# Opportunistic forwarding using rateless codes in OFDMA multihop networks

Fabian Hohmann and Anja Klein

Communications Engineering Lab, Technische Universität Darmstadt, 64283 Darmstadt, Germany

Email:{f.hohmann, a.klein}@nt.tu-darmstadt.de

*Abstract*—A major challenge for data transmission in wireless multihop networks is to efficiently utilize the present channel capacity provided by the variety of links within the network. To achieve this, we combine the concept of opportunistic routing with rateless coding and Orthogonal Frequency Division Multiple Access (OFDMA). Opportunistic routing exploits the broadcast nature of wireless transmissions by considering multiple nodes as potential next forwarder of a certain data packet and by selecting the next forwarder after transmission instead of prior to it. Rateless coding enables mutual information accumulation at subsequent nodes of a multihop transmission path which overhear the transmissions. Using a predefined selection of nodes as a support structure, consisting of stages of fully connected transmitters and receivers, allows for a local cooperation among the nodes. Thereby, an unnecessary and wasteful forwarding of data duplicates can be avoided. Furthermore, based on OFDMA, the nodes can exploit the diversity of links within each stage by an adaptive local resource allocation. For the operation of this concept, we propose suitable algorithms for scheduling of data packets and resource allocation and show that the proposed scheme provides significant throughput gains compared to forwarding without overhearing at subsequent nodes and forwarding along a unipath.

## I. Introduction

In wireless multihop networks, traditional routing schemes choose a fixed sequence of forwarding nodes based on a certain path metric like, for instance, the number of hops [1] or the expected transmission count (ETX) [2]. In such a unipath transmission between a source and a destination, each wireless link is prone to strong and quick fluctuations of the channel conditions due to multi-path propagation. To face the problem of unreliable wireless links, opportunistic routing [3], [4] exploits the broadcast nature of wireless transmissions by considering multiple nodes as possible next forwarder. Instead of selecting a fixed receiver before the transmission, any node closer to the destination that overhears the transmission is a possible forwarder. However, most of the proposed opportunistic routing schemes use fixed single rate transmissions [4], which means they do not adapt the transmission rate to the actual channel conditions and, therefore, they under-utilize the given channel capacity in most cases.

Rateless codes like LT codes [5], Raptor [6] or Strider [7] can automatically adapt the transmission rate to the actual channel conditions. Using rateless coding, the transmitter is theoretically able to generate an infinite number of coded symbols from a given set of information bits. These coded symbols are transmitted until the receiver is able to decode and sends back an acknowledgment (ACK) to inform the transmitter.

Furthermore, in multi-hop transmissions, all subsequent nodes of a transmission path can make use of mutual information accumulation [8]. In [9], it is shown that mutual information accumulation is superior to energy accumulation approaches in relay networks.

Efficient state-of-the-art physical layer techniques such as Orthogonal Frequency Division Multiple Access (OFDMA) enable high data rates by exploiting diversity and they are well studied for one-hop communications. In [10], the resource allocation problem for the transmission between a source and destination assisted by one relay is considered for an OFDMA system using rateless codes. To make use of OFDMA also for wireless multi-hop networks, [11] proposes the concept of corridor-based routing. The basic idea is to use a fixed support structure, named the corridor, consisting of multiple locally cooperating nodes in each hop which forward data in parallel. The nodes which belong to one hop share the available subcarriers while taking the local channel conditions into account.

In this work, we want to combine and benefit from all three concepts: opportunistic routing, rateless coding and OFDMA. Using OFDMA as a multiple access scheme and a given corridor as a support structure, we can exploit link diversity by an adaptive resource allocation based on local channel knowledge. By using rateless codes, we enable mutual information accumulation at subsequent nodes within the corridor and avoid undesired transmission failures which can occur with fixed-rate approaches. In addition, we do not select a fixed next forwarding node a priori to the transmission, but utilize the concept of opportunistic routing by selecting the next forwarder after reception. For the operation of this concept, we propose suitable algorithms for scheduling of data packets and resource allocation.

The remainder of this paper is structured as follows. The system model is introduced in Section II. In Section III, the proposed transmission strategy is explained. Section IV evaluates the performance of the proposed scheme and Section V concludes the paper.

## II. System model

We consider a multihop transmission between one source node S and one destination node D. Between S and D, multiple possible forwarding nodes are available. The nodes are organized in $N_{\mathrm{St}}$ stages as shown in Fig. 1. The stage $s$ consists of $N_{\mathrm{T}}^{(s)}$ transmitters and $N_{\mathrm{R}}^{(s)}$ receivers. The receivers

of stage $s$ are the transmitters of stage $s + 1$. It is assumed that all nodes of consecutive stages are fully connected, i.e., there exists a link from each transmitter of stage $s$ to each receiver of stage $s$ and also to each receiver of stage $s + 1$ (inter-stage link). Nodes which do not belong to the current or next stage are considered to be out of the transmission range. We assume that the involved nodes which form this support structure for the transmission are already selected. Possible node selection strategies for randomly distributed networks have been considered in [12], [13] and [14].

OFDMA is used as multiple access scheme and the available bandwidth is divided into $N_{\text{Sc}}$ orthogonal subcarriers. We assume multipath propagation of the signals which leads to Rayleigh fading on the channels. The channel transfer factor $H_{i,j,n}$ between transmitter $i$ and receiver $j$ concerning subcarrier $n$ is modeled as a complex Gaussian distributed random variable with variance one. The average available transmit power for each subcarrier in a stage is equal to 1. Therefore, the transmit power of each stage is limited by $P_{\text{stage}} = N_{\text{Sc}}$. The normalized Signal-to-Noise Ratio (SNR) of the channel, assuming a transmit power of $p_{i,n} = 1$, is given by

$$\gamma_{i,j,n} = \frac{1}{\sigma^2} \cdot d_{i,j}^{-\alpha_{\text{PL}}} \cdot |H_{i,j,n}|^2, \tag{1}$$

where $\sigma^2$ is the noise power, $d_{i,j}$ denotes the distance between the nodes $i$ and $j$ and $\alpha_{\text{PL}}$ is the path loss exponent. Each subcarrier has an independent and uncorrelated channel transfer factor which is assumed to be constant. At most one node can transmit on each subcarrier at a time and data is transmitted stage-by-stage which means that the transmitters of stage $s$ first start to transmit after they decoded all data sent from the transmitters of stage $s - 1$.
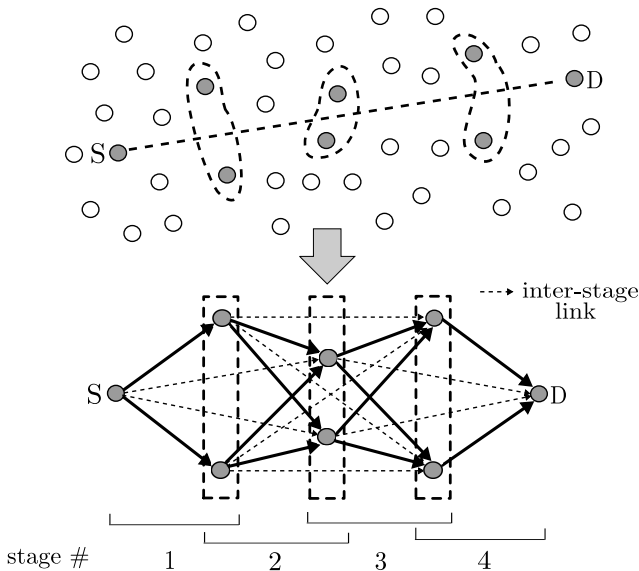


Fig. 1. Multi-hop network with $N_{\text{St}} = 4$ stages and $N_{\text{T}}^{(s)} = 2$ transmitters for $s = 2, 3$ and 4.

## III. RATELESS OPPORTUNISTIC FORWARDING

In the following, the design of the proposed rateless opportunistic forwarding concept for OFDMA multihop networks

is presented. Firstly, the rateless transmission strategy is described. Secondly, we present an opportunistic data scheduling algorithm and thirdly, we introduce an adaptive resource allocation algorithm.

### A. Rateless transmission using Strider

Rateless codes can generate a potentially unlimited number of encoded symbols from a set of source symbols [5]. The transmitter can send different linear combinations of the same data until the receiver has accumulated enough mutual information to decode. This has two advantages. Firstly, the transmitter does not need to decide for a fixed code rate prior to the transmission. The optimal code rate is found automatically. Secondly, in a multihop case, the channel capacities provided by a receiver placed close and by a receiver placed far away from a transmitter can be utilized simultaneously. In our scenario, a transmitter in stage $s$ transmits until at least one receiver of this stage is able to decode. In the meantime, the receivers of stage $s + 1$ can overhear these transmissions and start to accumulate mutual information. Thereby, less linear combinations of this data are required to be sent in stage $s + 1$ for a successful decoding compared to the case in which the receivers of stage $s + 1$ do not overhear the previous transmissions.

As a practical example of a rateless code, we use Strider [7] for our transmission scheme. Strider was proposed by Gudipati et al. [7] and owes its name to the **Stri**pping Deco**der** used. In Strider, data bits are first passed through a 1/5 rate convolutional channel code and then mapped to complex QPSK-symbols. Next, $K$ data packets, each containing $L$ complex symbols, are grouped together to one data batch with index $b$. Strider can generate multiple different linear combinations of the $K$ data packets using the coefficient matrix $\mathbf{R}$. Each linear combination represents the complete data of batch $b$. The $m$-th linear combination is described by the vector $\mathbf{p}_b^{(m)}$ and is given by

$$\mathbf{p}_b^{(m)} = r_{1m}\mathbf{x}_1 + r_{2m}\mathbf{x}_2 + ... r_{Km}\mathbf{x}_K, \tag{2}$$

where $r_{1m}$ is the first coefficient from the $m$-th row of $\mathbf{R}$ and the vector $\mathbf{x}_k$ represents the $k$-th data packet of the current batch. Each row of $\mathbf{R}$ can be used to generate a different linear combination. The matrix $\mathbf{R}$ can be used as a codebook at all nodes, since the used coefficients need to be known at the receiver. Instead of informing the receiver about all coefficients used, the transmitter just needs to indicate which row from $\mathbf{R}$ was used to generate $\mathbf{p}_b^{(m)}$. Since the different linear combinations all represent the same data, the resulting effective data rate decreases step-by-step with each additional transmission. Thereby, the data rate adapts automatically to the channel capacity. The transmitter sends these linear combinations until at least one receiver is able to decode the data batch, sends back an ACK and is then able to generate new linear combinations for the transmission in the next stage. A more detailed description of the operation of Strider can be found in [7].

## B. Opportunistic forwarding

In this section, we describe how the concept of opportunistic forwarding is used in our proposed transmission scheme. Instead of choosing a fixed path prior to the transmission of a data batch, the next forwarder is chosen after the reception of the batch. Each receiver which is able to decode the batch informs the transmitters and the other receivers of the current stage $s$ by an ACK. Based on the exchange of ACKs, each receiver of stage $s$ can track the decoding success of the other receivers. This information is stored in an availability matrix $\mathbf{A}^{(s)}$ wherein the $(i,b)$-th element is equal to $a_{i,b}^{(s)} = 1$ in case that node $i$ was able to decode batch $b$ and it equals 0 if this is not the case. Based on this availability matrix, the nodes of stage $s$ are able to coordinate which node forwards which batch.

Many opportunistic routing schemes consider a ranking of the receivers to decide which receiver should forward data that was received by multiple nodes [4]. A ranking can be based, for instance, on the distance between a receiver and the destination or on the expected transmission count (ETX). The distance is not always a suitable metric to find the best forwarder since it does not represent the actual channel condition of the remaining path. Determining the ETX for each forwarding node regarding the remaining multihop path and exchanging this information goes along with high overhead requirements. Furthermore, forwarding this information over multiple hops can lead to outdated information. Therefore, we do not consider a ranking of the different receivers, but consider them as equivalent to each other within each stage. To balance the load and to make use of the available transmit power of each node in a stage, it is beneficial that each node forwards approximately the same amount of data. Therefore, we propose a scheduling algorithms that aims at an equal allocation of the data batches among the forwarders while taking into account which batch is available at which node, indicated by the availability matrix $\mathbf{A}^{(s)}$.

The transmission is divided into slots, each consisting of a data transmission phase and an ACK phase. In the data transmission phase, each subcarrier is used to transmit a certain linear combination concerning a different batch. In case that the number of remaining batches is less than the number of subcarriers, multiple different linear combinations concerning the same batch are transmitted on different subcarriers. A simple example for the batch-subcarrier-scheduling is shown in Fig. 2, assuming one transmitter and one receiver, $N_{\text{sc}} = 4$ subcarriers and $N_{\text{batches}} = 4$ data batches to transmit. In the first transmission slot, the first linear combination $\mathbf{p}_b^{(1)}$ of each batch is transmitted on the different subcarriers. In the ACK phase, the receiver confirms a decoding success concerning batch $b = 2$. In the second transmission slot, the second linear combination of the remaining batches is transmitted. Since the second subcarrier is vacant, it is used to transmit the third linear combination of the first batch $\mathbf{p}_1^{(3)}$. This strategy is used until the receiver is able to decode all batches.

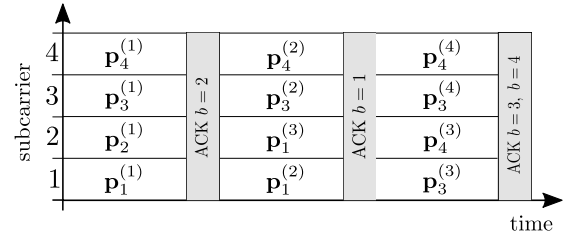To select one batch for each of the $N_{\text{sc}}$ subcarriers for the



Fig. 2. Batch-subcarrier-scheduling example for $N_{\text{Sc}} = 4$ subcarriers and 4 batches.

next transmission slot, Algorithm 1 is used which is aiming at a uniform distribution of batches among the transmitters. The iterative algorithm works with a temporary copy of $\mathbf{A}^{(s)}$, named $\mathbf{A}^{(s),\text{temp}}$. The temporary copy is changed during the algorithm, but for the next transmission slot, it is reset to the current values of $\mathbf{A}^{(s)}$. $\mathbf{A}^{(s)}$ is only changed in case of a decoding success of a receiver indicated during the ACK phase. If a receiver sends an ACK concerning batch $b$, all elements in the $b$-th column are set to 0. The iterative algorithm works as follows. First, a transmitter $i$ is selected which has the minimum number of already allocated batches to transmit, but still has at least one remaining batch in storage. Second, the batch $b$ is selected which is available at transmitter $i$ and available at a minimum number of other transmitters. The selected batch is stored in set $\mathcal{S}_i^{\text{batch}} = \{\}$ and is taken out of consideration for the next iteration. In case that no batches are left, the temporary availability matrix $\mathbf{A}^{(s),\text{temp}}$ is reset to its default values, the values of $\mathbf{A}^{(s)}$, for the next iteration. In this case, batches are selected multiple times and consecutive linear combinations of these batches are transmitted on different subcarriers in parallel.

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**Algorithm 1** Batch scheduling in stage $s$

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**Require:** availability matrix $\mathbf{A}^{(s)}$, $\mathbf{A}^{(s),\text{temp}}$ and a set $\mathcal{S}_i^{\text{batch}} = \{\}$ for each transmitter $i$ in current stage to store allocated batches

    **for** $n = 1$ to $N_{\text{sc}}$ **do**

      1) select transmitter $i$ with $\min_i |\mathcal{S}_i^{\text{batch}}|$ and $\sum_{b=1}^{N_{\text{batches}}} a_{i,b}^{(s),\text{temp}} \neq 0$

      2) select batch $b$ with $\min_b \sum_{i=1}^{N_{\text{T}}^{(s)}} a_{i,b}^{(s),\text{temp}}$ and $a_{i,b}^{(s),\text{temp}} = 1$

      3) add $b$ to set $\mathcal{S}_i^{\text{batch}}$ and put $a_{i,b}^{(s),\text{temp}} = 0$ for all transmitters $i$

      4) if $\sum_{b=1}^{N_{\text{batches}}} \sum_{i=1}^{N_{\text{T}}} a_{i,b}^{(s),\text{temp}} = 0$ set $\mathbf{A}^{(s),\text{temp}}$ back to default values of $\mathbf{A}^{(s)}$

    **end for**

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## C. Adaptive resource allocation

For the resource allocation, we assume that each transmitter has local channel knowledge in terms of SNR concerning the links within its stage. This requires channel estimation and 1-hop feedback within a stage before data transmission takes place and enables a common decision on the resource

allocation determined in a distributed way, except for the first stage. In the first stage, the source node can use all available subcarriers for the transmission. To maximize the achievable throughput, the source node allocates its transmit power among the subcarriers according to the water-filling principle [15], considering only the strongest link SNR concerning each subcarrier.

In the following stages, the diversity of links within each stage is exploited by allocating the subcarriers among the transmitters based on the current channel conditions. After the batches are allocated among the transmitters using Algorithm 1, the subcarriers are allocated according to Algorithm 2. The aim of Algorithm 2 is to maximize the channel capacity resulting from the subcarrier allocation. In each iteration, one available subcarrier is selected based on the highest SNR and allocated to the corresponding transmit node. If the number of allocated subcarriers to node $i$ is equal to the number of its assigned batches, node $i$ is taken out of consideration for the remaining iterations. This procedure is repeated until all subcarriers are allocated. For each transmission slot, the batch scheduling and resource allocation are repeated taking into account the previously received ACKs. After the subcarrier allocation, each node allocates its transmit power among the assigned subcarriers using water-filling [15].

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**Algorithm 2** Subcarrier allocation in stage $s$

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**Require:** SNR values $\gamma_{i,j,n}$ of current stage and set $\mathcal{S}_i^{\text{batch}}$ of
    batches to transmit for each transmitter $i$ of current stage
    **for** $n = 1$ to $N_{\text{Sc}}$ **do**
        1) determine subcarrier $n$ and transmitter $i$ with
        $\max_{n,i}(\gamma_{i,j,n})$ and $|\mathcal{S}_i^{\text{batch}}| \neq 0$
        2) allocate subcarrier $n$ to the corresponding transmitter
        $i$ and cancel out one batch of set $\mathcal{S}_i^{\text{batch}}$
    **end for**

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## IV. PERFORMANCE EVALUATION

In this section, the performance of the proposed opportunistic forwarding strategy using rateless codes, in the following termed OFR-OFDMA, is investigated through simulations. For comparison, we consider the proposed strategy also without overhearing of next stage receivers, which means that only the receivers of the current stage observe the transmissions. Thereby, we can determine the gain enabled by mutual information accumulation at subsequent nodes of the multihop path. For further comparison, we consider a unipath approach to highlight the benefit of link diversity exploited by our proposed scheme. For the unipath approach, also Strider is used, but only one receiver is considered per stage which means that the transmitter sends until this receiver is able to decode all data. In this case, overhearing in the next stage is also not considered. Note that the available transmit power per stage $P_{\text{stage}} = N_{\text{Sc}}$ is the same for all considered schemes. In case of multiple transmitters in a stage, the transmit power is equally distributed among them. The system parameters are given in Table I. Note that the batch size is the default value

used in [7] where it has shown good performance results in the considered SNR range.

TABLE I
SYSTEM PARAMETERS

| | |
|---|---|
| Number $N_{\text{St}}$ of stages | 4 |
| Number $N_{\text{T}}^{(s)}$ (for $s \geq 2$) of transmitters | 3 |
| Number $N_{\text{Sc}}$ of subcarriers | 12 |
| Pathloss exponent $\alpha_{\text{PL}}$ | 3 |
| Number of batches $N_{\text{batches}}$ | 24 |
| Batch size | 33 packets |
| Packet size | 378 bits |

Fig. 3 shows the average achievable throughput versus the average normalized SNR within each stage assuming a transmit power $p_{i,n}^{(s)} = 1$. For simplicity reasons, we assume that the distance between each transmitter and each receiver within a stage is the same. Furthermore, we assume that the distance from a transmitter of stage $s$ to a receiver of stage $s + 1$ equals two times the distance to a receiver of stage $s$. Therefore, corresponding to Eq. (1) and assuming a path loss exponent $\alpha_{\text{PL}} = 3$, an additional path loss of 9.03 dB occurs for all inter-stage links between transmitters of stage $s$ and receivers of stage $s + 1$. It can be seen that the proposed OFR-OFDMA strategy significantly outperforms the unipath approach within the considered SNR range. A maximum gain of approximately 77 % is achieved for an SNR of 10 dB compared to the unipath approach. Considering OFR-OFDMA with and without overhearing, it can be seen that a significant gain of up to 35 % is achieved by overhearing for an SNR of 20 dB.

Figure 4 shows the average number of required linear combinations per batch until a receiver was able to decode in each individual stage for an average SNR of 20 dB. As expected, the unipath approach requires the same number of linear combinations in each stage, since there is no diversity that can be exploited in a stage and the average SNR is the same in each stage. Considering the OFR-OFDMA without overhearing, it can be seen that the required number of linear combinations is higher in the last stage compared to the other stages, since in the last stage, there is only one receiver. Therefore, we need to transmit until the destination is able to decode all batches instead of transmitting until all batches are decoded by at least one out of multiple receivers. OFR-OFDMA requires less linear combinations in the second stage compared to the third stage due to the high number of linear combinations transmitted in the first stage and overheard by the receivers of the second. Because of the resulting low number of transmitted linear combinations in the second stage and overheard by the receivers of the third, the number of required linear combinations cannot be significantly reduced in the third stage by overhearing.

In Figure 5, the impact of the number of potential transmitters $N_{\text{T}}^{(s)}$ on the achievable throughput is shown. It can be seen that the achievable throughput increases for an increasing number of forwarding nodes due to the higher link diversity.

The additional gain becomes smaller with each additional node because a low number of potential forwarding nodes already offers the opportunity to find a link with high SNR for each subcarrier. Note that with every additional forwarding node, the required signaling overhead, which is not taken into account here, increases. Since a low number of forwarding nodes already provides enough diversity, the required signaling overhead can be kept low.
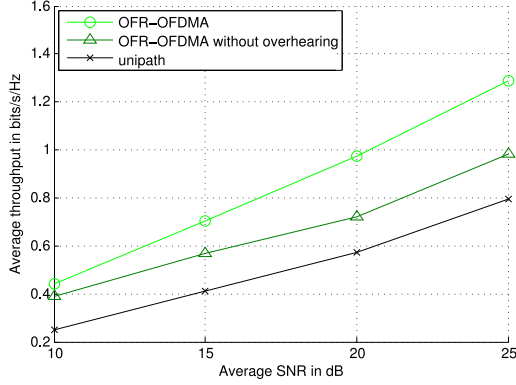


Fig. 3. Average achievable throughput versus average SNR for parameters of Table I.
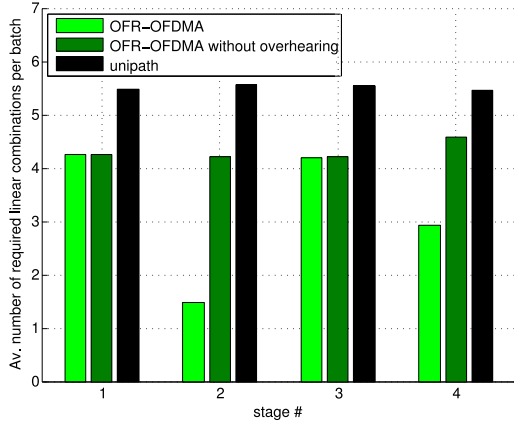


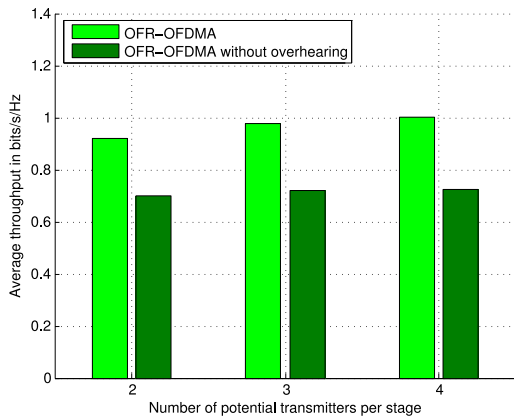Fig. 4. Average number of required linear combinations per batch in each stage for an average SNR of 20 dB.



Fig. 5. Average achievable throughput versus number of potential transmitters $N_{\mathrm{T}}^{(s)}$ (for $s = 2, 3, 4$) per stage for an average SNR of 20 dB.

## V. Conclusion

In this work, we have proposed an opportunistic forwarding strategy using rateless codes for OFDMA multi-hop networks. For the operation of this concept, termed OFR-OFDMA, we have proposed a data batch scheduling algorithm for handling the coordination of data forwarding over multiple parallel forwarders. Furthermore, we have proposed a suitable resource allocation algorithm which aims at maximizing the achievable throughput by exploiting link diversity and which works on local channel knowledge in terms of SNR values. Simulation results have shown that the proposed OFR-OFDMA strategy outperforms forwarding along a unipath by up to 77 %.

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