k-1)}_{v,j,n}) \\
& = \sum_{v=1}^{d} \sum_{n=1}^{N} z^{(k)}_{j,v,n} \log_2(1 + p^{(k)}_{j,n} \lambda^{(k)}_{j,v,n}) \\
& j = 1, .., d \text{ and } k = 2, .., h.
\end{aligned}$$

In other words, we have to determine the maximum amount of data transmitted in the first hop which can be forwarded through the network considering the channel conditions of all hops. From this, it follows that the amount of data transmitted in the first hop depends on the channel conditions of all other hops especially on the hop with the weakest channel conditions. Constraint 3a) considers that the aggregated transmit power per hop is limited by P_T. Constraint 3b) takes into account the exclusive subcarrier allocation per hop while constraint 3c) assures that the amount of data received at a given node equals the amount of data this node transmits in the next hop. Since this results in a combinatorial problem which makes it hard to find an optimal solution, we propose two suboptimal but feasible solutions for (3) in the following.

IV. Per-hop resource and power allocation scheme

In this section, problem (3) is simplified by considering the hops independently from each other. In each hop, the subcarriers are allocated to the different nodes assuming that each node has a full buffer of data to transmit. After resource allocation, power allocation is performed applying waterfilling [11]. As a result, one can determine for each hop, how much data can be transmitted on each link within this hop while fulfilling constraints 3a) and 3b). To find the optimal achievable capacity C_net of this network assuming the chosen per-hop resource and power allocation such that constraint 3c) is fulfilled, a linear programming problem can be formulated. In the following, first the per-hop resource and power allocation are presented followed by a description of the linear programming problem.

A. Resource allocation

In principle, one can use any type of allocation strategy for the per-hop resource allocation. However, one has to consider that from a network point of view, it is beneficial to allow each node to forward data in equal shares. Since the outcome of the resource allocation of the previous hops is not considered when allocating the resource of the current hop, it could be disadvantageous for the achievable network capacity to allow only the nodes with the best channel conditions to transmit their data as done when allocating in a greedy manner. In this case, it is possible that a node which has received a certain amount of data in the previous hop might not be able to forward this data in the next hop due to inferior channel conditions compared to its competing forwarding nodes. To avoid these kinds of bottlenecks, we apply a Fair Resource Scheduling approach using the Hungarian Method [10] which allocates the same amount of subcarriers to each forwarding node i while maximizing the sum capacity assuming equal power allocation of all forwarding nodes. For the resource allocation, 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 is considered for forwarding the data of node i on the n-th subcarrier in hop k.

As a result, we get a $d \times N$ allocation matrix $\hat{\mathbf{Z}}^{(k)}$ and a $1 \times N$ index vector $\mathbf{y}^{(k)}$ for each hop k. The i,n-th element of $\hat{\mathbf{Z}}^{(k)}$ equals $\hat{z}^{(k)}_{i,n} = 1$ if node i transmits on the n-th subcarrier and $\hat{z}^{(k)}_{i,n} = 0$ if node i does not transmit data on the n-th subcarrier. The n-th element $y^{(k)}_n$ of $\mathbf{y}^{(k)}$ 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 $\mathbf{y}^{(k)}$ is given by

$$y^{(k)}_n = j^\star(r(1, \hat{\mathbf{Z}}^{(k)}(:,n)), n, k) \tag{4}$$

where $\hat{\mathbf{Z}}(:,n)$ denotes the n-th column of matrix $\hat{\mathbf{Z}}$.

B. Power allocation

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

$$\lambda^{(k)}_{\mathrm{sc},n} = \lambda^{(k)}_{r(1,\hat{\mathbf{Z}}^{(k)}(:,n)),y^{(k)}_n,n}. \tag{5}$$

Applying waterfilling, the power allocation in each hop k leads to

$$p^{(k)}_n = \max\{0, P_\mathrm{W} - \frac{1}{\lambda^{(k)}_{\mathrm{sc},n}}\} \tag{6}$$

with $n = 1, .., N$ and $P_\mathrm{W} = \frac{1}{N}\sum_{v=1}^{N} p^{(k)}_v + \frac{1}{\lambda^{(k)}_{\mathrm{sc},n}}$ denoting the water level. Multiplying the elements of the i-th row vector of matrix $\hat{\mathbf{Z}}^{(k)}$ with the index vector $\mathbf{y}^{(k)}$ results in the vector $\tilde{\mathbf{y}}^{(k)}_i$ with $\tilde{y}^{(k)}_i(n) = y^{(k)}_n \cdot \hat{z}^{(k)}_{i,n}$. The achievable capacity $C^{(k)}_{i,j}$ for each link from node i to node j in hop k is then given by

$$C^{(k)}_{i,j} = \sum_{v=r(j,\tilde{\mathbf{y}}^{(k)}_i)} \log_2(1 + p^{(k)}_v \lambda^{(k)}_{\mathrm{sc},v}). \tag{7}$$

These capacity values are now used to determine how much data shall be transmitted over each link.

C. Linear programming problem

Having the link capacities $C^{(k)}_{i,j}$, the maximum amount of data which can be transmitted through this network considering the channel conditions of all hops can be determined, .i.e., the capacity of each link must be taken into account when determining the amount of data transmitted in the first hop. Considering a h-hop network with one source node, one destination node and d forwarding and receiving nodes per hop, we define $\mathbf{x}$ as the data vector with length $(h-2)d^2$:

$$\mathbf{x} = \left[x^{(2)}_{1,1}, \cdots, x^{(2)}_{1,d}, x^{(2)}_{2,1}, \cdots, x^{(2)}_{d,d}, \cdots, x^{(h-1)}_{d,d}\right] \tag{8}$$

The element $x^{(k)}_{i,j}$ of $\mathbf{x}$ with $i,j = 1, .., d$ and $k = 2, .., h-1$ corresponds to the amount of data transmitted on the link from node i to node j on the k-th hop where only the $h-2$ intermediate hops are considered.

Determining the maximum achievable capacity in this network, one has to maximize the sum over the first d^2 elements of $\mathbf{x}$ representing the total amount of data transmitted in the first hop and, thus, the network throughput subject to five constraints:

1) The elements of $\mathbf{x}$ are non-negative
2) The elements of $\mathbf{x}$ are upper bounded by the link capacities $C^{(k)}_{i,j}$
3) the amount of data transmitted to receiving node j in the first hop must be smaller or equal to the minimum of the link capacities $C^{(1)}_{1,j}$ and $\sum_{v=1}^{d} C^{(2)}_{j,v}$ which corresponds

to the amount of data node j is able to forward in the next hop

4) for the intermediate hops $k = 2, .., h-1$, the amount of data received by node j must be equal to the amount of data forwarded by node j in the next hop
5) the amount of data transmitted to the destination node from forwarding node j in the last hop must be smaller or equal to the minimum of the link capacities $C_{j,1}^{(h)}$ and $\sum_{v=1}^{d} C_{v,j}^{(2)}$ which corresponds to the amount of data node j is able to receive in the previous hop

For the general case having d forwarding nodes per hop and with $h \geq 3$, the problem can be translated into a linear programming problem given by

$$\begin{aligned} \mathbf{x}^\star \quad &= \quad \min_{\mathbf{x}} \mathbf{f}\mathbf{x}^{\mathrm{T}} \\ s.t. \quad & \\ & \mathbf{A}\mathbf{x} \leq \mathbf{b} \\ & \mathbf{A}_{\mathrm{eq}}\mathbf{x} = \mathbf{b}_{\mathrm{eq}} \\ & \mathbf{lb} < \mathbf{x} < \mathbf{ub} \end{aligned} \tag{9}$$

with the $1 \times (h-2)d^2$ row vector

$$\mathbf{f} = \left[-\mathbf{1}_{1\times d^2}, \mathbf{0}_{1\times(h-3)d^2}\right]. \tag{10}$$

The $2d \times (h-2)d^2$ matrix

$$\mathbf{A} = \begin{pmatrix} \mathbf{I}_{d\times d} \otimes \mathbf{1}_{1\times d} & \mathbf{0}_{d\times(h-3)d^2} \\ \mathbf{0}_{d\times(h-3)d^2} & \mathbf{1}_{1\times d} \otimes \mathbf{I}_{d\times d} \end{pmatrix}, \tag{11}$$

and the $(h-2)d^2 \times 1$ vector

$$\begin{aligned} \mathbf{b} = \Bigg[&\min\left\{C_{1,1}^{(1)}, \sum_{v=1}^{d} C_{1,v}^{(2)}\right\}, \cdots, \min\left\{C_{1,d}^{(1)}, \sum_{v=1}^{d} C_{d,v}^{(2)}\right\}, \\ &\min\left\{C_{1,1}^{(h)}, \sum_{v=1}^{d} C_{v,1}^{(h-1)}\right\}, \cdots, \min\left\{C_{d,1}^{(h)}, \sum_{v=1}^{d} C_{v,d}^{(h-1)}\right\}\Bigg]^{\mathrm{T}} \end{aligned} \tag{12}$$

take into account constraints number 3) and 5). Furthermore, constraint 4) is considered with the $(h-3)d \times (h-2)d^2$ matrix

$$\mathbf{A}_{\mathrm{eq}} = \begin{pmatrix} \mathbf{\Lambda} & \mathbf{0}_{(h-3)d\times d^2} \\ \mathbf{0}_{(h-3)d\times d^2} & \mathbf{\Omega} \end{pmatrix}, \tag{13}$$

with

$$\mathbf{\Lambda} = \mathbf{I}_{(\mathbf{h-3})\times(\mathbf{h-3})} \otimes \mathbf{1}_{\mathbf{1}\times\mathbf{d}} \otimes \mathbf{I}_{\mathbf{d}\times\mathbf{d}}, \tag{14}$$

$$\mathbf{\Omega} = -\mathbf{I}_{(\mathbf{h-3})\times(\mathbf{h-3})} \otimes \mathbf{I}_{\mathbf{d}\times\mathbf{d}} \otimes \mathbf{1}_{\mathbf{1}\times\mathbf{d}}. \tag{15}$$

and with the $(h-3)d \times 1$ vector

$$\mathbf{b}_{\mathrm{eq}} = \mathbf{O}_{(h-3)d\times 1}. \tag{16}$$

Finally, the constraints number 1) and 2) are taken into account with the $(h-2)d^2 \times 1$ upper bound vector

$$\begin{aligned} \mathbf{ub} \quad &= \\ & \left[C_{1,1}^{(2)}, \cdots, C_{1,d}^{(2)}, C_{2,1}^{(2)}, \cdots, C_{d,d}^{(2)}, \cdots, C_{d,d}^{(h-1)}\right]^{\mathrm{T}} \end{aligned} \tag{17}$$

and the $(h-2)d^2 \times 1$ lower bound vector

$$\mathbf{lb} = \mathbf{O}_{(\mathbf{h-2})\mathbf{d^2}\times\mathbf{1}}. \tag{18}$$

Such kind of linear programming problems can be solved numerically using for example the *linprog* function in MATLAB™. The total achievable capacity C_{net} over this network is then given by $C_{\mathrm{net}} = -\frac{1}{h}\mathbf{f}\mathbf{x}^{\star\mathrm{T}}$.

Note that for the case $h = 2$, the problem simplifies to the problem of finding the minimum of the link capacities $C_{1,j}^{(1)}$ and $C_{j,1}^{(2)}$ for each forwarding node j with $j = 1, .., d$.

V. Iterative max-flow scheme

Another way to find a solution for (3) is to consider the transmission over one subcarrier from end-to-end, i.e., we are considering all hops but not jointly for all subcarriers. For each link in each hop, only the subcarrier with the best channel condition is considered in a greedy manner. By doing so, constraint 3b) is fulfilled. With this approach, the problem transforms into a max-flow problem as each link in the network is represented by only one value. For the chosen subcarriers, the path from the source node to the destination node which results in the highest minimum link SNR has to be found. For this problem there exist several solutions in the literature [12] assuming arbitrary networks with different complexity orders. As shown in the Appendix, one can use a low complexity Viterbi-based approach to solve the max-flow problem by taking into account the trellis structure of the considered network. The subcarriers of the selected path are taken out of consideration and the procedure is then repeated iteratively until all subcarriers are allocated.

Finally, the transmit power is adjusted according to the corresponding end-to-end SNRs of the allocated subcarriers applying waterfilling. By doing so, constraints 3a) and 3c) are fulfilled.

A. Resource allocation

In the following, the resource allocation applying an iterative max-flow approach is presented in details. The resource allocation works as follows:

1) Set subcarrier counter to $n = 1$
2) For each link from forwarding node i to receiving node j in each hop k determine the index $I_{\mathrm{best},i,j}^{(k)}$ of all considered subcarriers with the highest link SNR $\lambda_{\mathrm{best},i,j}^{(k)}$
3) Use $\lambda_{\mathrm{best},i,j}^{(k)}$ as entries on the edges of the graph of the network and find the route $\mathbf{r}^{(n)} = [r_0, r_1, \cdots, r_h]$ which provides the highest minimum link SNR $\lambda_{\mathrm{route}}^{(n)}$ solving the max-flow problem. The elements r_l with $l = 0, .., h$ denote the index of the l-th node in the route with $r_0 = 1$ and $r_h = 1$.
4) Determine the subcarrier index vector $\mathbf{I}_{\mathrm{route}}^{(n)} = [I_{\mathrm{best},r_0,r_1}^{(1)}, \cdots, I_{\mathrm{best},r_{h-1},r_h}^{(h)}]$ of this route and store it together with $\lambda_{\mathrm{route}}^{(n)}$
5) In each hop k erase all subcarriers with index $I_{\mathrm{route}}^{(n)}(k)$ and set $n = n + 1$
6) if $n < N$ go to 2), else algorithm finished

The final outcome of this algorithm are N different routes $\mathbf{p}^{(n)}$ with the corresponding end-to-end SNRs $\lambda_{\mathrm{route}}^{(n)}$ and subcarrier index vectors $\mathbf{I}_{\mathrm{route}}^{(n)}$.

B. Power allocation

For power allocation, again waterfilling is applied. To do so, an SNR vector λ_{sc} of length N containing the corresponding end-to-end SNRs of the subcarriers in the first hop is extracted from $\lambda_{\mathrm{route}}^{(n)}$ and $\mathbf{I}_{\mathrm{route}}^{(n)}$. For this purpose, we define the inverse subcarrier index function $\tilde{\mathbf{I}}_{\mathrm{route}}^{(n)}$ which returns the index of the subcarrier allocated to the n-th route in the first hop. From this, it follows that the elements of λ_{sc} are given by

$$\lambda_{\mathrm{sc},v} = \lambda_{\mathrm{route}}^{(\tilde{\mathbf{I}}_{\mathrm{route}}^{(v)})} \tag{19}$$

with $v = 1, .., N$. Using λ_{sc} to apply waterfilling as shown in Section IV-B, the total achievable capacity C_{net} over this network is then given by

$$C_{\mathrm{net}} = \frac{1}{h} \sum_{n=1}^{N} \log_2(1 + p_n^{(1)} \lambda_{\mathrm{sc},n}). \tag{20}$$

Note that for the next hops, the same power allocation is applied at the nodes for the corresponding subcarriers, i.e., if the subcarrier of a given flow uses a particular power in the first hop, then the same power is allocated to this flow in the next hops independent from the subcarrier and the node over which this flow is transmitted through the network.

VI. Numerical results

In this section, the performance of the two presented algorithms is discussed. We assume an OFDMA multi-hop network with $N = 64$ subcarriers, h hops and d forwarding nodes per hop. The average Signal-to-Noise-Ratio (SNR) $\bar{\gamma} = \frac{P_{\mathrm{T}}}{N\sigma^2}$ is assumed to be equal for all links within one hop and the same for all hops. 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 waterfilling. The network throughput is then determined by the throughput of the weakest hop of this path. For this scenario, two unipath schemes are considered. With the first scheme referred to as random forwarding along unicast route, the path is chosen randomly out of the network. With the second scheme referred to as opportunistic forwarding along unicast route, the path which contains the highest minimum hop capacity is chosen out of the network solving the corresponding max-flow problem with the algorithm presented in the Appendix.

In Fig. 2(a), the network throughput is depicted as a function of the average SNR $\bar{\gamma}$ applying the unipath routing scheme for $h = 3$ hops and different number d of forwarding nodes. In Fig. 2(b), the network throughput is depicted applying the per-hop scheme for $h = 3$ hops and in Fig. 2(c), the network throughput is shown for the case applying the iterative max-flow scheme for $h = 3$ hops. The throughput is averaged over 1000 independent Monte Carlo simulations. 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.

From all figures, it can be seen that for an increasing number d of forwarding nodes, the throughput performance increases for all schemes due to the higher node diversity. However, the gain of having more forwarding nodes is rather small for the opportunistic forwarding along unicast. This is due to the fact that the variance of the throughput applying waterfilling over $N = 64$ subcarriers is already rather small, i.e., the difference in the achievable throughput for a given hop choosing one node or another node is small as $N = 64$ is already a statically large number. Obviously, the corrdidor-based routing schemes can exploit the node diversity much more efficiently.

In Fig. 3(a), the performance of the different schemes is compared for $d = 4$ forwarding nodes. It can be seen that both corridor-based routing schemes outperform forwarding along unicast route where the iterative max-flow scheme slightly outperforms the per-hop resource and power allocation scheme.

In Fig. 3(b) and 3(c), the same comparison is shown for the cases of $h = 4$ and $h = 5$ hops. One can observe that also for higher number of hops, the corridor-based routing schemes outperform forwarding along unicast route. Note that the network throughput decreases due to the increased number of hops.

In Table I, the gain in network throughput of the iterative max-flow scheme compared to forwarding along unicast route is depicted for $h = 3$ hops. As one can see, the gain is especially large for low SNRs even for small number d of forwarding nodes which makes corridor-based routing using opportunistic forwarding particularly interesting for such kind of networks.

TABLE I
Gain factor corridor-based routing ($h = 3$)

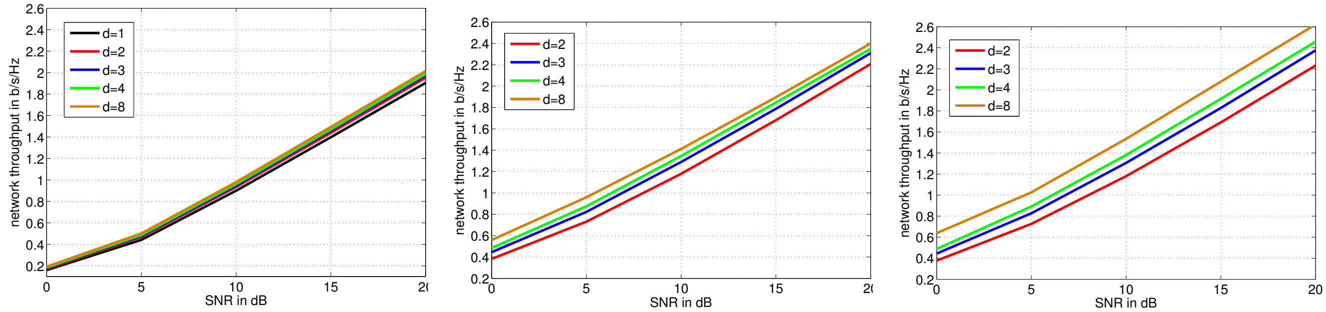
SNR	0 dB	5 dB	10 dB	15 dB	20 dB
$d = 2$	2.17	1.55	1.26	1.18	1.14
$d = 3$	2.46	1.73	1.38	1.25	1.20
$d = 4$	2.65	1.83	1.44	1.30	1.24
$d = 8$	3.05	2.04	1.57	1.39	1.30

VII. Conclusions

In this work, we presented the concept of corridor-based routing using opportunistic forwarding in multi-hop OFDMA networks. 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 two algorithms to maximize network throughput by means of resource and power allocation. Compared to the OFDMA forwarding along unicast route approach both algorithms provide significant gains in network throughput especially for low SNRs.

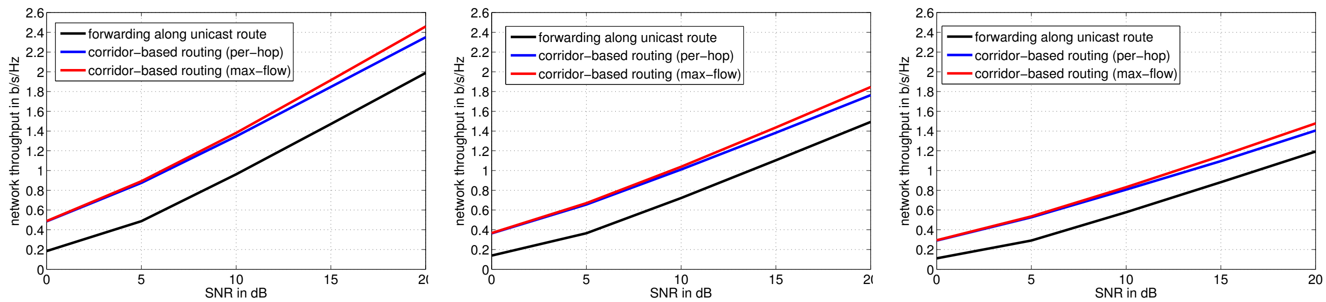
Appendix

For a trellis-structured network as in our problem, solving the max-flow problem is of low complexity applying a Viterbi-based path finding approach where the metric is the minimum link capacity of a path so far. The algorithm works as followed:



(a) (b) (c)

Fig. 2. 3-hop network throughput vs. average SNR $\bar{\gamma}$ applying (a) forwarding along unicast route, (b) corridor-based routing using the per-hop resource and power allocation scheme and (c) corridor-based routing using the iterative max-flow scheme



(a) (b) (c)

Fig. 3. Network throughput vs. average SNR $\bar{\gamma}$ with $d = 4$ forwarding nodes and (a) $h = 3$ hops, (b) $h = 4$ hops and (c) $h = 5$ hops.

1) start at the nodes in the second stage of the network ($S = 2$)
2) at each node of the current stage S of the network, determine the minimum link capacity of all considered paths which lead to this node and save only the path with the highest minimum link capacity (surviving path)
3) increase S: $S = S + 1$ and go to 2) until the final node of the network is reached

It can be seen that the number $N_\mathrm{p} = 2d + (h-2) \cdot d^2$ of paths which have to be compared equals the number E of edges in the graph, i.e., the complexity order is given by $\mathcal{O}(E)$.

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