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Integrating Broadcasting and NOMA in Full-Duplex Buffer-Aided Opportunistic Relay Networks

Nikolaos Nomikos, *Member, IEEE*, Themistoklis Charalambous, *Member, IEEE*, Demosthenes Vouyioukas, *Senior Member, IEEE*, Risto Wichman, *Member, IEEE*, and George K. Karagiannidis, *Fellow, IEEE*

***Abstract*—This paper proposes the integration of non-orthogonal multiple access (NOMA) and broadcasting with buffer-aided (BA) full-duplex (FD) relaying to improve the spectral efficiency of a single-source two-user network. Furthermore, opportunistic relay selection is employed, activating one or two FD relays to support the end-to-end communication. The network performance is improved through buffers, allowing to switch to half-duplex (HD) transmission/reception when FD operation is not feasible. A hybrid BA FD/HD NOMA relay selection algorithm is proposed, herein called $\mathrm{BAHyNOMA}$, orchestrating the three aforementioned techniques, towards a simple yet efficient and robust relay selection. $\mathrm{BAHyNOMA}$ is evaluated in terms of outage probability, average sum-rate and average delay, and it is observed that the average sum-rate can be doubled, while maintaining low latency.**

***Index Terms*—Non-orthogonal multiple access, full-duplex, buffer-aided relaying, broadcasting, relay selection.**

I. INTRODUCTION

An important technique to improve the quality of wireless transmissions is cooperative relaying. The seminal work of [1] spurred a flurry of research, resulting in novel techniques, such as opportunistic relay selection (ORS) [2] and buffer-aided (BA) relaying (see, e.g., [3], [4] and references therein). Various BA–ORS schemes were proposed [5]–[7] for increased diversity. Recently, broadcasting in the source-relay ($\{S \to R\}$) links for BA–ORS was proposed in [8], increasing the number of packets at the relays and reducing the delay. In [9], broadcasting led to low–complexity (LoCo) selection with asymmetric links, outdated CSI, and feedback errors.

In order to improve the spectral efficiency, non-orthogonal multiple access (NOMA) has been deployed, where users share the same wireless resources, exploiting channel quality differences [10]. A survey of novel cooperation techniques integrating NOMA, was given in [11]. Thus, relaying and NOMA have been jointly studied in various works. So and Sung in [12] studied user cooperation, where a user performed FD relaying, forming a relay broadcast channel with network coding, improving the achievable rate region. Also, the study in [13] used a dedicated FD relay in a two-user network. Compared to HD, FD operation improved the ergodic sum capacity for low-to-medium signal-to-noise ratio (SNR), even with residual self-interference (SI). Then, ORS with NOMA was studied in [14], developing two-stage ORS and improving the diversity, compared to conventional $\max-\min$ ORS.

More recently, NOMA and BA relays were combined in [15] where Luo and Teh proposed adaptive mode selection in a single relay network, switching between NOMA and OMA. Compared to OMA with BA relays and NOMA without BA relays, using this method, the sum-throughput was increased. Then, Zhang *et al.* in [16] proposed adaptive link selection for scenarios with full CSI at the transmitter (CSIT) and no CSIT in the relay-destination ($\{R \to D\}$) links. The results showed that a diversity gain equal to two can be achieved for buffer sizes larger than two. Finally, Nomikos *et al.* in [17] developed BA–ORS algorithms integrating broadcasting in the $\{S \to R\}$ link and combining NOMA with OMA for robustness against outages, increasing the average sum-rate and reducing the delay. Furthermore, Nomikos *et al.* in [7] combined HD and FD BA relays with the objective of minimizing the power expenditure. Relay selection among HD and FD operation is decided at the beginning of a transmission frame, consisting of multiple time-slots, by relying on statistical CSI only.

Until now, NOMA and FD have been jointly studied in BA relay networks, as is the case with NOMA and broadcasting. Still, the integration of NOMA, FD and broadcasting in BA ORS has yet to be investigated. So, this work aims to bridge this gap, proposing a BA hybrid FD/HD NOMA ORS algorithm ($\mathrm{BAHyNOMA}$), which has the following features:

i) $\{S \to R\}$ broadcasting allows more than one relays to receive the users' signals and CSI overheads are reduced. Additionally, broadcasting when relays have more than one antenna, not only increases the degrees of freedom of ORS, but also allows for combining techniques in which the signals are combined to maximize the received Signal-to-Interference-and-Noise (SINR) ratio;
ii) BA relays store packets and forward them at a later instant, when FD transmission is not deployed, enabling the $\mathrm{BAHyNOMA}$ to seamlessly switch between FD and HD operation, exploiting instantaneous CSI;
iii) NOMA takes place from the relays to the destinations, considering the users' CSI and the required data rate;
iv) distributed coordination using timers is adopted, avoiding the shortcomings of centralized network coordination and reducing communication and computational complexity.

Our scheme, $\mathrm{BAHyNOMA}$, was evaluated and was found to achieve twice the average sum-rate compared to HD NOMA and OMA with, additionally, low packet delay.

N. Nomikos and D. Vouyioukas are with the Department of Information and Communication Systems Engineering, University of the Aegean, Samos, Greece. *Emails:* `{nnomikos,dvouyiou}@aegean.gr`.

T. Charalambous and R. Wichman are with the School of Electrical Engineering, Aalto University, Finland. *Emails:* `name.surname@aalto.fi`.

G. K. Karagiannidis is with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece. *Email:* `geokarag@auth.gr`.

II. SYSTEM MODEL AND PRELIMINA

A two-hop network consisting of a source,
nations, D_1 and D_2, and a cluster $\mathcal{C}$ of K FD
forward (DF) relays $R_k \in \mathcal{C}$ ($k \in \{1, \dots, K\}$)
and depicted in Fig. 1. Due to severe fading, c
is only established via the relays. Each R_k is e
a buffer of size L, where L denotes the maxi
of packets that can be stored. The number of pa
buffer is denoted by Q_k. Here, a relay either tra
D_1, D_2 or is in outage and equal buffer allocati
i.e., the same amount of packets for D_1 and D_2

Time is divided into "frames" of one pa
(e.g., fixed-size packets). At any arbitrary time
the link $\{i \to j\}$, the channel coefficient h_{ij} i
statistically independent complex normal rand
with zero mean, and variance σ_{ij}^2, i.e., $h_{ij} \sim \mathcal{C}$
envelope of the channel coefficients is Rayleig
i.e., $|h_{ij}| \sim \text{Rayleigh}(\sigma_{ij})$. The channel gains g_{ij}
therefore, exponentially distributed, i.e., $g_{ij} \sim \text{Exp}(\sigma_{ij}^2/2)$.

A saturated source is assumed and the information rate, r_i, for successful reception at each D_i is fixed and may differ, depending on the application. So, a transmission from a transmitter i to a receiver j is successful, if the SNR Γ_{ij} at the receiver is greater than or equal to the *capture ratio* γ_j. The thermal noise variance at R_k is denoted by σ_k^2, assumed to be AWGN. At each time-slot, S and/or one of the relays R_k transmits a packet, using a fixed power level P_i, $i \in \{S, R_1, \dots, R_K\}$. As FD relaying is supported, SI exists and $h_{R_kR_k}$ denotes the instantaneous residual SI between the two antennas of relay R_k, following a complex Gaussian distribution and taking values in the range $(0, \sigma_{R_kR_k}^2)$. Retransmissions are based on an Acknowledgements/Negative-Acknowledgements (ACKs/NACKs), where receivers broadcast short-length error-free packets over a separate narrow-band channel.

A link is *feasible* if it is not in outage and fulfills the queue conditions (i.e., for non-full buffers in $\{S \to R\}$ links and for non-empty buffers in $\{R \to D\}$ links). Set $\mathcal{F}_{SR}$ contains the relays with feasible $\{S \to R\}$ links and $\mathcal{F}_{SR}^{\text{tx}}$ contains the relays with feasible $\{S \to R\}$ links when R_{tx} is transmitting to the destinations (causing inter-relay interference (IRI)). Sets $\mathcal{F}_{RD_1}$ and $\mathcal{F}_{RD_2}$ contain the relays with feasible $\{R \to D_1\}$ and $\{R \to D_2\}$ links, respectively. Set $\mathcal{F}_{RD}$ contains the relays that can transmit to both D_1, D_2, simultaneously.

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

In general, D_1 and D_2 might demand a different rate r_ℓ, $\ell \in \{1, 2\}$, and to avoid buffer overflow/underflow, S transmits with rate $r_1 + r_2$ [16]. Since the $K-1$ relays not transmitting simultaneously with the source have two available antennas for reception it is better to implement an optimum combiner (OC) [18], which combines the diversity branches and maximizes the SINR, allowing for better performance than other techniques, such as maximal-ratio combining (MRC) [19]. The received signal vector $\mathbf{y}_{R_k}$ at relay R_k is given by

$$\mathbf{y}_{R_k} = \mathbf{h}_{SR_k}\sqrt{P_S}x_S + \mathbf{h}_{R_jR_k}\sqrt{P_{R_j}}x + \boldsymbol{\eta}_{R_k},$$

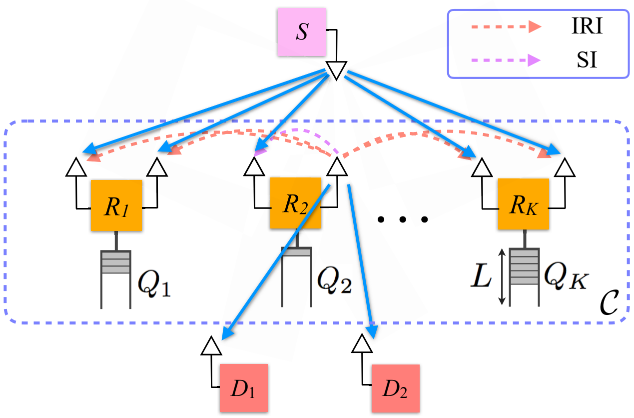


Fig. 1. A buffer-aided full-duplex NOMA relay network.

where x_S is the signal transmitted by the source and x is the signal transmitted by the interfering relay R_j. The vector $\mathbf{h}_{i\ell}$ corresponds to the fading coefficients of the links connecting the transmitter i to the antennas of ℓ. Note that the antennas are assumed to be placed distantly enough such that the fading at each antenna is independent from others, i.e., $\mathbb{E}\left\{\mathbf{h}_{i\ell}\mathbf{h}_{i\ell}^H\right\} = I$. Note that if the transmitting relay is also receiving, then $j = k$ and, as expected, only one antenna is available for receiving. Hence, the SINR is given by

$$\Gamma_{SR_j} \triangleq \frac{g_{SR_j}P_S}{g_{R_jR_j}P_{R_j} + \sigma_j^2} \geq \gamma_0 \triangleq 2^{r_1+r_2} - 1, \ j \in \mathcal{F}_{RD}.$$

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

If a relay R_j is selected, the information symbols of D_1 and D_2 are superimposed and NOMA is performed. Thus, the superimposed information symbol consisting of the symbols x_1 and x_2 of each destination, is defined as $x = \sqrt{\alpha_j}x_1 + \sqrt{1-\alpha_j}x_2$ with $\mathbb{E}[|x_1^2|] = \mathbb{E}[|x_2^2|] = 1$ and $0 \leq \alpha_j \leq 1$. Then, D_1 will receive an information symbol y_1 containing the desired symbol, as well as the symbol of D_2, i.e.,

$$y_1 = h_{R_jD_1}\sqrt{\alpha_j P_{R_j}}x_1 + h_{R_jD_1}\sqrt{(1-\alpha_j)P_{R_j}}x_2 + \eta_1.$$

Similarly, the received information symbol y_2 at D_2 is

$$y_2 = h_{R_jD_2}\sqrt{\alpha_j P_{R_j}}x_1 + h_{R_jD_2}\sqrt{(1-\alpha_j)P_{R_j}}x_2 + \eta_2,$$

where η_1 and η_2 denote the AWGN at each destination. Since full CSIT is available at the relay, the power allocation coefficient α can be calculated in each time-slot. The value of α is chosen to ensure that the x_1 and x_2 are decoded successfully. For example, for decoding x_2 at both destinations,

$$\Gamma_{R_jD_\ell}(P_{R_j}) = \frac{(1-\alpha_j)P_{R_j}g_{R_jD_\ell}}{\alpha_j P_{R_j}g_{R_jD_\ell} + \sigma_{D_\ell}^2} \geq \gamma_\ell, \quad \ell \in \{1, 2\}, \quad (1)$$

where $\gamma_\ell \equiv 2^{r_\ell} - 1$. Once x_2 is successfully decoded, x_1 can be decoded interference-free at destination D_1 according to

$$\Gamma_{R_jD_1}(P_{R_j}) = \frac{\alpha_j P_{R_j}g_{R_jD_1}}{\sigma_{D_1}^2} \geq \gamma_1. \quad (2)$$

III. BAHyNOMA: BUFFER-AIDED H
FULL-DUPLEX/HALF-DUPLEX NOMA S

At each time frame, BAHyNOMA is com
following steps:
Step 1: After both destinations broadcast a pi
R_j, assuming reciprocity of the channel [26], fi
its $\{R\to D\}$ link with each of the destinations. T
a power allocation factor α_j for NOMA trar
§ II-B). After the calculation of α_j is finished
(i.e., $\mathcal{F}_{RD}$ is a non-empty set), a relay R_j, i
selected to be the transmitting relay R_{tx}, with
queue length (if more than one relays are in
same maximum queue size, one is chosen at
procedure can be implemented in a fully distr
with the use of timers [25]: each relay R_j comp
the channel by starting a timer whose value i
to $(Q_j + 1 + \nu_j)^{-1}$, where ν_j is uniformly
$(-0.5, 0.5)$. As a result, the relay whose timer has the *maximum* buffer size expires first. If more than one relays have the same size, random variable ν_j guarantees different expiration times. So, a flag packet is transmitted by the relay with the largest buffer, notifying the other relays to remain silent, as all the relays are in listening mode during that time. When the flag packet or forwarding information of another relay is sensed by the other relays, they back off. Note that, if $\mathcal{F}_{RD} = \emptyset$, no relay is chosen for transmission.

Step 2: Source S broadcasts the combined signals for D_1 and D_2 with a rate $r = r_1 + r_2$, while the transmitting relay R_j (if there is a feasible one) simultaneously transmits with one of its antennas to the destinations, leading to FD operation, whenever S and R_j are activated at the same time. All the remaining $K-1$ relays use both of their antennas for receiving the packets broadcasted by the source, thus increasing the number of receiving antennas per relay and, by adopting OC (in which the signals received through the multiple antennas are combined), the SINR is maximized. Relays belonging in $\mathcal{F}_{SR}^{\text{tx}}$ receive the source's signal.

Step 3: Once the destinations receive the packets from the transmitting relay R_{tx} and the broadcasting from the source is over, each of them in turn broadcasts an ACK that includes the identity (ID) of the packet received, so that the relays that have stored the same packets in their buffers (due to the source broadcasting) discard them before the beginning of the next time frame, to avoid retransmitting the same packets unnecessarily and clogging up their buffers with obsolete packets. Note that in imperfect conditions where the ACKs are not received by some relays, the overall performance of the network will degrade.

The operation of BAHyNOMA in the duration of a time frame is depicted at Fig. 2.

The procedure followed by each relay R_j in each time frame is given in Algorithm 1.

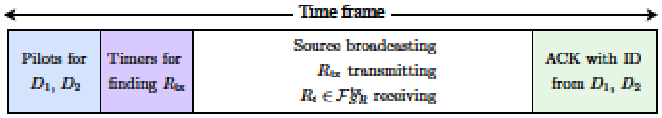


Fig. 2. Operation of BAHyNOMA during a time frame. The first two parts (called slots herein) take place in Step 1; the source broadcasting, the relay transmitting and the receiving from the relays take place in Step 2 (slot 3); finally, the ACK broadcast from the destinations take place in Step 3 (slot 4).

Algorithm 1 Distributed BAHyNOMA for each relay R_j

```
input $Q_j$, $\nu_j$
Slot 1:
listen to the pilots from $D_1$ and $D_2$
use channel reciprocity for acquiring CSI for $\{R_j \to D_1\}$ and $\{R_j \to D_2\}$ links
Selects $\alpha_j$ for NOMA transmission (see (14))
Slot 2:
if $R_j \in \mathcal{F}_{RD}$ then
    claim transmission using timers, based on the queue size $Q_j$ [25]
end if
Slot 3:
if $R_j$ is selected for transmission then
    a) use one antenna for reception
    b) use the other antenna to transmit to destinations
else
    use both antennas for reception adopting OC
end if
Slot 4:
discard packets from the buffer based on the ACKs from destinations (if $R_j \neq R_{\text{tx}}$)
output Number and IDs of packets in the buffer
```

IV. THEORETICAL ANALYSIS

A. *Outage probability*

The outage probability for each time frame is defined as the probability that no relays can be selected for transmission or reception; analytically, this can be expressed as follows:

$$p_{\text{out}} = \mathbb{P}\Big\{\{\Gamma_{SR_i} < \gamma_0 \ \forall R_i : Q_i \neq L\} \bigcap \{\Gamma_{R_j D_\ell} < \gamma_\ell \text{ for any of } \ell \in \{1,2\} \ \forall R_j : Q_j \neq 0\}\Big\}. \tag{3}$$

The probability of outage ($\Gamma_{SR_j} < \gamma_0$) of the $\{S\to R_j\}$ link, provided the same relay is transmitting, is given by [7]

$$p_{\text{out}\{S\to R_j|R_j\}} = 1 - \frac{P_S \lambda_{jj}}{P_S \lambda_{jj} + \gamma_0 P_{R_j} \mu_j} \exp\left(-\mu_j \frac{\gamma_0 \sigma_j^2}{P_S}\right), \tag{4}$$

where $\mu_j, \lambda_{jj} > 0 \, \forall j \in \{1, \ldots, K\}$ are obtained from $g_{SR_j} \sim \text{Exp}(\mu_j)$ and $g_{R_j R_j} \sim \text{Exp}(\lambda_{jj})$, where $\mu_j = \sigma_{SR_j}^{-1}/2$ and $\lambda_{jj} = \sigma_{R_j R_j}^{-1}/2$. Since the SI channel gain is assumed known, interference cancellation takes place in FD relays and, hence, the residual SI gain $g_{R_j R_j}$ can be considered to be a lot smaller than the IRI channel gain $g_{R_j R_i}$, $i \neq j$. When there are FD transmissions (and the residual SI is negligible or the transmitting relay is causing no/negligible interference to the receiving relay) or there is no transmission from the relay but still one antenna is used for reception, the distribution simplifies to an exponential distribution, corresponding to the case where $\lambda_{jj} \to \infty$ (not used within this paper), i.e.,

$$p_{\text{out}\{S\to R_j|R_j\}} \equiv p_{\text{out}\{S\to R_j\}} = 1 - \exp\Big(-\mu_j \frac{\gamma_0\sigma_j^2}{P_S}\Big). \quad (5)$$

In case the receiving and transmitting relays differ, it is possible to implement OC with 2 receiving antennas. So, the outage probability ($\Gamma_{SR_i} < \gamma_0$) of the $\{S\to R_i\}$ link, provided that the transmitting relay is R_j, $j \neq i$, is given by $p_{\text{out}\{S\to R_i|R_j\}} = \int_0^{\gamma_0} f(\gamma)d\gamma$, where $f(\gamma)$ is the probability density function (pdf) for the SINR distribution (for two receiving antennas and one interferer), given by [20, Eq. (8)]

$$f(\gamma) = \left(1 + \frac{2\bar{P}_{R_j}\left(1+\frac{\bar{P}_{R_j}\gamma}{2\bar{P}_S}\right)}{1+\frac{\bar{P}_{R_j}\gamma}{\bar{P}_S}}\right)\frac{\gamma\exp\left(-\frac{\gamma}{\bar{P}_S}\right)}{\bar{P}_S^2\left(1+\frac{\bar{P}_{R_j}\gamma}{\bar{P}_S}\right)}, \quad (6)$$

where $\bar{P}_S \triangleq P_S/\mu_i\sigma_i^2$ and $\bar{P}_{R_j} \triangleq P_{R_j}/\lambda_{ji}\sigma_i^2$. Hence, the outage probability is equal to its cumulative distribution function (cdf) and it is given by

$$p_{\text{out}\{S\to R_i|R_j\}} = 1 - \frac{(\bar{P}_S + \gamma_0 + \gamma_0\bar{P}_{R_j})\exp\left(-\frac{\gamma_0}{\bar{P}_S}\right)}{(\bar{P}_S + \bar{P}_{R_j}\gamma_0)}. \quad (7)$$

Remark 1. *In case there is no interference, i.e.,* $P_{R_j} = 0$, (6) *becomes* $f(\gamma) = \frac{\gamma\exp\left(-\frac{\gamma}{\bar{P}_S}\right)}{\bar{P}_S^2}$, *which is a second order Erlang distribution. The outage probability* $p_{\text{out}\{S\to R_i|R_j\}}$ *is equivalent to* $p_{\text{out}\{S\to R_i\}}$ *and is equal to its* cdf, *given by [21, Section 1.7.7]*

$$p_{\text{out}\{S\to R_i\}} = 1 - \sum_{n=0}^{1}\left(\mu_i\frac{\gamma_0\sigma_i^2}{P_S}\right)^n \exp\left(-\mu_i\frac{\gamma_0\sigma_i^2}{P_S}\right). \quad (8)$$

Since the source is broadcasting its packets, the probability of at least one link from the source to any relay R_i not being in outage is thus

$$p_s = 1 - \prod_{i\in\mathcal{C}} p_{\text{out}\{S\to R_i|R_j\}}. \quad (9)$$

The probability of the transmitting relay R_j to be in outage is to have at least a packet not transmitted to its intended destination. Suppose, as it is the case in Section II-B, x_2 is decoded first and x_1 second. Then, the probability of success of the packets transmitted to D_2 according to (1) and the pdf given in [7] is

$$p_s(D_2) = \frac{1-\alpha_j}{1-\alpha_j+\gamma_2\alpha_j}\exp\left(-\frac{\nu_{j2}\gamma_2\sigma_2^2}{(1-\alpha_j)P_{R_j}}\right), \quad (10)$$

where $\nu_{j2} > 0\ \forall j \in \{1,\dots,K\}$ are obtained from $g_{R_jD_2} \sim \text{Exp}(\nu_{j2})$. Furthermore, due to NOMA, the probability of success of the packets transmitted to D_1, require the successful reception of the packets transmitted to D_2, in the same way as (10), but for the parameters of D_1 according to (1), i.e.,

$$p_{s_1}(D_1) = \frac{1-\alpha_j}{1-\alpha_j+\gamma_1\alpha_j}\exp\left(-\frac{\nu_{j1}\gamma_1\sigma_1^2}{(1-\alpha_j)P_{R_j}}\right), \quad (11)$$

and, subsequently, the successful reception of x_1, according to (2), i.e.,

$$p_{s_2}(D_1) = \exp\left(-\frac{\nu_{j1}\gamma_1\sigma_1^2}{\alpha_jP_{R_j}}\right). \quad (12)$$

Therefore, the probability of success of the packets transmitted to D_1 is $p_s(D_1) = p_{s_1}(D_1)p_{s_2}(D_1)$. Hence, the outage probability is given by

$$p_{\text{out}\{R_j\to D_\ell\}} = 1 - p_s(D_1)p_s(D_2). \quad (13)$$

The outage probability is a function of α_j. So, α_j can be chosen to minimize the outage probability. In other words, α_j is the outcome of the following optimization problem:

$$\max_{\alpha}\ \exp\left(-\frac{\beta_1}{\alpha}\right)\prod_{i=1}^{2}\frac{1-\alpha}{1-\alpha+\gamma_i\alpha}\exp\left(-\frac{\beta_i}{1-\alpha}\right), \quad (14a)$$

$$\text{s.t. } \alpha \in (0,1), \quad (14b)$$

where $\beta_\ell = \frac{\nu_{j\ell}\gamma_\ell\sigma_\ell^2}{P_{R_j}}$, $\ell \in \{1,2\}$.

Remark 2. *From definition* (3) *for the outage, the overall network is in outage when all links are in outage, i.e.,*

$$p_{\text{out}} = \prod_{j\in\mathcal{C}} p_{\text{out}\{R_j\to D_\ell\}} \prod_{i\in\mathcal{C}} p_{\text{out}\{S\to R_i|R_j\}}$$

Note that the distributed nature of BAHyNOMA *does not allow for evaluating all the combinations before choosing the transmitting relay* R_j *and, as a consequence, the outage probability of* BAHyNOMA *will be higher than a centralized approach with information about the instantaneous CSI of all the available links in the network.*

B. Diversity order

Before deriving the diversity order[1] of BAHyNOMA, we provide Proposition 1, which basically states that if the source and transmitting relay powers, P_S and $P_{R_{\text{tx}}}$ respectively, are large enough (thus not imposing any limitations/constraints), for each feasible (in terms of queue feasibility) pair of relays, R_{rx} (receiving) and R_{tx} (transmitting), then we can find power levels such that interference cancellation conditions are satisfied and the outage probability tends to zero.

Proposition 1 ([9, Proposition 1])**.**
Let $\sup\{P_S\} = \sup\{P_{R_{\text{tx}}}\} = \infty$. *For each pair of relays* R_{rx} *and* R_{tx}, *there exist* P_S *and* $P_{R_{\text{tx}}}$ *such that* $\mathit{SNR}_{R_{\text{tx}}D_\ell} \geq \gamma_\ell$ *and* $\mathit{SINR}_{SR_{\text{rx}}} \geq \gamma_0$.

But even without invoking Proposition 1, we can simply consider the cases in which either the $\{S\to R\}$ link or the $\{R\to D\}$ link experience no interference. As a result, the outage probability of the network (either when there is successive relaying or a single link transmission) is exponentially distributed and, for symmetric i.i.d. channels, is given by

$$p_{\text{out}\{S\to R\}} = \varepsilon^K, \quad (15a)$$

$$p_{\text{out}\{R\to D\}} = \delta^K, \quad (15b)$$

where $\varepsilon \triangleq 1 - \exp(-\beta_0/\phi) - (\beta_0/\phi)\exp(-\beta_0/\phi)$, $\delta \triangleq 1 - a\exp(-\beta_1/\rho)\exp(-\bar{\beta}_1/\rho)\exp(-\beta_2/\rho)$, $a \in (0,1]$, $\beta_0, \beta_1, \bar{\beta}_1, \beta_2$ are constants, and ϕ and ρ are the power levels of the source and transmitting relay, respectively. The

---

[1] The diversity order (or diversity gain), denoted herein by d, is the gain in spatial diversity, used to improve the reliability of a link and it is defined as follows: $d = -\lim_{\text{SNR}\to\infty}\frac{\log\mathbb{P}_{\text{out}}(\text{SNR})}{\log\text{SNR}}$.

system is in outage when all the links are in c
$p_{\text{out}} = \varepsilon^K \delta^K$. Therefore, provided the buffer si
enough, the diversity order of the system is

$$
\begin{aligned}
d &= -\lim_{\phi\to\infty} \frac{\log p_{\text{out}\{S\to R\}}}{\log \phi} - \lim_{\rho\to\infty} \frac{\log p_{\text{out}\{R\to D\}}}{\log \rho} \\
&= -K\Big[\lim_{\phi\to\infty} \frac{\log\left(1-\exp\left(-\beta_0/\phi\right) - \left(\beta_0/\phi\right)\exp\right.}{\log \phi} \\
&\quad + \lim_{\rho\to\infty} \frac{\log\left(1 - a\exp\left(-\beta_1/\rho\right)\exp\left(-\bar{\beta}_1/\rho\right)\exp\right.}{\log \rho} \\
&\overset{(a)}{\approx} -K \lim_{\sigma\to\infty} \Big[\frac{\log\left(-\beta_0/\sigma\right)^2}{\log \sigma} + \frac{\log\Big(1 - a + \frac{a(\beta_1}{}}{} \\
&\overset{(b)}{=} \begin{cases} 2K, & \text{if } 0 < a < 1, \\ 3K, & \text{if } a = 1, \end{cases}
\end{aligned}
$$

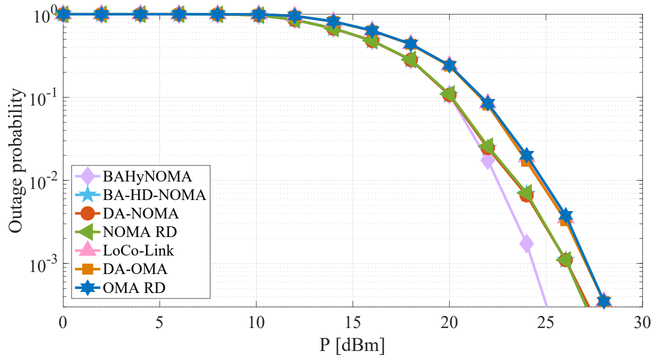
where (a) stems from $1-\exp(-x) \approx x$ (a
Erlang distribution) and (b) from algebraic

V. NUMERICAL RESULT

BAHyNOMA is evaluated for $K = 4$ r
of size of $L = 4$ packets. In the compa
values correspond to the maximum transmi
Also, due to non-ideal SIC, the SI channel c
characterized by $\sigma^2_{R_k R_k} = 10^{-3}\sigma^2_{SR_k}$ [22
noise level is equal to 1 mW and the us
independent non identically distributed (i.n.i
two users require equal rates $r_1 = r_2 =$
channel-use (BPCU) and their channel asy
as $\sigma^2_{SR_k} = \sigma^2_{R_k D_1} = 4\sigma^2_{R_k D_2}$. For a fair c
transmissions are performed with twice the rate, as end-to-end communication demands twice the time-slots of NOMA. With OMA, D_1 is served in odd time-slots and D_2 in even time-slots and outages occur if at two consecutive time-slots all the relays fail to successfully transmit/receive. OMA schemes include LoCo–Link [9], the $\{R\to D\}$ prioritization algorithm of [24] (OMA RD) and the delay-aware (DA) algorithm of [25] (DA–OMA). Furthermore, NOMA versions of the algorithms of [24] (NOMA RD) and [9] (DA–NOMA) are considered. In NOMA, outages occur if at a given time-slot, no relay can transmit/receive. Finally, the hybrid BA–HD–NOMA/OMA of [17] is compared, where if the NOMA transmission fails, a user is selected in the $\{R\to D\}$ link to be served with rate r_D. BA–HD–NOMA/OMA is not included in the outage results, as it cannot be directly compared to NOMA and OMA [16].

In Fig. 3 outage results are given. As D_1 has a stronger $\{R\to D\}$ channel compared to D_2, NOMA exploits this asymmetry through optimal power allocation, outperforming OMA. For low transmit power, NOMA and OMA experience increased outages, while after 15 dBm performance improves. All NOMA schemes offer equal diversity, due to $\{R\to D\}$ prioritization, and the same applies to OMA. For high transmit power, BAHyNOMA reduces the outages, as FD relaying is unaffected by empty buffers.

Fig. 4 depicts the average sum-rate performance. BAHyNOMA can double the average sum-rate for high transmit power, while for medium transmit power, BA–HD–NOMA/OMA offers the best performance, switching to OMA in the $\{R\to D\}$ link, when NOMA fails, and due to its HD operation, SI is avoided. Then, for transmit power values close to 10 dBm, OMA slightly outperforms NOMA, as the interference between the users' signals reduces the probability of successful decoding. However, for higher transmit power, NOMA surpasses OMA, due to appropriate power allocation. Also, in order to provide a clear view on BAHyNOMA's performance, its real average power consumption has been calculated, including for comparison the HD NOMA RD. So, for low transmit power, the two schemes behave similarly and their real power consumption is less than the nominal transmit power of the nodes, because of frequent outages when the transmission is suspended. For higher values, BAHyNOMA's FD capability can be exploited without increased power consumption, by adopting lower maximum transmit power levels than the HD schemes, while achieving higher sum-rate.



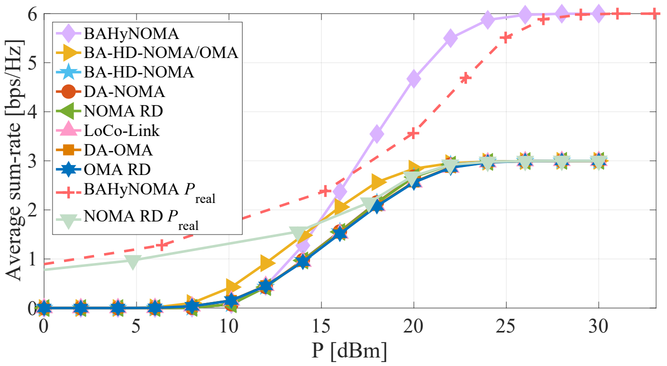


Fig. 4. Average sum-rate for $K = 4$, $L = 4$ and various algorithms.

Then, the average delay performance is shown in Fig. 5. For low transmit power, hybrid BA–HD–NOMA/OMA exhibits reduced delay and any differences are due to OMA switching and channel asymmetry. As transmit power increases, the NOMA schemes reduce the packet delay. Nonetheless, compared to hybrid BA–HD–NOMA/OMA, they transmit less packets. Moreover, BAHyNOMA performs similar to the NOMA schemes, transmitting twice the number of packets for high transmit power, due to FD transmissions. Also, since packets might not stay in the buffers at all, the average delay is reduced to less than one time-slot for high transmit power.

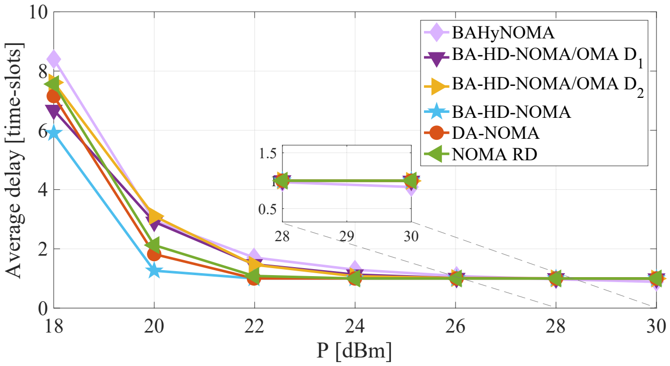


Fig. 5. Average delay for $K = 4$, $L = 4$ and various algorithms.

VI. CONCLUSIONS

In this work, NOMA, BA FD relaying and broadcasting were combined to improve relay selection with low complexity. *NOMA* allowed two users to share the same wireless resources, thus increasing the spectral efficiency of the transmission. *Buffers* enabled the relays to operate in HD mode, when FD was infeasible. Through *broadcasting*, more copies of the same packets are available at the relays' buffers (thus offering increased robustness to the system) and, more importantly, CSIT is not required at the source (thus significantly reducing the implementation complexity). BAHyNOMA was evaluated and was found to achieve twice the average sum-rate compared to HD NOMA and OMA with, additionally, low packet delay.

This work creates a lot of opportunities for the orchestration of NOMA and broadcasting in BA FD networks. Specifically, possible future directions include:

- NOMA/OMA switching can provide performance gains, when the transmission to at least one destination is possible by the relay, thus increasing the sum-rate [17], [27].
- The impact of the direct $\{S\to D\}$ link should be investigated. As it has been shown in BA OMA relay networks, improved diversity can be harvested [28]. However, in NOMA networks, the interference might result in degradation of the SIC's performance at the destinations.

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