Della Penda, Demia; Nomikos, Nikolaos; Charalambous, Themistoklis; Johansson, Mikael

Minimum Power Scheduling under Rician Fading in Full-Duplex Relay-Assisted D2D Communication

Published in:
2017 IEEE Globecom Workshops (GC Wkshps) - Proceedings

DOI:
10.1109/GLOCOMW.2017.8269122

Published: 01/01/2017

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Della Penda, D., Nomikos, N., Charalambous, T., & Johansson, M. (2017). Minimum Power Scheduling under Rician Fading in Full-Duplex Relay-Assisted D2D Communication. In *2017 IEEE Globecom Workshops (GC Wkshps) - Proceedings* IEEE. https://doi.org/10.1109/GLOCOMW.2017.8269122

Relay Selection for Buffer-Aided Non-Orthogonal Multiple Access Networks

Nikolaos Nomikos*, Themistoklis Charalambous§, Demosthenes Vouyioukas*,
George K. Karagiannidis‡, Risto Wichman†
*Department of Information and Communication Systems Engineering, University of the Aegean, Samos, Greece
Emails: {nnomikos,dvouyiou}@aegean.gr
§Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, Espoo, Finland
Email: themistoklis.charalambous@aalto.fi
‡Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece
Email: geokarag@auth.gr
†Department of Signal Processing and Acoustics, School of Electrical Engineering, Aalto University, Espoo, Finland
Email: risto.wichman@aalto.fi

***Abstract*—Non-Orthogonal Multiple Access (NOMA) has the potential to increase the spectral efficiency of fifth generation (5G) networks by allowing simultaneous transmission to/from multiple users in the same wireless channel. In this work, a Buffer-Aided (BA) NOMA multiple relay network is considered, where the source transmits with fixed rate towards two users. By adopting BA relays, increased robustness can be achieved, as additional degrees of freedom are provided to relay selection. In order to increase the diversity of NOMA transmissions, two BA Half-Duplex (HD) relay selection algorithms are developed, considering the required transmission rate for each user, for Successive Interference Cancellation (SIC) at the reception and the Buffer State Information (BSI) at the relays. Then, results are provided in terms of outage probability, average throughput and average delay for the two algorithms. Finally, conclusions and possible future directions are given.**

***Index Terms*—NOMA, BA relays, relay selection, cooperative diversity**

I. Introduction

The development of fifth generation (5G) networks requires novel techniques, originating from the current communication paradigms. Among these techniques, Non-Orthogonal Multiple Access (NOMA) differentiates from traditional orthogonal multiple access (OMA) schemes, permitting users to share the same resource (time/frequency/code), exploiting different channel power levels [1]. NOMA transmissions adopt superposition coding, while at the reception Successive Interference Cancellation (SIC) is employed, decoding first the strongest signal and then, subtracting it, in order to decode the desired signal with minimum interference [2]. The survey in [3] presents various challenges of NOMA, including the need for dynamic user pairing, as users must be divided in groups that are allocated different channels to perform NOMA, while the potential of NOMA for increasing the resource efficiency was underlined. Recently, NOMA was extended to scenarios targeting data rate optimization and fairness for wireless powered nodes [4].

Furthermore, a technique that has been standardized in the current fourth generation (4G) Long-Term Evolution Advanced (LTE-A) networks is cooperative relaying. In LTE-A, relays are divided in two categories, namely type 1 and type 2, based on their capability to control or not, their resources, respectively [5]. Moreover, the study in [6] presented several challenges for relays in LTE-A including the necessity for cost efficiency and modifications to integrate Half-Duplex (HD) relays in the network's operation. Also, future trends were identified such as mobile relays and multi-hop transmissions. In a recent paper, Lien *et al.* [7] presented standardization activities for LTE rel. 12 focusing on public safety applications. More specifically, LTE rel. 12 includes various cases of Device-to-Device (D2D) communication where direct transmissions and relaying between the devices is possible when the communication infrastructure might be offline due to a physical disaster or when many users aim to communicate simultaneously in emergency situations.

In order to harvest increased performance gains and more efficient spectrum sharing, NOMA has been combined with relaying in a number of papers. The authors in [8] proposed to exploit the ability of the users with good channels to decode the messages of other users. Then, by forming user pairs, these decoded messages can be relayed to users with poor channels towards the information source. In [9], a HD relay assists the base station in transmitting data to two users. Compared to OMA, NOMA achieves the same diversity gain, while offering improved spectral efficiency and fairness. Next, the authors in [10] study a network, where a source communicates with two receivers. Since communication between the receivers is allowed, one of them operates also, as a Full-Duplex (FD) relay. By forming a relay broadcast channel, the achievable rate region of the network is improved when noisy network coding and dirty paper coding are employed. Then, the study in [11] proposed using a dedicated FD relay in a two-user NOMA network. Compared to HD relaying, FD cooperative NOMA improves the ergodic sum capacity for low-to-medium Signal-to-Noise Ratio (SNR), even when perfect self-interference cancellation cannot be achieved. In addition, NOMA has been studied in the context of Opportunistic Relay Selection (ORS) networks. Furthermore, Ding *et al.* in [12] proposed a two-stage ORS algorithm minimizing the outage probability. Results showed that, by adopting the proposed algorithm, improved diversity gain is achieved compared to conventional $\max - \min$ ORS. Furthermore, partial ORS using Channel State Information at the Transmitter (CSIT) of only the Source-Relay ($\{S \rightarrow R\}$) or Relay-Destination ($\{R \rightarrow D\}$) links has been analyzed in [13]. It is shown that significant performance gains are provided when relays increase from one to two, while for a larger number of relays the performance gains are negligible.

Meanwhile, several studies in cooperative relaying investigated Buffer-Aided (BA) ORS; for an extensive literature review, see the survey in [14]. Various BA–ORS algorithms target the reduction of the outage probability in cases where delay can be tolerated. The work in [15] proposed a Hybrid Relay Selection (HRS) based on the Max-Max Relay Selection (MMRS) allocating one time-slot to two different relays, considering the strongest $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ links. Performance evaluation showed that HRS offers equal diversity with non-BA ORS and increases the coding gain. Then, $\max - \text{link}$ algorithm with adaptive link selection was developed by Krikidis *et al.* in [16], providing increased diversity gain. In $\max - \text{link}$, each time-slot is allocated to either an $\{S \rightarrow R\}$ transmission towards a non-full relay or to an $\{R \rightarrow D\}$ transmission by a non-empty relay. When a large number K of relays is available, the diversity gain reaches a value of $2K$. Furthermore, a number of works have provided delay-aware versions of HRS see, e.g., [17]) and $\max - \text{link}$ (see, e.g., [18], [19]) to improve delay performance. Within this context, in [20], through centralized coordination, Buffer State Information (BSI) is exchanged and the best relay is selected, as long as buffers are not empty or full. Numerical results show that for a buffer size $L \leq 3$ the proposed algorithm offers lower delay than $\max - \text{link}$. Finally, in [19] two $\max - \text{link}$ modifications were provided exploiting BSI. The delay-aware version of $\max - \text{link}$ achieves low average delay, while diversity is sacrificed, as buffers tend to be empty, thus reducing the number of available relays for selection. Then, the delay- and diversity-aware $\max - \text{link}$ selection increases the number of available links, by avoiding empty and full buffers. On the downside, this algorithm tends to distribute packets to multiple relays and delays might be increased.

Recently, the adoption of BA–ORS in cooperative NOMA has been proposed. The authors of [21] proposed adaptive mode selection in a single relay network. Aiming to improve the throughput of the network, the system selects between NOMA, serving concurrently two users or single user transmission when NOMA is infeasible. From the analysis it is concluded that the system throughput can be enhanced compared to BA relaying without NOMA and conventional relaying with NOMA. In a similar setup, the work in [22] proposed adaptive link selection for the cases of full CSIT and no CSIT in the $\{R \rightarrow D\}$ links. Expressions for the outage probability were derived and results showed that a diversity order of two can be achieved when the buffer size is larger than or equal to three.

In this work, contrary to the two aforementioned BA NOMA works, a multi-relay topology is studied. Moreover, the process for choosing the optimal power allocation coefficient α for NOMA is given in detail, assuming the existence of two users requiring a fixed rate r_0. Then, two BA ORS algorithms are proposed based on the delay- and diversity-aware algorithms of [19]. The first algorithm, namely Delay-Aware NOMA (DA-NOMA), prioritizes the transmission in the $\{R \rightarrow D\}$ link from the relay with the maximum buffer length and if a feasible set of links to the two destinations does not exist, a transmission in the $\{S \rightarrow R\}$ link is performed towards the relay with the minimum buffer length. Then, a Delay and Diversity-Aware NOMA (DDA-NOMA) algorithm is developed to avoid the instances of full or empty buffers. Results show that both algorithms can provide robustness as the number of relays increases, especially for the case of DDA-NOMA, while the average delay performance is maintained.

The structure of this paper is as follows. Section II presents the system model and Section III provides the process for choosing the optimal power allocation coefficient α. Then, Section IV includes the proposed selection algorithms while in Section V, performance evaluation results are presented, while conclusions and future directions are discussed in Section VI.

II. System model and Preliminaries

A. System model

We consider a relay-assisted network consisting of one source, S, two destinations, D_1 and D_2, and a cluster $\mathcal{C}$ of K HD Decode-and-Forward (DF) relays $R_k \in \mathcal{C}$ $(1 \leq k \leq K)$. Due to severe fading, the direct links between the source and the destinations do not exist and we assume that communication is established via the relays. Each relay R_k is equipped with a buffer Q_k of size L denoting the maximum number of data elements, that can be stored from the source's transmissions. The system model is depicted in Fig. 1.

The quality of the wireless channels is degraded by Additive White Gaussian Noise (AWGN) and frequency non-selective Rayleigh block fading, according to a complex Gaussian distribution with zero mean and variance σ_{ij}^2 for the $\{i \rightarrow j\}$ link. For simplicity, the AWGN is assumed to be normalized with zero mean and unit variance. The channel gain, $g_{ij} \triangleq |h_{ij}|^2$, is assumed to be exponentially non-identically distributed, as is the case of asymmetric topology.

The source node is assumed to be saturated (it has always data to transmit) and the required information rate for a successful reception at each destination, is fixed and equal to r_0 bps/Hz. Equivalently, a transmission from a transmitter to its corresponding receiver is successful if the SNR of the receiver is greater or equal to a threshold γ_0, called the *capture ratio*. The value of γ_0 depends on the modulation and coding characteristics of the application. So, the transmission from a transmitter i to its corresponding receiver j is successful (error-free) if the SNR of the receiver j, denoted by γ_j, is greater or equal to the *capture ratio* γ_0. The variance of

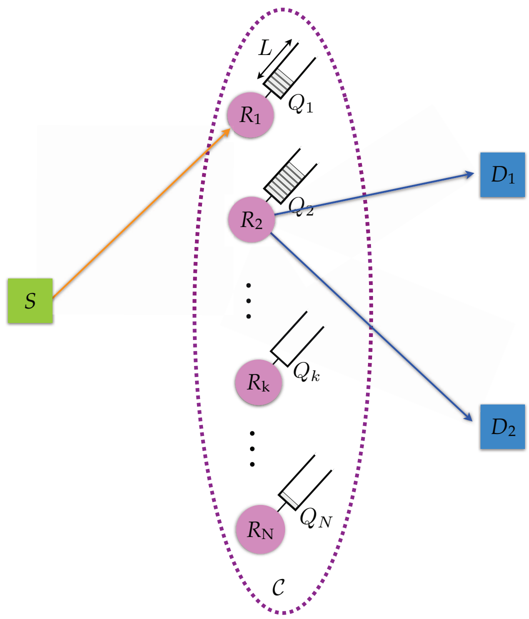

Fig. 1. BA-NOMA two-hop relay network.

thermal noise at relay R_j is denoted by σ_j^2 and it is assumed to be AWGN. The transmission is divided in time-slots of equal length and at each time-slot, the source S or one of the relays R_k attempts to transmit a packet using a fixed power level P_i. The retransmission process is based on an Acknowledgement/Negative-Acknowledgement (ACK/NACK) mechanism, in which short-length error-free packets are broadcasted by the receivers over a separate narrow-band channel. Finally, as CSIT is available, unicast $\{S\to R\}$ transmissions towards the best relay are performed, and the other relays are not activated, increasing the energy efficiency of the network.

B. Transmission in the $\{S\to R\}$ link

In this topology, a time-slot is dedicated for $\{S\to R\}$ or a $\{R\to D\}$ transmission. Without losing generality, we assume that each destination demands the same rate r_0, and thus, the source transmits with rate $2r_0$. Therefore,

$$\gamma_{SR_k}(P_S) \triangleq \frac{g_{SR_k}P_S}{\sigma_k^2} \geq 2^{2r_0}-1. \quad (1)$$

On the contrary, a $\{S\to R\}$ link is in outage if $\gamma_{R_k}(P_S) < 2^{2r_0}-1$, and the probability of outage is given by

$$p_{\text{out}\{S\to R\}} = \mathbb{P}\left[g_{SR_k} < \frac{(2^{2r_0}-1)\sigma_k^2}{P_S}\right]. \quad (2)$$

Let $b_{SR} \triangleq (b_{SR_1}, b_{SR_2}, \ldots, b_{SR_K})$ be the binary representation of the feasible $\{S\to R\}$ links due to the fulfillment of eq. (1) (i.e., if transmission on link $\{S\to R_k\}$ is possible, then $b_{SR_k}=1$). Moreover, let $q_{SR} \triangleq (q_{SR_1}, q_{SR_2}, \ldots, q_{SR_K})$ be the binary representation of the feasible links due to the fulfillment of the queue conditions (i.e., for a $\{S\to R\}$ link the buffer in a relay is not full). By $\mathcal{F}_{SR}$, we denote the sets of $\{S\to R\}$ links that are feasible having a cardinality of F_{SR}.

C. Transmission in the $\{R\to D\}$ link

On the other hand, if a relay R_k is selected, the information symbols of D_1 and D_2 are superimposed and a NOMA transmission is performed. Since full CSIT is available at the relay, the power allocation coefficient α can be calculated in each time-slot. More specifically, the transmitted superimposed information symbol consisting of the information symbols x_1 and x_2 of each destination, is defined as,

$$x = \sqrt{\alpha}x_1 + \sqrt{1-\alpha}x_2 \quad (3)$$

with $\mathbb{E}[|x_1^2|] = \mathbb{E}[|x_2^2|] = 1$ and $0<\alpha<1$.

Then, D_1 will receive an information symbol y_1 containing the desired symbol, as well as the symbol of D_2

$$y_1 = h_{R_kD_1}\sqrt{\alpha P_{R_k}}x_1 + h_{R_kD_1}\sqrt{(1-\alpha)P_{R_k}}x_2 + \eta_1, \quad (4)$$

while the received information symbol y_2 at D_2 is

$$y_2 = h_{R_kD_2}\sqrt{\alpha P_{R_k}}x_1 + h_{R_kD_2}\sqrt{(1-\alpha)P_{R_k}}x_2 + \eta_2, \quad (5)$$

where η_1 and η_2 denote the AWGN at each destination.

III. Choosing the optimal α for NOMA

In this section, the selection of α determining the power allocation for each destination is presented. The value of α is chosen to ensure that the x_1 and x_2 are decoded successfully. In other words, in order to have SIC, the SINR, for at least one of the symbols, should be greater than or equal to a threshold at both destinations D_1 and D_2. This process must be performed by each relay in order to define the set of relays that can perform NOMA transmissions in the $\{R\to D\}$ links.

For example, for decoding x_2 at both destinations,

$$\gamma_{R_kD_j}(P_{R_k}) = \frac{(1-\alpha)P_{R_k}g_{R_kD_j}}{\alpha P_{R_k}g_{R_kD_j}+\sigma_{D_j}^2} \geq \gamma_0, \quad j\in\{1,2\}. \quad (6)$$

Note that $\gamma_0 \equiv 2^{r_0}-1$. Then, at destination D_1, x_1 can be decoded interference-free according to

$$\gamma_{R_kD_1}(P_{R_k}) = \frac{\alpha P_{R_k}g_{R_kD_1}}{\sigma_{D_1}^2} \geq \gamma_0. \quad (7)$$

For this example, from inequalities (6) and (7) we get that

$$\alpha \leq \frac{P_{R_k}g_{R_kD_2} - \gamma_0\sigma_{D_2}^2}{P_{R_k}g_{R_kD_2}(1+\gamma_0)}, \quad (8a)$$

$$\alpha \leq \frac{P_{R_k}g_{R_kD_1} - \gamma_0\sigma_{D_1}^2}{P_{R_k}g_{R_kD_1}(1+\gamma_0)}, \quad (8b)$$

$$\alpha \geq \frac{\gamma_0\sigma_{D_1}^2}{P_{R_k}g_{R_kD_1}}. \quad (8c)$$

Then, α can take values in the range

$$\alpha_{\min} \leq \alpha \leq \max\{0, \min\{1, \alpha_{\max}\}\}, \quad (9)$$

where

$$\alpha_{\min} \triangleq \frac{\gamma_0\sigma_{D_1}^2}{P_{R_k}g_{R_kD_1}},$$

$$\alpha_{\max} \triangleq \min\left\{\frac{P_{R_k}g_{R_kD_1} - \gamma_0\sigma_{D_1}^2}{P_{R_k}g_{R_kD_1}(1+\gamma_0)}, \frac{P_{R_k}g_{R_kD_2} - \gamma_0\sigma_{D_2}^2}{P_{R_k}g_{R_kD_2}(1+\gamma_0)}\right\}.$$

Similarly, for decoding x_1 first at both destinations, we have

$$\alpha_{\min} \triangleq \max\left\{\frac{\gamma_0(P_{R_k}g_{R_kD_1}+\sigma_{D_1}^2)}{P_{R_k}g_{R_kD_1}(1+\gamma_0)}, \frac{\gamma_0(P_{R_k}g_{R_kD_2}+\sigma_{D_2}^2)}{P_{R_k}g_{R_kD_2}(1+\gamma_0)}\right\},$$

$$\alpha_{\max} \triangleq \frac{P_{R_k}g_{R_kD_2}-\gamma_0\sigma_{D_1}^2}{P_{R_k}g_{R_kD_2}}.$$

The outage probability of NOMA is equal to

$$p_{\text{out}\{R\to D\}} = \mathbb{P}\left[\alpha_{\min} > \min\{1, \alpha_{\max}\}\right]. \quad (10)$$

The values $\alpha_{\min}$ and $\alpha_{\max}$ for each case can be computed at each R_k. Assuming that each R_k has the CSIT for D_1, D_2 the range of α values given by eq. (9) is accurately calculated. Nonetheless, in practical systems channel estimation errors might occur. In this case, we propose to choose α to be

$$\alpha = \frac{\alpha_{\min} + \max\{0, \min\{1, \alpha_{\max}\}\}}{2}, \quad (11)$$

in order to provide robustness against CSIT estimation errors.

In addition, the selected relay must inform the two destinations on the decoding strategy that they must adopt. This is achieved by adding an extra bit to the packet's header. If the bit value is "0", D_1 will perform SIC, decoding its packet interference-free while D_2 will decode its packet by considering the signal intended for D_1, as interference. The reverse strategies are adopted when the bit value is "1". It must be noted that each R_k examines sequentially the possible decoding strategies and when the first strategy fullilling the rate requirements is found, its decision is transmitted by the selected relay to D_1 and D_2.

Let $b_{RD} \triangleq (b_{R_1D}, b_{R_2D}, \dots, b_{R_KD})$ be the binary representation of the feasible $\{R\to D\}$ links due to the fulfillment of eqs. (6), (7) (i.e., if a NOMA transmission on the set of links $\{R_k \to D_1\}$, $\{R_k \to D_2\}$ is possible, then $b_{R_kD} = 1$). Similarly, let $q_{RD} \triangleq (q_{R_1D}, q_{R_2D}, \dots, q_{R_KD})$ be the binary representation of the feasible links due to the fulfillment of the queue conditions. By $\mathcal{F}_{RD}$, we denote the sets $\{R\to D\}$ links that are feasible, having a cardinality of F_{RD}.

IV. Selection algorithms

A. Delay-aware NOMA (DA-NOMA)

The first selection algorithm targets to reduce the average delay and prioritizes the selection of the relay with the maximum number of packets in its queue. If a feasible set of links to the two destinations does not exist, the relay with the minimum number of packets in its queue is selected to receive a packet from the source. The DA-NOMA link selection algorithm for a single time-slot is summarized in Algorithm 1.

By selecting the relay with the maximum number of packets for $\{R\to D\}$ transmission, diversity can be maintained. Nonetheless, the probability that $\mathcal{F}_{RD}$ will be empty increases and thus, another selection algorithm must be devised to provide a trade-off between the delay performance and diversity.

Algorithm 1 The DA-NOMA link selection algorithm

input $\mathcal{F}_{SR}$, $\mathcal{F}_{RD}$
if $\mathcal{F}_{RD} \neq \emptyset$ **then**
  $i = \arg\max_{i\in\mathcal{F}_{RD}} Q_i$ ($\{R\to D\}$ link)
  if more than one relays have the same maximum queue length **then**
    i^* is chosen randomly among the set of relays in i'.
  else
    $i^* = i'$.
  end if
  $Q_{i^*} \leftarrow Q_{i^*} - 1$
else
  $i = \arg\min_{i\in\mathcal{F}_{SR}} Q_i$ ($\{S\to R\}$ link)
  if more than one relays have the same minimum queue length **then**
    i^* is chosen randomly among the set of relays in i'.
  else
    $i^* = i'$.
  end if
  $Q_{i^*} \leftarrow Q_{i^*} + 1$
end if
Output Link $\{S\to R_i\}$ is activated for a reception by R_{i^*} or the set of links $\{R_{i^*}\to D_1\}$, $\{R_{i^*}\to D_2\}$ are activated for a NOMA transmission by R_{i^*}.

B. Delay and diversity aware NOMA (DDA-NOMA)

The second selection algorithm aims to avoid the instances of full or empty buffers at the relays, thus increasing the diversity at the cost of additional delay. The DDA-NOMA link selection algorithm for a single time-slot is summarized in Algorithm 2.

Algorithm 2 The DDA-NOMA link selection algorithm

input $\mathcal{F}_{SR}$, $\mathcal{F}_{RD}$
if $\mathcal{F}_{SR} = \emptyset$ **then**
  $i = \arg\max_{i\in\mathcal{F}_{RD}} Q_i$ ($\{R\to D\}$ link)
else
  $\widetilde{\mathcal{F}}_{SR} \triangleq \{i : i \in \mathcal{F}_{SR}, Q_i \leq 1\}$
  if $\widetilde{\mathcal{F}}_{SR} \neq \emptyset$ **then**
    $i = \arg\min_{i\in\widetilde{\mathcal{F}}_{SR}} Q_i$ ($\{S\to R\}$ link)
  else
    $\widetilde{\mathcal{F}}_{RD} \triangleq \{i : i \in \mathcal{F}_{RD}, Q_i \geq 2\}$
    if $\widetilde{\mathcal{F}}_{RD} \neq \emptyset$ **then**
      $i = \arg\max_{i\in\widetilde{\mathcal{F}}_{RD}} Q_i$ ($\{R\to D\}$ link)
    else
      $\hat{\mathcal{F}}_{SR} \triangleq \{i : i \in \mathcal{F}_{SR}, Q_i \geq 2\}$
      $i = \arg\min_{i\in\hat{\mathcal{F}}_{SR}} Q_i$ ($\{S\to R\}$ link)
    end if
  end if
end if
Output Link $\{S\to R_i\}$ is activated for a reception by R_i or the set of links $\{R_i\to D_1\}$, $\{R_i\to D_2\}$ are activated for a NOMA transmission by R_i.

DDA-NOMA selects a relay for transmission or reception based on the number of packets residing in its buffer. More specifically, if a relay is at the verge of starvation and can transmit it will not be selected for a $\{R \to D\}$ transmission if another relay is capable of transmitting without being empty afterwards. Equivalently, if a relay is close to being full and another relay has less packets in its buffers and can receive a packet from the source, it will be selected to maintain the diversity of the $\{S \to R\}$ link in the next time-slot.

V. Numerical Results

Next, performance evaluation results are given for DA-NOMA and DDA-NOMA. The topology consists of a two-hop network with two users and the number of available relays varies ($K = 2, 3, 4$) while $L = 10$. To provide additional insight on the performance of the two selection algorithms, the possibility of asymmetric links (independent non identically distributed - i.n.i.d,) is considered. In this case, the asymmetry is defined as $\sigma^2_{SR} = 2\sigma^2_{RD}$ or $\sigma^2_{RD} = 2\sigma^2_{SR}$. The required rate by each user is $r_0 = 1$ bps/Hz and outages occur according to eq. (2) and eq. (10). Furthermore, the DA and DDA cases of OMA have been included in the outage comparisons. For OMA, a Time-Division Multiple Access (TDMA) scheme is considered where the first user is served at the odd time-slots and the second user is served at the even time-slots. For fair comparison, a successful OMA transmission occurs when both users are not in outage.

A. Outage probability

The outage probability for the three network topologies, for $K = 4$ is illustrated in Fig. 2. For all cases, DDA-NOMA reduces the outage probability compared to DA-NOMA by avoiding empty and full buffers. Moreover, the symmetric case exhibits the lowest outage probability since buffers are more stable compared to the asymmetric cases. The asymmetric case where $\{S \to R\}$ links are stronger has almost identical performance for both algorithms. Also, until medium SNR values, it exhibits increased outages. Since $\{R \to D\}$ links are weak, the chances for successful NOMA transmissions are low. Nonetheless, for high SNR, buffers become stable since DA-NOMA prioritizes $\{R \to D\}$ transmissions, while DDA-NOMA avoids buffer overflow and underflow. In addition, $\{R \to D\}$ outages are reduced and NOMA transmissions can be performed. The case where $\{R \to D\}$ links are stronger provides the worst outage performance, as the probability of achieving an $\{S \to R\}$ rate of $2r_0$ is reduced and buffers tend to be empty. More importantly, NOMA is superior to OMA as the value of the power coefficient α considers the instantaneous channel quality of both users, efficiently allocating the power to each signal.

After, Fig. 3 depicts the outage probability for a symmetric topology and a varying number of available relays. It is evident that as K increases, the diversity of the network increases and the chances of satisfying the $\{S \to R\}$ rate of $2r_0$ and the NOMA transmission increase. Moreover, for $r_0 = 1$, the transition from $K = 2$ to $K = 3$ offers increased gain compared to the transition from $K = 3$ to $K = 4$.

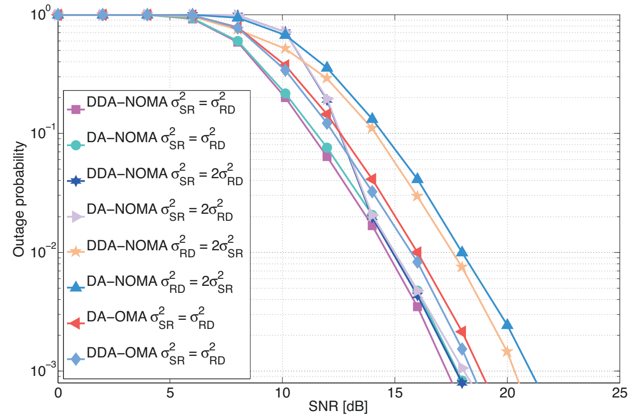

Fig. 2. Outage probability for $K = 4$, $L = 10$ and various topologies.

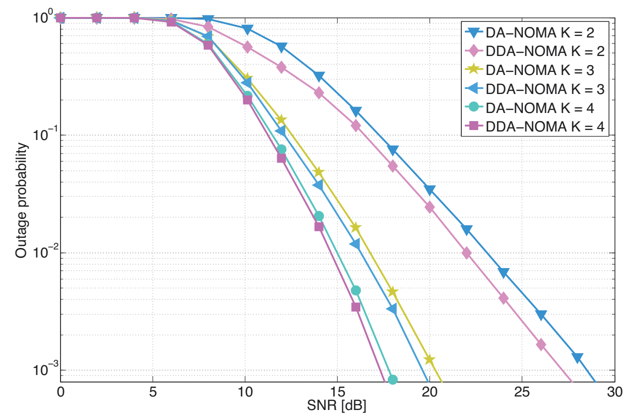

Fig. 3. Outage probability for varying K.

B. Average throughput

Fig. 4 shows the average throughput performance for a symmetric topology and different K. The throughput performance shows that DA-NOMA outperforms DDA-NOMA for all cases. The prioritization of $\{R \to D\}$ transmission reduces the diversity but results in increased packet delivery for medium SNR values. This observation follows the outage probability results where the two algorithms have identical performance for low and medium SNR. Thus, for such cases, DA-NOMA benefits $\{R \to D\}$ transmissions and improves the average throughput. Finally, for higher SNR values, both algorithms provide a stable throughput of $2r_0$ for the NOMA transmission, and thus, each user achieves the desired rate.

C. Average delay

Next, Fig. 5 depicts the average delay performance for a symmetric topology with varying K. The behavior of the algorithms follows that of the average throughput providing a trade-off between performance and robustness. DA-NOMA achieves lower delay than DDA-NOMA and as the number of relays increase, outages and excessive delays are avoided. Similarly, DDA-NOMA is characterized by reduced delay with increasing K. Contrary to single user transmissions, NOMA transmission achieves reduced delay as additional relays are

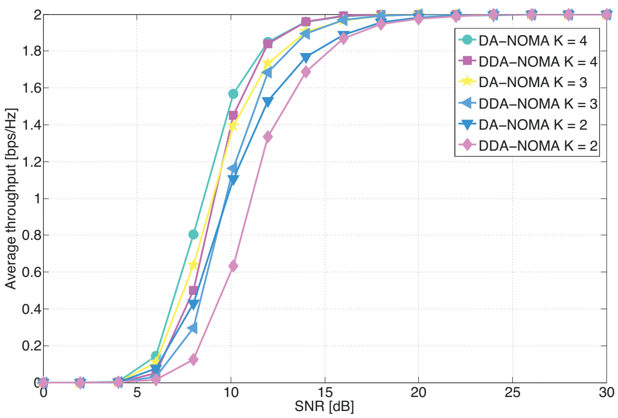

Fig. 4. Average throughput performance for varying K.

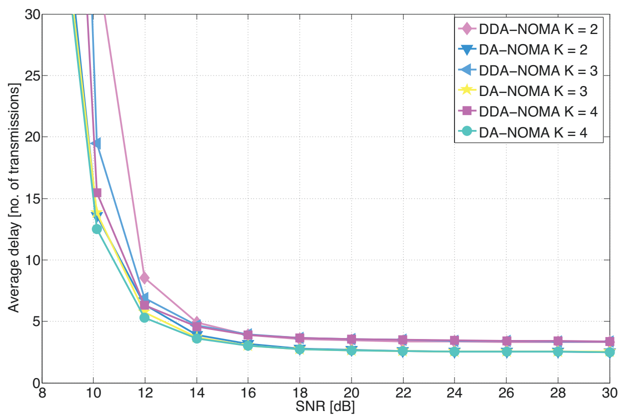

Fig. 5. Average delay performance for varying K.

added to the network. Finally, both algorithms offer a stable delay performance for high SNR independently of K, as it is shown in [19] for the delay-aware and diversity-aware $\max - \text{link}$ algorithms.

VI. Conclusions and Future Directions

In this paper, a two-hop topology where two users communicate with a source through NOMA was examined. Also, the process of determining the power allocation coefficient α was presented. Then, two relay selection algorithms were proposed aiming to reduce the average delay without sacrificing the diversity of the network. Finally, performance evaluation for asymmetric topologies and varying relay number showed that DA-NOMA provides superior average throughput and delay performance, while DDA-NOMA offers reduced outages.

Possible future directions consist of developing selection algorithms, aiming to maximize the throughput of the network and the consideration of BA full-duplex relaying. Also, a scheme based on OMA when NOMA transmission is infeasible may improve the performance, as at least one destination will receive its packet, thus avoiding a complete outage.

References

[1] L. Lei, D. Yuan, C. K. Ho and S. Sun, "Power and channel allocation for non-orthogonal multiple access in 5G systems: Tractability and computation," in *IEEE Trans. on Wireless Commun.*, vol. 15, no. 12, pp. 8580-8594, Dec. 2016.

[2] H. Haci, H. Zhu and J. Wang, "Performance of on-orthogonal multiple access with a novel asynchronous interference cancellation technique," in *IEEE Trans. on Commun.*, vol. 65, no. 3, pp. 1319-1335, March 2017.

[3] S. M. R. Islam, N. Avazov, O. A. Dobre and K. S. Kwak, "Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges," *IEEE Commun. Sur & Tut.*, 2016.

[4] P. D. Diamantoulakis, K. N. Pappi, Z. Ding and G. K. Karagiannidis, "Wireless-powered communications with non-orthogonal multiple access," in *IEEE Trans. on Wireless Commun.*, vol. 15, no. 12, pp. 8422-8436, Dec. 2016.

[5] K. Loa, C. C. Wu, S. T. Sheu, Y. Yuan, M. Chion, . Huo and L. Xu, "IMT-advanced relay standards [WiMAX/LTE Update]," in *IEEE Commun. Mag*, vol. 48, no. 8, pp. 40-48, August 2010.

[6] C. Hoymann, W. Chen, J. Montojo, A. Golitschek, C. Koutsimanis and X. Shen, "Relaying operation in 3GPP LTE: challenges and solutions," in *IEEE Commun. Mag.*, vol. 50, no. 2, pp. 156-162, Feb. 2012.

[7] S. Y. Lien, C. C. Chien, F. M. Tseng and T. C. Ho, "3GPP device-to-device communications for beyond 4G cellular networks," in *IEEE Commun. Mag.*, vol. 54, no. 3, pp. 29-35, March 2016.

[8] Z. Ding, M. Peng and H. V. Poor, "Cooperative non-orthogonal multiple access in 5G systems," in *IEEE Commun. Lett*, vol. 19, no. 8, pp. 1462-1465, Aug. 2015.

[9] J. Men and J. Ge, "Performance analysis of non-orthogonal multiple access in downlink cooperative network," in *IET Commun.*, vol. 9, no. 18, pp. 2267–2273, Dec. 2015.

[10] J. So and Y. Sung, "Improving non-orthogonal multiple access by forming relaying broadcast channels," in *IEEE Commun. Lett.*, vol. 20, no. 9, pp. 1816–1819, Sept. 2016.

[11] C. Zhong and Z. Zhang, "Non-orthogonal multiple access with cooperative full-duplex relaying," in *IEEE Commun. Lett.*, vol. 20, no. 12, pp. 2478–2481, Dec. 2016.

[12] Z. Ding, H. Dai and H. V. Poor, "Relay selection for cooperative NOMA," in *IEEE Wireless Commun. Lett.*, vol. 5, no. 4, pp. 416–419, Aug. 2016.

[13] S. Lee, D. Benevides da Costa and T. Q. Duong, "Outage probability of non-orthogonal multiple access schemes with partial relay selection," presented at *IEEE Int. Symp. on Pers., Ind., and Mob. Radio Commun. (PIMRC)*, pp. 1–6, Dec. 2016.

[14] N. Nomikos, T. Charalambous, I. Krikidis, D. N. Skoutas, D. Vouyioukas, M. Johansson, C. Skianis, "A survey on buffer-aided relay selection," in *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1073–1097, Secondquarter 2016.

[15] A. Ikhlef, D. S. Michalopoulos and R. Schober, "Max-max relay selection for relays with buffers," *IEEE Trans. Wireless Commun.*, vol. 11, pp. 1124–1135, March 2012.

[16] I. Krikidis, T. Charalambous and J. S. Thompson, "Buffer-aided relay selection for cooperative diversity systems without delay constraints," in *IEEE Trans. Wireless Commun.*, vol. 11, pp. 1957–1967, May 2012.

[17] D. Poulimeneas, T. Charalambous, N. Nomikos, I. Krikidis, D. Vouyioukas and M. Johansson, "A delay-aware hybrid relay selection policy," *Int. Conf. on Telecommun. (ICT)*, May 2016.

[18] Z. Tian, Y. Gong, G. Chen and J. Chambers, "Buffer-aided relay selection with reduced packet delay in cooperative networks," in *IEEE Trans on Vehic. Tech.*, vol. PP, no. 99, pp. 1–1, May 2016.

[19] D. Poulimeneas, T. Charalambous, N. Nomikos, I. Krikidis, D. Vouyioukas and M. Johansson, "Delay- and diversity-aware buffer-aided relay selection policies in cooperative networks," *IEEE Wireless Commun. and Net. Conf. (WCNC)*, April 2016.

[20] S. Luo and K. C. Teh, "Buffer state based relay selection for buffer-aided cooperative relaying systems," in *IEEE Trans. on Wireless Commun.*, vol. 14, no. 10, pp. 5430–5439, Oct. 2015.

[21] S. Luo and K. C. Teh, "Adaptive transmission for cooperative NOMA system with buffer-aided relaying," in *IEEE Commun. Lett.*, vol. 21, no. 4, pp. 937–940, April 2017.

[22] Q. Zhang, Z. Liang, Q. Li and J. Qin, "Buffer-aided non-orthogonal multiple access relaying systems in Rayleigh fading channels," in *IEEE Trans. on Commun.*, vol. 65, no. 1, pp. 95–106, Jan. 2017.