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Node Selection for Corridor-based Routing in OFDMA Multihop Networks

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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 forwarding data along a unicast route. However, the problem of selecting potential nodes to act as forwarding nodes within the corridor has not been addressed in the literature, as in general a rather homogeneous network topology with equally spaced relay clusters per hop between source and destination node has been assumed. In this paper, a more realistic heterogeneous network is considered where the nodes in the area between source and destination are randomly distributed instead of being clustered with equal distance. A node selection scheme is presented which selects the forwarding nodes within the corridor based on a given unicast route between source and destination node. In simulations, it is shown that with the proposed node selection scheme, considerable throughput gains of up to 50 % compared to forwarding along unicast route can be achieved applying corridor-based routing in heterogeneous networks especially in sparse networks.**

I. INTRODUCTION

In wireless ad hoc or sensor networks, multihop 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. For that purpose, routing is required as presented e.g. in [1] and [2] where it has been shown how to determine a single route from a source node to a destination node in a mobile ad hoc network. The use of Orthogonal Frequency Division Multiplexing (OFDM) to enhance the performance in multihop networks applying forwarding along a unicast route has been studied in the literature, e.g. in [3]-[7]. In [3]-[6], the problem of resource and power allocation in multi-hop OFDM networks is considered where in [3] amplify-and-forward is applied while in [4]-[6] decode-and-forward is considered. In [7], 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.

As an alternative to unicast routing, multipath routing can be applied to balance the load, to increase the fault tolerance and the aggregated bandwidth [8]. In this paper, we present another approach in combination with Orthogonal Frequency Division Multiple Access (OFDMA) to enhance the throughput performance of the system assuming that a unicast route has already been established. The idea is to widen this unicast route to create a corridor of forwarding nodes to introduce flexibility and diversity. Inside this corridor, data can be split and joined as it travels towards the destination node. To split data at a given node, OFDMA is used. Having access to the instantaneous channel conditions from the physical layer, OFDMA offers the possibility of opportunistically allocating different subcarriers to different nodes according to their channel quality. Interference between subcarriers can be avoided assuming that each subcarrier is only allocated once per hop. This approach can be interpreted as a non-disjoint multipath routing [8] within a corridor of a given unicast route, i.e., the reliability and aggregated throughput of the unicast route can be enhanced without having to establish a new route by considering the current channel conditions of the nodes using OFDMA within the corridor.

In the literature, routing within such a clustered multihop network with multiple relays per hop has already been investigated. In [9], different routing strategies for clustered multihop network with multiple relays per hop are analyzed with respect to the outage performance assuming single carrier transmission.

In [10], OFDMA is applied in a clustered multihop network with L relays per hop referred to as Selective OFDMA Relaying where the system is analyzed with respect to the outage performance. The relay selection is performed in a per subcarrier manner. It is shown that applying Selective OFDMA Relaying, full L-fold diversity gain can be exploited while applying Selective OFDM Relaying where a given relay is selected at each hop to forward the entire OFDM block no diversity gain can be obtained. In [11] and [12], the performance of a multihop OFDMA network applying corridor-based routing is analyzed with respect to throughput where it was shown that considerable gains compared to the case of forwarding along unicast route can be achieved having either global Channel State Information (CSI) [12] or only local CSI for the next hop [11], respectively. However, in all mentioned works, it is not taken into account how the relay clusters for each hop are selected [9] [10] or how the selection of the forwarding nodes in the corridor is performed [11] [12]. The network topology is simply assumed to be given considering a rather homogeneous topology between source and destination node with equally spaced relay clusters each having the same amount of relays. Hence, assuming a more realistic network with heterogeneous topology, a node selection scheme to build up the relay clusters for each hop to form the corridor along a given unicast route between source and destination node is missing as well as a performance analysis for such kind of heterogeneous networks. The present paper will take into account these aspects providing the following contributions:

- Distributed node selection scheme which selects potential forwarding nodes for corridor-based routing based on a given unicast route assuming non-clustered, randomly distributed nodes in the network
- Simulative investigation of throughput performance applying node selection scheme assuming different node densities in the network

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 is introduced. In Section IV, the node selection for the corridor-based routing is presented. In Section V, the performance of the node selection scheme is investigated and compared to the conventional approach applying only forwarding along unicast route. Finally, conclusions are drawn in Section VI.

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 multihop transmission over N_H hops with hop index $h = 1,..,N_\mathrm{H}$. In each of the intermediate $N_\mathrm{H} - 1$ hops there are $N_\mathrm{F}(h)$ possible forwarding nodes as shown in Fig. 1 assuming $N_\mathrm{H} = 5$ and $N_\mathrm{F}(h) = 3$ for $h = 2,..,5$. Note that the number $N_\mathrm{F}(h)$ of forwarding nodes can be different for each hop h.

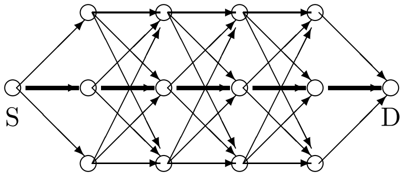


Fig. 1. Multi-hop transmission ($h = 5$) with one source (S), one destination (D) and $N_\mathrm{F} = 3$ forwarding nodes per hop

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.

OFDMA is used as multiple access scheme and the bandwidth is subdivided into N orthogonal subcarriers with frequency spacing Δf. 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 in hop h described by the transfer factor $H^{(h)}_{i,j,n}$ is modeled as a complex Gaussian distributed random process with variance one.

From each node i on each subcarrier n in each hop h, data is transmitted with power $p^{(h)}_{i,n}$ where the total transmit power P_T per hop is given by $P_\mathrm{T} = \sum_{n=1}^{N} \sum_{i=1}^{d} p^{(h)}_{i,n}$. Hence, the normalized transmit power $P_\mathrm{T,sc}$ per subcarrier assuming $p^{(h)}_{i,n} = 1 \; \forall \; h, i, n$ is $P_\mathrm{T,sc} = \frac{P_\mathrm{T}}{N}$. With the noise power spectral density N_0, the noise power $P_\mathrm{N,sc}$ per subcarrier is given by $P_\mathrm{N,sc} = N_0 \cdot \Delta f$. From this it follows that the normalized average SNR $\bar{\gamma}^{(h)}_{i,j}$ for the transmission from node i to node j in hop h can be calculated by

$$\bar{\gamma}^{(h)}_{i,j} = \frac{P_\mathrm{T,sc}}{P_\mathrm{N,sc}} \cdot \left(\frac{d_{i,j}}{d_0}\right)^{-\alpha_\mathrm{PL}}, \tag{1}$$

with $d_{i,j}$ denoting the distance between node i and node j, d_0 the minimum distance between two nodes and α_PL the pathloss coefficient. The normalized instantaneous SNR $\gamma^{(h)}_{i,j,n}$ from node i to node j on subcarrier n in hop h is then given by

$$\gamma^{(h)}_{i,j,n} = \bar{\gamma}^{(h)}_{i,j} \cdot \left|H^{(h)}_{i,j,n}\right|^2. \tag{2}$$

III. CORRIDOR-BASED ROUTING USING OPPORTUNISTIC FORWARDING IN MULTI-HOP OFDMA NETWORKS

In this section, the idea of corridor-based routing using opportunistic forwarding in multi-hop OFDMA networks is introduced and the iterative max-flow scheme from [12] is shortly presented which solves the power and subcarrier allocation problem to maximize the throughput applying corridor-based routing.

A. Opportunistic forwarding

In unicast routing through a network, the transmission of the data from a source node S to a destination node D 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 D as shown in Fig. 1.

Note that how to establish the unicast route and how to select the nodes for the corridor will be shown in Section IV.

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. How this can be done is shown in the following section.

B. Iterative max-flow scheme

For a given multihop OFDMA network with established unicast route and corridor as given in Fig. 1 and assuming perfect knowledge of (2), it was shown in [12] how to find a solution for the power and subcarriers allocation problem to maximize the network throughput with feasible effort. The idea 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, 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. As shown in [12], a low complexity Viterbi-based approach to solve the max-flow problem can be used 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 [13]. For further details, the reader is referred to the algorithm description in [12].

IV. NODE SELECTION FOR CORRIDOR-BASED ROUTING

In this section, it is shown how to build up the corridor of forwarding nodes assuming that the unicast route has been previously established. Before, the routing for the unicast case is also briefly presented.

A. Forwarding along unicast route

In this paper, we apply a geographical routing [14] approach to establish the unicast route between source node S and destination node D. Applying geographical routing, it is assumed that all nodes involved in the multihop transmission know their own geographical position, the geographical position of the destination node and the geographical position of their neighboring nodes. This can be achieved assuming either fixed nodes with known positions or nodes equipped with GPS receivers which share their position information with their neighboring nodes on a regular basis using 'Hello' messages.

The applied unicast routing now searches for the most direct route between source and destination while limiting the distance between hops in order to keep energy consumption low. The routing algorithms runs as follows.

Starting from the source node, a sector with angle α_{R} and radius r_{R} is spanned which points in the direction towards the destination node. At the beginning, $\alpha_{\mathrm{R}} = \alpha_0$ and $r_{\mathrm{R}} = r_0$. Now, it is checked whether there are neighboring nodes which lie within this sector. If this is the case, then the node with the smallest distance to the source node is chosen as forwarding node. If no node is located within the sector, α_{R} is increased by $\Delta\alpha$ and it is checked whether any nodes are located in the increased sector. If not, the angle is further increased by $\Delta\alpha$ until a node is found or and maximum angle $\alpha_{\max}$ has been reached. In this case, α_{R} is set back to $\alpha_{\mathrm{R}} = \alpha_0$ and the radius r_{R} is increased by Δr. This procedure is repeated until a forwarding node is found. For the next hops towards the destination node, the same steps are performed in a distributed manner.

Note that our scheme provides similar routes than trajectory-based forwarding (TBF) [15] when using a straight line from the current node to the destination as a reference. At each node our mechanism spans a sector pointing to the destination and increases its angle if no neighbor is contained in it. Essentially, this is equivalent to the TBF policy that chooses as a next node the neighbor closest to the reference line and closest to the current node, assuming the sector angle is increased in small step sizes. We have formulated our approach in terms of angles and radii in order to match the nomenclature of the corridor-based routing scheme we will present in Section IV-B. There, we need these concepts in order to control the width and the density of selected nodes in the corridor.

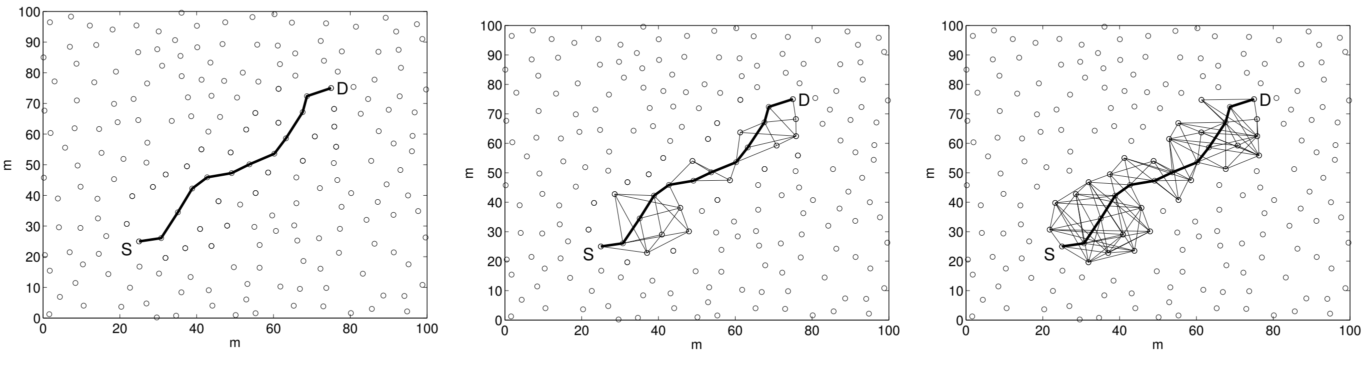
As our approach is equivalent to a specific case of TBF, it also suffers similar limitations. The most significant and well-known one is caused by local minima, which are regions of the network where no next node can be found as no neighbor falls into the sector even when spanned over the maximum angle $\alpha_{\max}$ and a radius equal to the transmission range of the node. Hence, our approach cannot provide delivery guarantees, similarly to most greedy geographical routing schemes. While this problem could be tackled using planar graph routing [16], we consider it to be marginal for the issues addressed in this paper and thus out of scope. Regarding the scalability of the proposed node selection scheme, similarly to TBF our approach is fully localized, making it suitable for large scale wireless multihop networks.

B. Node selection for Corridor-based Routing along unicast route

In the following, the node selection scheme based on a given unicast route is presented. Each node along the unicast route is responsible to select potential forwarding nodes for the next hop beside the already chosen one of the unicast route. From this, it follows that the node selection can be performed in a distributed manner.

Let us assume a multi-hop transmission along a unicast route with N_{H} hops from the source node to the destination node. To select the forwarding nodes of the h-th hop with $h = 1, .., N_{\mathrm{H}}$, the h-th node along the route forms a sector with a sector angle $\alpha_{\mathrm{sec}} = 2\alpha$ and a sector radius r_{sec} where $r_{\mathrm{sec}} = f_{\mathrm{sec}} \cdot d(h, h+2)$ with $d(h, h+2)$ denoting the distance between the h-th and the $h+2$-th node along the unicast route and f_{sec} denoting a radius factor where $f_{\mathrm{sec}} \leq 1$. The sector points in the direction of the $h+2$ nodes as shown in Fig. 2.

The idea is that potential forwarding nodes should be close to the h-th node since they act as receivers in the h-th hop



(a) (b) (c)

Fig. 3. Corridor-based routing applying $f_{\mathrm{sec}} = 1$ (a) $\alpha = 0°$, (b) $\alpha = 45°$ and (c) $\alpha = 90°$.

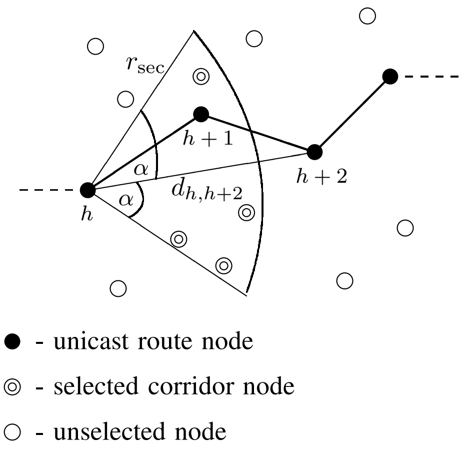


Fig. 2. Node selection scheme

but also close to the $(h+2)$-th node as they act as forwarding nodes transmitting data to node $h+2$ in the $(h+1)$-th hop. All nodes which lie within the sector and which have not yet been chosen as forwarding nodes are selected as forwarding nodes for the h-th hop. By changing α and f_{sec}, the size of the sector and thus the number of forwarding nodes can be adjusted. This procedure is repeated from the first node along the unicast route until the $(N_{\mathrm{H}}-1)$-th node since for the last hop, the only receiving node is the destination node. In Fig. 3(a) to 3(c), the node selection for the corridor is shown for a scenario with $M = 100$ nodes uniformly distributed over an area of 100 m x 100 m for $f_{\mathrm{sec}} = 1$ and angles $\alpha = 0°$, $\alpha = 45°$ and $\alpha = 90°$. The thick lines represent the established unicast route between source node S and destination node D, the thin lines the connections within the corridor. It can be seen that with increasing α, the width of the corridor also increases.

V. NUMERICAL RESULTS

In this section, the performance of the node selection scheme is discussed for scenarios with different node densities. In the following, an area of 100 m x 100 m is assumed where M nodes are uniformly distributed. The source node is placed at the coordinates $x_{\mathrm{S}} = 25$ m and $y_{\mathrm{S}} = 25$ m and the destination node at $x_{\mathrm{S}} = 75$ m and $y_{\mathrm{S}} = 75$ m as shown in Fig. 3(a) to 3(c). We run all simulations using the same source and destination nodes in order to obtain comprehensible results that allow us to gain insights on the influence of node selection parameter α and f_{sec} on the system performance. The system parameters are given in Table I.

TABLE I
SYSTEM PARAMETERS

Number N of subcarriers	64
Subcarrier spacing Δf	40 kHz
Transmit power $P_{\mathrm{T,sc}}$ per subcarrier	-14 dBm (-60 dBm/Hz)
Noise power $P_{\mathrm{N,sc}}$ per subcarrier	-44 dBm (-90 dBm/Hz)
Minimum node distance d_0	5 m
Pathloss coefficient α_{PL}	3.5

Between source and destination node, a unicast route is established according to Section IV-A assuming $\alpha_0 = 10°$, $\Delta\alpha = 5°$, $\alpha_{\max} = 60°$, $r_0 = 10$ m and $\Delta r = 5$ m. Note that r_0 is set according to $P_{\mathrm{T,sc}}$ and $P_{\mathrm{N,sc}}$ to provide a good trade-off between average receive SNR and number of hops. For the first scenario, $M = 100$ nodes in the area under consideration are assumed. In Fig. 4, the average achievable throughput per hop applying corridor-based routing using the iterative max-flow algorithm is depicted as a function of the angle α for different sector radius factors f_{sec}. The throughput is averaged over 500 independent Monte Carlo simulations. As seen from Fig. 3(a), $\alpha = 0°$ corresponds to conventional forwarding along a unicast route, i.e., no corridor is built. Increasing the sector angle, the number of forwarding nodes in the corridor also increases as seen in Fig. 3(a) to 3(c). From Fig. 4, it can be seen that this also corresponds to an increase in throughput. However, the throughput only increases

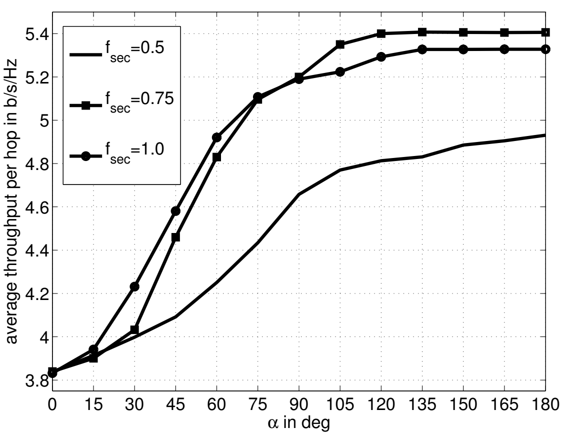


Fig. 4. Average throughput per hop vs. angle α for $M = 100$ nodes in the area.

with increasing forwarding nodes as long as the nodes in the corridor have approximately the same average channel quality since the corridor-based routing applying the iterative max-flow scheme only takes into account forwarding nodes with good channel conditions. Otherwise, the throughput performance is mainly dominated by the nodes with the best channel conditions and no further diversity can be exploited introducing nodes with weak channel conditions. Hence, at a certain sector angle, no further throughput improvement can be observed. Furthermore, increasing the angle larger than $\alpha = 135°$ does only introduce new forwarding nodes to the corridor in the very first hop. For the next hops towards the destination node, potential nodes in this direction have already been chosen to act as forwarding nodes in previous hops.

Concerning the sector radius, it can be seen that the maximum throughput is achieved applying a sector radius factor of $f_{\mathrm{sec}} = 0.75$ together with an angle of $\alpha = 135°$. Compared to $f_{\mathrm{sec}} = 0.5$, one can find more potential forwarding nodes which are still in a good transmission range, i.e., they can actually contribute to the transmission. If one further increases f_{sec}, the maximum achievable throughput decreases. This is because having a larger sector radius, the probability increases that the sectors spanned by two consecutive nodes along the unicast route overlap. Then, it can happen that a node is selected to act as forwarding node in the h-th hop which could have also been selected as forwarding node for the $(h+1)$-th hop where it might have contribute much more to the transmission than in the h-th hop.

In Fig. 5, the same investigation is shown for a scenario with only $M = 50$ nodes in the considered area. It can be seen that the achievable throughput is less compared to the case of $M = 100$ due to the larger distances between the nodes and, thus, a lower SNR at the receive nodes. In Fig. 6, the number M of nodes is set to $M = 200$. In this case, the achievable throughputs are higher as the nodes are closer to each other. Interestingly, the sector setting $f_{\mathrm{sec}} = 0.75$ and $\alpha = 135°$ provides the best throughput in all scenarios. However, the relative gain between optimal corridor-based routing and conventional forwarding along a unicast route differs for the different scenarios. In case of $M = 50$, the gain is 1.5 while for $M = 100$ the gain is 1.4 and for $M = 200$ the gain is 1.3. Obviously, with densely-deployed nodes in the network, the gain applying corridor-based routing is less prominent as the unicast route already provides high throughput due to the short distances between the nodes. In sparse networks, potential forwarding nodes in the corridor can beneficially contribute to the transmission as the unicast route is less strong.

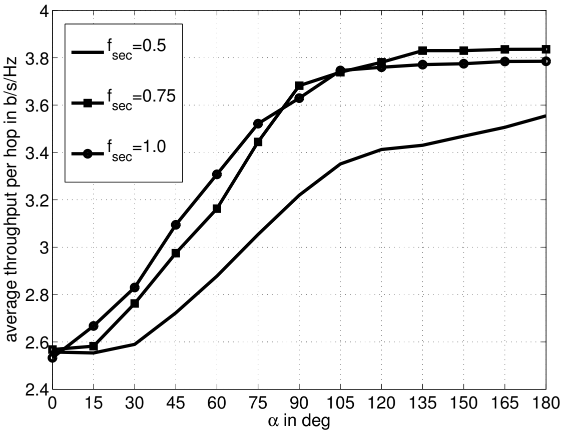


Fig. 5. Average throughput per hop vs. angle α for $M = 50$ nodes in the area.

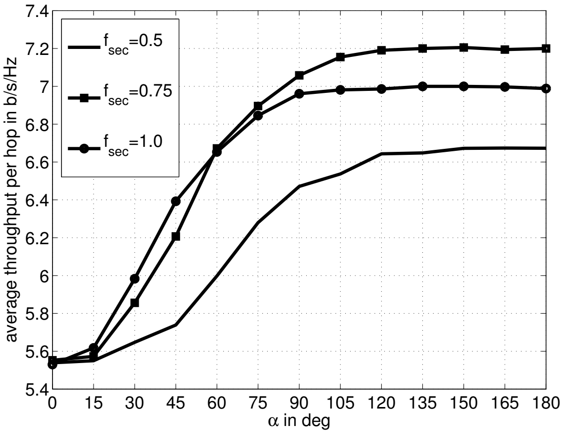


Fig. 6. Average throughput per hop vs. angle α for $M = 200$ nodes in the area.

VI. CONCLUSIONS

In this work, a node selection scheme for corridor-based routing in heterogeneous multi-hop OFDMA networks is presented. Based on a given unicast route, potential forwarding nodes are selected to build the corridor in which the data is forwarded from the source node towards the destination node. For the actual corridor-based data transmission, a maxflow-based opportunistic forwarding approach is applied. Simulations show that with the proposed node selection scheme, considerable throughput gains of up to 50 % compared to forwarding along unicast route can be achieved applying corridor-based routing in heterogeneous networks especially in sparse networks.

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