Spatial reuse in OFDMA multi-hop networks applying corridor-based routing

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Abstract—**In multi-hop networks, conventional forwarding along a unicast route forces the data transmission to follow a fixed sequence of nodes. In previous works, it has been shown that widening this path to create a corridor of forwarding nodes and applying OFDMA to split and merge the data as it travels through the corridor towards the destination node leads to considerable gains in achievable throughput compared to the case of forwarding data along a unicast route. However, the possibility of applying spatial reuse in such kind of networks has not been investigated. In this paper, three different schemes for spatial reuse in multi-hop OFDMA networks applying corridor-based routing are presented and compared to the case without spatial reuse. From simulations it can be seen that spatial reuse increases the throughput. For different signal-to-noise ratio regions, different schemes perform best due to the way the interference is handled by the schemes.**

I. Introduction

In wireless ad hoc and sensor networks, multi-hop transmissions are required to exchange data with any node in the network as a direct transmission is not always possible due to the limited transmission ranges of the nodes. In such kind of multi-hop networks, routing is required as presented for example in [1] and [2] where it has been shown how to determine a single unicast route from a source node to a destination node in a mobile ad hoc network. As an alternative to unicast routing, multipath routing can be applied to balance the load, to increase the fault tolerance and the aggregated bandwidth [3].

A third approach is to widen a given unicast route to create a corridor of forwarding nodes to introduce flexibility and diversity [6]. Inside this corridor, data can be split and merged as it travels towards the destination node. To split data at a given node, Orthogonal Frequency Division Multiple Access (OFDMA) is used.

For single carrier transmission, routing within such a clustered multi-hop network with multiple relays per hop has already been investigated in literature. In [4], different routing strategies for clustered multi-hop networks with multiple relays per hop are analyzed with respect to the outage performance.

In [5], the use of OFDMA in multi-hop networks has been investigated with respect to outage using Selective Relaying and in [6] with respect to throughput maximization using corridor-based routing. However, applying spatial reuse, i.e., allowing nodes of different hops to transmit simultaneously to further increase the throughput, has not been addressed for such kind of multi-hop OFDMA networks. In [7], spatial reuse has been discussed for single carrier networks where in each hop, only one forwarding node is available. In [8], spatial reuse is investigated for the same kind of multi-hop network as in [7] applying Orthogonal Frequency Division Multiplexing (OFDM). In [8], a frequency sharing approach is proposed to avoid inter-hop interference.

The present paper considers spatial reuse in a multi-hop OFDMA network with several forwarding nodes per hop applying corridor-based routing as introduced in [6] and proposes the following interference management schemes:

- Spatial reuse scheme which minimizes the impact of inter-hop interference by iteratively maximizing the end-to-end Signal-to-Interference-and-Noise-Ratio (SINR).
- Spatial reuse scheme which cancels all inter-hop interference using a recursive backward Interference Cancellation (IC) scheme.
- Inter-hop interference avoidance scheme which exclusively allocates subcarriers to different simultaneously transmitting node clusters based on subcarrier ranking.

The remainder of this paper is organized as follows. In Section II, the system model is presented. In Section III, the concept of corridor-based routing using OFDMA without spatial reuse as presented in [6] is revisited. In Section IV to VI, the proposed interference management schemes are presented. In Section IV, the inter-hop interference minimization scheme is presented followed by the description of the inter-hop interference cancellation scheme V. Section VI presents the inter-hop interference avoidance scheme. In Section VII, the performance of the different spatial reuse schemes is investigated and compared to the case of applying no spatial reuse. Finally, conclusions are drawn in Section VIII.

II. System model

In this work, we consider a multi-hop transmission between one source node S and one destination node D which is performed via multi-hop transmission over N_{H} hops applying decode-and-forward. In each of the intermediate $N_{\mathrm{H}}-1$ hops, there are N_{F} possible forwarding nodes referred to as cluster (see Fig. 1). OFDMA is used as multiple access scheme and the bandwidth is subdivided into N orthogonal subcarriers with frequency spacing Δf.

Applying spatial reuse with factor r, the available subcarriers are reused between transmit clusters with a separation

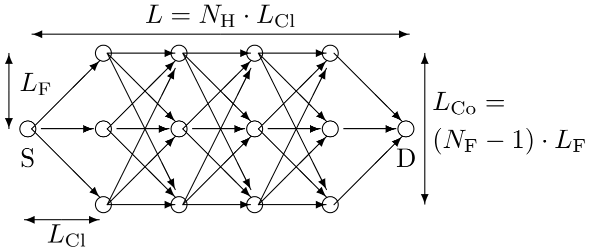

Fig. 1. Multi-hop communication with $N_{\mathrm{H}} = 5$ hops and $N_{\mathrm{F}} = 3$ forwarding nodes per hop

of $r-1$ clusters between simultaneously transmitting clusters. From this, it follows that there are r different time slots where the different clusters transmit. Vector $\mathbf{S}_t$ contains the indices of the clusters which simultaneously transmit in the t-th time slot with $t = 1, ..., r$ given by

$$\mathbf{S}_t = \left[t, t+r, t+2r, ..., N_{\mathrm{H}} - \left(\left\lfloor \frac{r}{t} \right\rfloor - 1\right)\right] \tag{1}$$

with $\lfloor . \rfloor$ the nearest integer lower than or equal to the argument. From (1), it follows that in the t-th time slot, there are

$$N_{\mathrm{TX},t} = \left\lfloor \frac{N_{\mathrm{H}} - t + 1}{r} \right\rfloor \tag{2}$$

simultaneous transmissions. Note that we assume $r \geq 2$ due to the half-duplex assumption, i.e., nodes cannot transmit and receive data at the same time.

It is assumed that within one cluster, each subcarrier is allocated only once to avoid intra-cluster interference. Vector $\mathbf{S}_{t,n}$ contains the corresponding indices of the forwarding nodes which transmit simultaneously on a given subcarrier with index n in the t-th time slot, i.e., the l-th entry $\mathbf{S}_{t,n}(l)$ contains the index of the forwarding node in the l-th cluster which transmits on the n-th subcarrier in the t-th time slot. Note that $\mathbf{S}_{t,n}$ depends on the resource allocation strategy which will be explained later on.

Block 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 of the k-th cluster to node j of the l-th cluster described by the transfer factor $H_{i,j,n}^{(k,l)}$ is modeled as a complex Gaussian distributed random process with variance one.

The attenuation depends on the distance between the nodes assuming a path loss exponent α. The distance between S and D is set to $L = 1$ without loss of generality as we only look at the Signal-to-Interference-and-Noise-Ratio (SINR) and not at absolute values. The clusters are equidistantly placed on the line from S to D, i.e., the distance between adjacent clusters is $L_{\mathrm{Cl}} = \frac{1}{N_{\mathrm{H}}}$. The corridor width is set to $L_{\mathrm{Co}} = \frac{L_{\mathrm{Cl}}}{2}$ to almost have equal path loss conditions for all nodes transmitting from one cluster to all nodes of the next cluster. The nodes within a cluster are also equidistantly placed resulting in a node spacing of $L_{\mathrm{F}} = \frac{L_{\mathrm{Co}}}{N_{\mathrm{F}}-1}$.

The pathloss $P_{\mathrm{L},i,j}^{(k,l)}$ between node i of the k-th cluster to node j of the l-th cluster is given by

$$P_{\mathrm{L},i,j}^{(k,l)} = \left(\frac{d_{i,j}^{(k,l)}}{L_{\mathrm{Cl}}}\right)^{-\alpha}, \tag{3}$$

with $d_{i,j}^{(k,l)}$ denoting the distance between node i of the k-th cluster to node j of the l-th cluster.

With the noise power spectral density N_0, the noise power $P_{\mathrm{N,sc}}$ per subcarrier is given by $P_{\mathrm{N,sc}} = N_0 \cdot \Delta f$. Assuming equal power allocation over all subcarriers in each hop with P_{T} denoting the total transmit power per hop, the instantaneous SINR in time slot t for the transmission from a node i of the k-th cluster to node j of the $(k+1)$-th cluster on subcarrier n is given by

$$\gamma_{i,j,n}^{(k,k+1)} = \frac{\frac{P_{\mathrm{T}}}{N} \cdot P_{\mathrm{L},i,j}^{(k,k+1)} \cdot \left|H_{i,j,n}^{(k,k+1)}\right|^2}{P_{\mathrm{N,sc}} + \sum\limits_{\substack{v \in \mathbf{S}_t \\ v \neq k}} \frac{P_{\mathrm{T}}}{N} \cdot P_{\mathrm{L},\mathbf{S}_{t,n}(v'),j}^{(v,k+1)} \cdot \left|H_{\mathbf{S}_{t,n}(v'),j,n}^{(v,k+1)}\right|^2} \tag{4}$$

with $v' = \mathrm{pos}(v, \mathbf{S}_{t,n})$ where the function $\mathrm{pos}(x, \mathbf{Y})$ returns the position of entry x in vector $\mathbf{Y}$.

In the following, the notation $(k, k+1)$ is substituted by k for a better readability. With the normalized average SNR

$$\bar{\gamma} = \frac{P_{\mathrm{T}}}{N \cdot P_{\mathrm{N,sc}}} \tag{5}$$

which is experienced by the nodes on the straight line between source and destination ($d_{i,j}^{(k,l)} = L_{\mathrm{Cl}}$) in case of no simultaneous transmissions, (4) can then be written as

$$\gamma_{i,j,n}^{(k)} = \frac{\bar{\gamma} \cdot P_{\mathrm{L},i,j}^{(k)} \cdot \left|H_{i,j,n}^{(k)}\right|^2}{1 + \bar{\gamma} \sum\limits_{\substack{v \in \mathbf{S}_t \\ v \neq k}} P_{\mathrm{L},\mathbf{S}_{t,n}(v'),j}^{(v,k+1)} \cdot \left|H_{\mathbf{S}_{t,n}(v'),j,n}^{(v,k+1)}\right|^2} \tag{6}$$

III. Corridor-based routing without spatial reuse

In [6], it has been shown how to maximize the throughput of an OFDMA multi-hop network with a corridor as given in Fig. 1 assuming no spatial reuse, i.e., if no inter-hop interference occurs. Since the proposed schemes in this paper are all based on the algorithm presented in [6], we shortly revisit its idea and procedure.

In case of no interference, the SINR of (6) simplifies to the Signal-to-Noise-Ratio (SNR) given by

$$\gamma_{i,j,n}^{(k)} = \bar{\gamma} \cdot P_{\mathrm{L},i,j}^{(k)} \cdot \left|H_{i,j,n}^{(k)}\right|^2, \tag{7}$$

since $\mathbf{S}_t = [k]$ for each time slot t when transmitting from the k-th cluster to the $(k+1)$-th cluster.

The idea of [6] is to consider the transmission over one subcarrier from end-to-end. For each link in each hop, only the subcarrier with the best SNR is considered in a greedy manner. By doing so, the problem can be transformed into a max-flow problem as each link in the network is represented by only one value. Now, 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 which can be done by applying a low complexity Viterbi-based path finding algorithm [6]. The subcarriers of the selected path are taken out of consideration, i.e., in each hop each subcarrier is allocated exclusively. The procedure is then repeated iteratively until all subcarriers are allocated.

In the following, this iterative max-flow approach of [6] is briefly summarized:

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 $I^{(k)}_{\text{best},i,j}$ of all considered subcarriers with the highest link SNR $\gamma^{(k)}_{\text{best},i,j}$.
3) Use $\gamma^{(k)}_{\text{best},i,j}$ as entries on the edges of the graph of the network and find the route $\mathbf{r}^{(n)} = [r_0, r_1, \cdots, r_{N_\text{H}}]$ which provides the highest end-to-end SNR $\gamma^{(n)}_{\text{e2e}}$ solving the max-flow problem. The elements r_l with $l = 0, .., N_\text{H}$ denote the index of the l-th node in the route with $r_0 = 1$ and $r_{N_\text{H}} = 1$.
4) Determine the subcarrier index vector $\mathbf{I}^{(n)}_{\text{route}} = [I^{(1)}_{\text{best},r_0,r_1}, \cdots, I^{(h)}_{\text{best},r_{h-1},r_h}]$ of this route and store it together with $\gamma^{(n)}_{\text{e2e}}$.
5) In each hop k erase all subcarriers with index $I^{(n)}_{\text{route}}(k)$ 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 $\gamma^{(n)}_{\text{e2e}}$ and subcarrier index vectors $\mathbf{I}^{(n)}_{\text{route}}$.

The total achievable capacity C over this network is then given by

$$C = \frac{1}{N_\text{H}} \sum_{n=1}^{N} \log_2(1 + \gamma^{(n)}_{\text{e2e}}). \tag{8}$$

IV. Spatial reuse applying Interference minimization

Assuming spatial reuse, interference is introduced. The idea for the interference minimization (IM) scheme is to apply the corridor-based routing scheme of Section III taking into account inter-hop interference. Hence, now one has to search for the path with the highest minimum SINR to minimize the interference. However, the resulting SINR of a given link strongly depends on the chosen paths $\mathbf{p}^{(n)}$ and the corresponding subcarrier index vectors $\mathbf{I}^{(n)}_{\text{route}}$ which are not known a priori, i.e., the criterion to find the best inter-hop interference aware paths, namely the SINR, itself depends on the chosen paths.

To overcome this problem, an iterative approach is applied. In the first iteration, one assumes no interference, i.e., the paths are determined applying the max-flow algorithm of Section III using only the SNR values of (7). In order to incorporate inter-hop interference in the next iteration, the resulting chosen paths $\mathbf{p}^{(n)}$ and corresponding subcarrier index vectors $\mathbf{I}^{(n)}_{\text{route}}$ are now used to determine vector $\mathbf{S}_{t,n}$ indicating the indices of the forwarding nodes which transmit simultaneously on a given subcarrier with index n in the t-th time slot.

In the following, the N vectors $\mathbf{p}^{(n)}$ and $\mathbf{I}^{(n)}_{\text{route}}$ of length N_H are each put into one $N \times N_\text{H}$ matrix $\mathbf{p}$ and $\mathbf{I}_{\text{route}}$, respectively. To determine the node $\mathbf{S}_{t,n}(k)$ which transmits on subcarrier n in time slot t in the k-th cluster, one has to search for the row index $n_{\text{row}}(n, k)$ of entry n in the k-th column of matrix $\mathbf{I}_{\text{route}}$ indicating the index of the flow where the n-th subcarrier has been used in the k-th hop. This leads to

$$n_{\text{row}}(n, k) = \text{pos}(n, \mathbf{I}_{\text{route}}(:, k)) \tag{9}$$

with $\mathbf{Y}(:, k)$ denoting the k-th column vector of matrix $\mathbf{Y}$. Knowing $n_{\text{row}}(n, k)$, and thus, the corresponding flow index, one can determine $\mathbf{S}_{t,n}(k)$ using the paths matrix $\mathbf{p}$ which contains the node indices of the different flows:

$$\mathbf{S}_{t,n}(k) = \mathbf{p}(n_{\text{row}}(n, k), k). \tag{10}$$

With $\mathbf{S}_{t,n}$, the resulting SINR $\gamma^{(k)}_{i,j,n}$ for each link can be determined using (6). Based on these SINR values, the paths are determined again, i.e., the max-flow algorithm of Section III is applied but now with the calculated SINR $\gamma^{(k)}_{i,j,n}$. This procedure is repeated for N_{it} iterations until the resulting paths eventually do not change any more, i.e., the solution converges. Simulations have shown that for $N_{\text{it}} = 5$ the solution converges in most of the cases. The total achievable capacity C_{IM} over this network applying IM is then given by

$$C_{\text{IM}} = \frac{1}{r} \sum_{n=1}^{N} \log_2(1 + \gamma^{(n)}_{\text{e2e},N_{\text{it}}}) \tag{11}$$

with $\gamma^{(n)}_{\text{e2e},N_{\text{it}}}$ the corresponding end-to-end SINR values of the N_{it}-th iteration.

V. Spatial reuse applying Interference cancellation

In this section, we introduce a spatial reuse scheme which perfectly cancels all interferences for the given multi-hop OFDMA network.

In [7], it has been shown how to perfectly cancel all inter-hop interference for a multi-hop single carrier transmission from a source node to a destination node using one forwarding node per hop. The scheme works recursively and relies only on buffering, interference cancellation and point-to-point decoding [7]. After each recursion, an interference-free transmission over an additional hop is possible, i.e., the scheme is complete after N_H of these recursions. The idea of recursive backward IC is to first buffer the received data blocks at a given node k in the multi-hop network not attempting to decode them. For one time slot, only the previous node $k-1$ transmits allowing node k to receive the last data block with no interference. Now, node k can decode this last data block and uses it to cancel the interference corrupting the previously received data blocks. Eventually, all data blocks can be decoded at node k, i.e., for transmitting B data blocks in one recursion, $B+1$ time slots are required. Finally, $B^{N_\text{H}-1}$ data blocks are transmitted from source to destination using $(B + 1)^{N_\text{H}-1}$ time slots [7].

Hence, a complete removal of all interferences is indeed possible at an arbitrarily small rate loss when B goes to infinity. However, one has to accept an exponential growth in delay with respect to N_H which makes this scheme rather impractical for delay-sensitive applications [7].

For a multi-carrier transmission applying OFDMA having multiple forwarding nodes per hop, this scheme can be adopted straightforwardly using the iterative max-flow scheme of Section III. Applying the interference-free SNR values of (7) as input, one can determine the N different paths through the network with the corresponding end-to-end SNRs $\gamma_{\mathrm{e2e}}^{(n)}$ which maximize the throughput of the network assuming no interference. Each of these N paths can now be considered as an independent multi-hop single carrier transmission from a source node to a destination node with only one forwarding node per hop which corresponds to the scenario as used in [7]. Hence, for each of the N paths, the inter-hop interference can be perfectly canceled applying recursive backward IC which leads to a total achievable capacity C_IC over this network given by

$$C_\mathrm{IC} = \frac{1}{r}\sum_{n=1}^{N}\log_2(1+\gamma_{\mathrm{e2e}}^{(n)}). \tag{12}$$

Note that $C_\mathrm{IC} = \frac{N_\mathrm{H}}{r}\cdot C$, with C denoting the capacity applying no spatial reuse given by (8).

VI. Interference avoidance scheme

For the two spatial reuse schemes presented above, all inter-hop interference channels need to be known. To overcome this problem, we also propose a scheme which avoids interference by exclusively allocating subcarriers to different simultaneously transmitting node clusters. By doing so, the interference channels do not need to be known, but only the channels between adjacent clusters.

Applying a spatial reuse factor r,

$$N_\mathrm{C} = \frac{N}{\lfloor N_\mathrm{H}/r \rfloor} \tag{13}$$

subcarriers are exclusively allocated to each transmit cluster in each time slot t with $t = 1, ..., r$. Hence, there is actually no spatial reuse of subcarriers within one time slot.

Keeping in mind that in time slot t, there are $N_{\mathrm{TX},t}$ simultaneous transmissions as shown in (2), each cluster can choose its best N_C out of N subcarriers in competition with the other $N_{\mathrm{TX},t} - 1$ transmit clusters. To do so, a subcarrier ranking is set up by each cluster $k \in \mathbf{S}_t$ transmitting simultaneously in time slot t. For each subcarrier n, a ranking value $\bar{r}_{k,n}^{(t)}$ is determined by summing up all SNR values of all links on subcarrier n

$$r_{k,n}^{(t)} = \sum_{i=1}^{N_\mathrm{F}}\sum_{j=1}^{N_\mathrm{F}}\gamma_{i,j,n}^{(k)} \tag{14}$$

followed by a normalization:

$$\bar{r}_{k,n}^{(t)} = \frac{r_{k,n}^{(t)}}{\sum_{n=1}^{N} r_{k,n}^{(t)}}. \tag{15}$$

As a result, one gets a $N_{\mathrm{TX},t} \times N$ matrix $\bar{\mathbf{r}}^{(t)}$. The higher $\bar{r}_{k,n}^{(t)}$, the more beneficial is subcarrier n for cluster k.

To allocate the subcarriers to the different clusters, a fair resource scheduling approach using the Hungarian Method [9] is used. This scheduling approach uses matrix $\bar{\mathbf{r}}^{(t)}$ to allocate the same amount of subcarriers to each cluster while maximizing the sum of the corresponding ranking.

The outcome of the Hungarian Method is a $N_{\mathrm{TX},t} \times N$ allocation matrix $\mathbf{Z}^{(t)}$. The (k, n)-th element of $\mathbf{Z}^{(k)}$ equals $z_{k,n}^{(t)} = 1$ if cluster k transmits on the n-th subcarrier and $z_{k,n}^{(t)} = 0$ if cluster k does not transmit data on the n-th subcarrier.

Having assigned the subcarriers to the different clusters to guarantee an inter-hop interference free transmission, the iterative max-flow of Section III can be applied with the restriction that only the pre-defined subcarriers are allowed to be used for the corresponding clusters. Hence, in the description of the max-flow algorithm of Section III, step 2) and step 6) need to be modified as follows:

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 $\gamma_{\mathrm{best},i,j}^{(k)}$ fulfilling $z_{k,n}^{(t)} = 1$

6⋆) if $n < N_\mathrm{C}$ go to 2⋆), else algorithm finished

Compared to the original iterative max-flow algorithm, we now only get N_C different routes $\mathbf{p}^{(n)}$ with the corresponding end-to-end SNRs $\gamma_{\mathrm{e2e}}^{(n)}$ and subcarrier index vectors $\mathbf{I}_{\mathrm{route}}^{(n)}$.

The total achievable capacity C_IA applying the interference avoidance (IA) scheme over this network is then given by

$$C_\mathrm{IA} = \frac{1}{r}\sum_{n=1}^{N_\mathrm{C}}\log_2(1+\gamma_{\mathrm{e2e}}^{(n)}). \tag{16}$$

VII. Performance Results

In the following, the performance of the proposed schemes is presented for an OFDMA network as shown in Fig. 1 with $N = 60$ subcarriers and $N_\mathrm{H} = 6$ hops for different spatial reuse factors ($2 \leq r \leq 5$) and compared to the scheme with no spatial reuse ($r = 6$). In Fig. 2, the average throughput is depicted as a function of the average SNR as defined in (5). The number of forwarding nodes per hop is $N_\mathrm{F} = 3$, a path loss exponent of $\alpha = 3$ is assumed and spatial reuse factors of $r = 2$ and $r = 3$ are investigated. For the iterative IM scheme, we apply $N_\mathrm{it} = 5$ iterations.

It can be seen that the schemes with perfect IC perform best especially for high SNR values. However, due to their limited applicability, we will consider them only as upper bounds and focus on the two other schemes. For this particular scenario, the IM scheme with $r = 2$ performs best for small SNR values from -10 dB to 5 dB due to the small impact of the interference compared to the noise. For SNR values from 5 dB up to 25 dB, the interference minimization scheme with $r = 3$ performs best due to the larger distance between simultaneously transmitting clusters. For SNR values larger than 25 dB, the IA scheme with $r = 2$ performs best as the interference minimization schemes go into saturation due to the remaining interference. The gain of the IA scheme

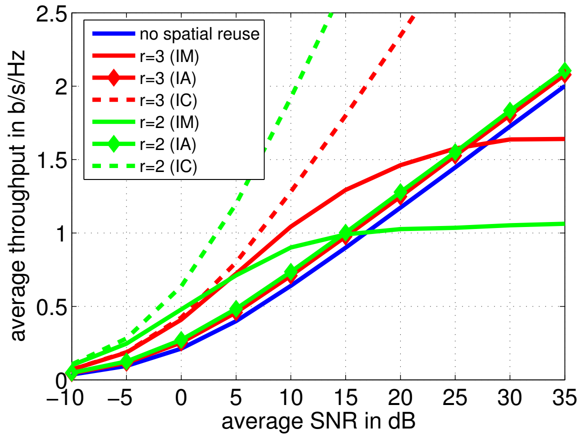

Fig. 2. Average throughput vs. average SNR with $N_{\mathrm{H}} = 6$ hops, $N_{\mathrm{F}} = 3$ forwarding nodes per hop, $\alpha = 3$ and $N = 60$ subcarriers

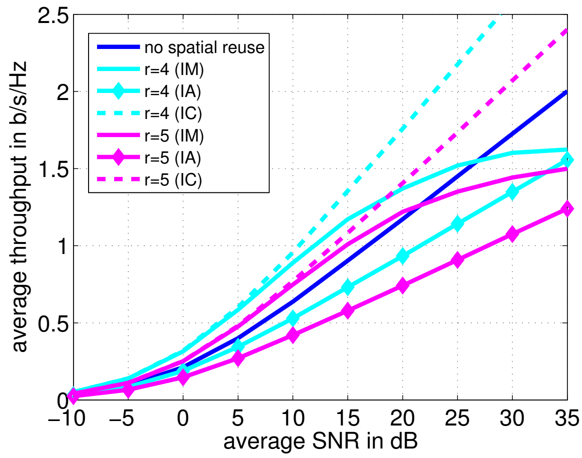

Fig. 3. Average throughput vs. average SNR with $N_{\mathrm{H}} = 6$ hops, $N_{\mathrm{F}} = 3$ forwarding nodes per hop, $\alpha = 3$ and $N = 60$ subcarriers

compared to the scheme without spatial reuse comes from the selection diversity of the different subcarriers. Applying a random subcarrier allocation for the different clusters instead of the Hungarian Method as shown in Section VI, would lead to the same performance as the scheme without spatial reuse.

In Fig. 3, the same investigation is performed for spatial reuse factors of $r = 4$ and $r = 5$, respectively. It can be seen that when applying the IA scheme in this scenario with $N_{\mathrm{H}} = 6$ hops, a spatial reuse factor $3 < r < 6$ leads to worse performances compared to the case of applying a spatial reuse factor of $1 < r \leq 3$. This is due to the fact that the number N_C of (13) of usable subcarriers per cluster and time slot for $r = 4$ and $r = 5$ is the same as for $r = 3$, i.e., the same amount of subcarriers per hop is used performing less simultaneous transmissions leading to worse performances. In case of applying the IM scheme, the performances are better compared to the case of no spatial reuse for SNR values up to 22 dB ($r = 5$) and 27 dB ($r = 4$), respectively. For larger SNR values, the remaining interferences lead to saturation as already seen with $r = 2$ and $r = 3$, respectively. However, the scheme applying $r = 3$ outperforms both schemes with $r = 4$ and $r = 5$. Hence, in the remaining investigations, we only consider spatial reuse factors of $1 < r \leq 3$. In general, only integer spatial reuse factors r are reasonable for which $N_{\mathrm{H}} = r \cdot m$ with $m \in \mathbb{N}^{+}$.

In the following, the impact of the number N_{F} of forwarding nodes per cluster is investigated. In Fig. 4 and Fig. 5, the number of forwarding nodes per cluster is set to $N_{\mathrm{F}} = 2$ and $N_{\mathrm{F}} = 4$, respectively, while all the other system parameters remain the same. It can be seen that increasing N_{F}, the performance of all schemes increases due to the higher node diversity in the corridor. However, the intersection points of the IM scheme and the IA scheme are shifted to the right when increasing N_{F}, i.e., having a larger choice selecting a forwarding node when applying the IM scheme increases the probability of finding a node with low interference even for large SNR values.

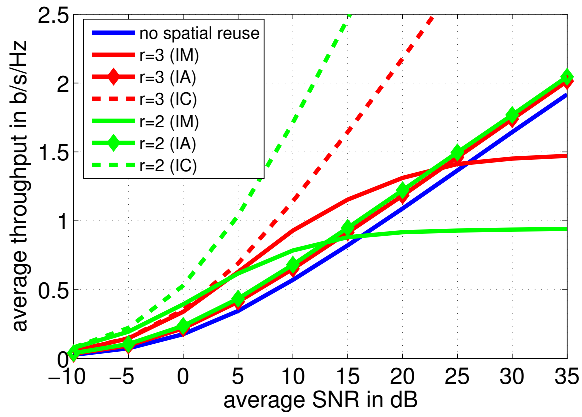

Fig. 4. Average throughput vs. average SNR with $N_{\mathrm{H}} = 6$ hops, $N_{\mathrm{F}} = 2$ forwarding nodes per hop, $\alpha = 3$ and $N = 60$ subcarriers

Finally, the impact of the pathloss exponent α is investigated assuming $N_{\mathrm{F}} = 3$ forwarding nodes. In Fig. 6 and Fig. 7, the pathloss exponent is set to $\alpha = 2$ and $\alpha = 4$, respectively. Decreasing α, the throughput marginally increases for all schemes which are not affected by the resulting increased interference, namely the scheme without spatial reuse, the IA scheme and the IC scheme. However, for the IM scheme, the performance significantly changes for different α. Increasing α leads to less interference which results in a much broader SNR region in which the IM scheme outperforms the IA scheme, e.g. for SNR values up to 33 dB in case of $\alpha = 4$, which makes the IM scheme particularly interesting for high pathloss scenarios.

VIII. Conclusions

In this paper, spatial reuse is considered in multi-hop OFDMA networks. To handle the introduced inter-hop interference, three interference management schemes are proposed which all are based on the corridor-based routing scheme presented in our previous work [6]. With the IM scheme, the

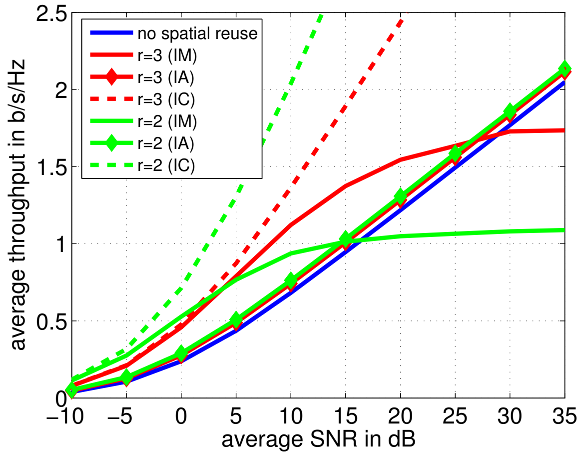

Fig. 5. Average throughput vs. average SNR with $N_{\mathrm{H}} = 6$ hops, $N_{\mathrm{F}} = 4$ forwarding nodes per hop, $\alpha = 3$ and $N = 60$ subcarriers

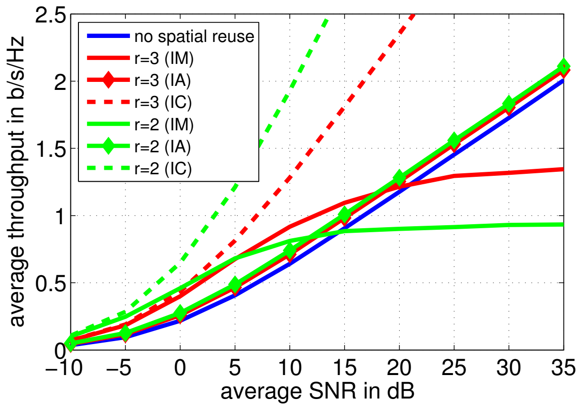

Fig. 6. Average throughput vs. average SNR with $N_{\mathrm{H}} = 6$ hops, $N_{\mathrm{F}} = 3$ forwarding nodes per hop, $\alpha = 2$ and $N = 60$ subcarriers

impact of inter-hop interference caused by simultaneous transmissions is minimized by iteratively maximizing the end-to-end SINR values. In the IC scheme, the inter-hop interference is perfectly canceled applying a recursive backward IC scheme adopted from [7]. In the IA scheme, inter-hop interference is avoided by exclusively allocating subcarriers to the different simultaneously transmitting clusters. From simulation results, it can be seen that IC performs best but has to be regarded as an upper bound due to its limited applicability in practical systems. For the IM and IA scheme, it can be concluded that for low to medium SNR regions, IM outperforms IA where the intersection point depends on the number N_{F} of forwarding nodes per hop and on the pathloss exponent α. The higher N_{F} and α, the broader the SNR region where IM is superior to IA due to higher selection diversity and lower inter-hop interference.

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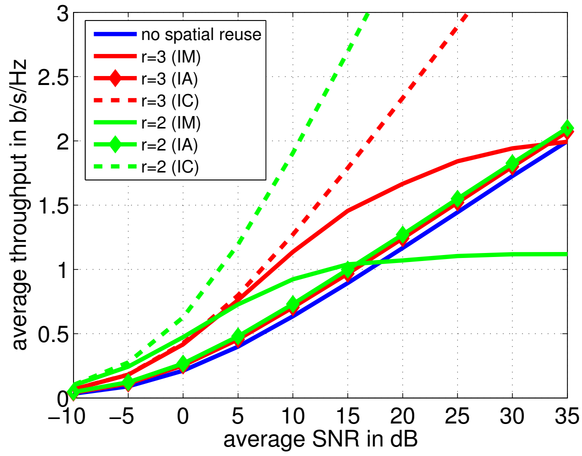

Fig. 7. Average throughput vs. average SNR with $N_{\mathrm{H}} = 6$ hops, $N_{\mathrm{F}} = 3$ forwarding nodes per hop, $\alpha = 4$ and $N = 60$ subcarriers

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