Another Perspective on Interference Channels for Non-Orthogonal Multiple Access Communications

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***Abstract*—In this letter, a new perspective on non-orthogonal multiple access (NOMA) is given, relying on the established model of interference channels (IC) from information theory. Establishing links with studies on ICs enables a new framework for the application of NOMA, especially in the context of distributed antenna systems. Thanks to this common framework, a fair and comprehensive evaluation of single antenna NOMA and IC-based NOMA is provided first. Then, a simple transmit coordination scheme, termed *antenna switching*, is proposed to switch the IC scenario from strong to weak IC leading to an increase in the achievable capacity under some system and channel conditions. Finally an application example is provided to show the advantage of the proposed approach that enables to match the type of NOMA to the deployment context according to the desired trade off between system throughput and user fairness.**

***Index Terms*—Distributed antenna systems, non orthogonal multiple access, successive interference cancellation, interference channel, antenna switching.**

I. Introduction

As the demand for high data rates and connected devices continues to rise, paradigm shifts are proposed for the efficient management of the available resources in wireless communication systems. One promising solution resides in non-orthogonal multiple access (NOMA) schemes. NOMA finds its roots in the study of broadcast channels in information theory which consist of a single transmitter sending separate information to multiple receivers. In the early seventies, a proposed coding scheme applying superposition coding (SC) at the transmitter, coupled with successive interference cancellation (SIC) at the receiver, was shown to be optimal [1], [2], i.e. actually achieving system capacity. The SC-SIC scheme was then referred to as NOMA by the wireless communications community following [3], [4] which introduced the SC-SIC scheme as a new multiple access (MA) technique for wireless communications. Since then, academia and industry heavily investigated the subject from different perspectives with system-level simulations [5]–[8], and also more practical aspects such as channel state imperfection and SIC error propagation [9]. The obtained results promote NOMA as the better MA scheme when compared to orthogonal signaling strategies, leading to its adoption since release 14 in the long term evolution (LTE) standard as an efficient component to tackle the capacity demand [10].

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Moreover, system architectures underwent an evolution from the unique central antenna system (CAS) per cell, to distributed antenna systems (DAS) and cloud radio access networks (C-RAN) [11]. Motivated by a denser deployment of antennas in the cell that enhances the link quality and enables higher spatial spectrum reuse, this evolution tries to better cope with the exponential increase in the number of connected devices. However, it raises the question related to the efficient integration of NOMA into such distributed network architectures and the evaluation of its potential benefits. The current work shows how IC is relevant for NOMA application in DAS and proposes a framework for its evaluation. The two main contributions of this letter are as follows:

- We resort to the studies of the two-user interference channels (IC) [12], [13] to propose means for efficient integration of NOMA to DAS where different antennas serve the paired users on a subcarrier. Then, the proposed IC-based NOMA is compared to *classical* or *single antenna* NOMA.
- We propose a simple but effective modification to the two-user IC model, through enabling flexible user-antenna association, resulting in an increased capacity. We also apply this modification directly to the proposed *IC-based* or *distributed* NOMA scheme.

The letter is organized as follows: System model is presented in section II where the concept of distributed NOMA is introduced along with its achievable capacity region. The antenna switching (AS) proposal is detailed in section III and its effects on the IC are analyzed. The achievable capacity regions are provided in section IV and system level simulations are presented in section V, before concluding the paper in section VI.

II. System Model

Classical NOMA denotes a MA scheme where multiple transmissions are allowed over the same time/frequency/space resources. Distributed NOMA represents the case where the signals of the non-orthogonally multiplexed users are powered from distinct antennas. In the following, the case of 2 non-orthogonally multiplexed users on the same resource is considered. In information-theoretic terms, distributed NOMA consists of two sender-receiver pairs forming an interference channel (IC). Hence, the concept of interference channels provides a solid foundation for tackling NOMA in DAS (i.e. distributed NOMA) that is yet to be explored. To set a unique framework for both classical single antenna NOMA and IC-based NOMA, we first start by presenting the network architecture, and then proceed to the description of each of these NOMA variants.

A. Network Architecture

A distributed system architecture consists in deploying multiple antennas or remote radio heads (RRHs) connected to a central baseband unit (BBU) through high capacity optical fibers [14]. The BBU handles medium access control, user scheduling and radio resource management. In this context, the system model for the two-user IC is depicted in Fig. 1 where user $i \in \{1, 2\}$ is served by antenna i whose transmit power is P_i and is subject to a Gaussian noise of variance σ^2. The channel gains between antenna 1 and users 1 and 2 are $h_{1,1}$ and h_b respectively, and the channel gains between antenna 2 and users 1 and 2 are h_a and $h_{2,2}$ respectively.

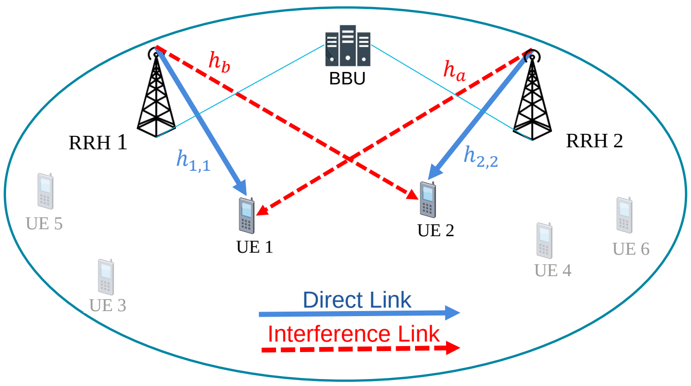


Fig. 1: System Model of the two-user IC setup behaving as NOMA.

In the following, $h_{1,1}$ and $h_{2,2}$ correspond to the direct information links whereas h_a and h_b correspond to the interfering links. The signal-to-noise ratios (SNRs) S_1 and S_2 at the levels of users 1 and 2, and the interference-to-noise ratios (INRs) I_1 and I_2 at the levels of users 1 and 2 are given by:

$$S_1 = P_1 \frac{|h_{1,1}|^2}{\sigma^2}, \qquad S_2 = P_2 \frac{|h_{2,2}|^2}{\sigma^2}, \tag{1}$$

$$I_1 = P_2 \frac{|h_a|^2}{\sigma^2}, \qquad I_2 = P_1 \frac{|h_b|^2}{\sigma^2}. \tag{2}$$

B. Single antenna NOMA

The classical NOMA scheme is obtained by powering down one antenna (e.g. antenna 2) and transmitting the super-imposed signals of users 1 and 2 through antenna 1. Hence P_1 is split into γP_1 and $(1-\gamma)P_1$ to power the signals of users 1 and 2 respectively ($\gamma \in [0, 1]$). Assuming that $|h_{1,1}| > |h_b|$, user 1 is said to be the strong user. Through implementing a SIC receiver, user 1 first detects, demodulates and decodes the signal of user 2 with a power level $(1-\gamma)P_1|h_{1,1}|^2$, and then re-encodes and subtracts it from the superimposed signal to retrieve its own interference-free signal. User 2 is the weak user, treating the interference signal of user 1 (with a received power level $\gamma P_1 |h_b|^2$) as noise while decoding its own signal ($(1-\gamma)P_1|h_b|^2$). With $C(x) = \frac{1}{2}\log_2(1+x)$, the achievable user rates R_1, R_2 by users 1 and 2 are given by:

$$R_1 = C(\gamma S_1), \tag{3}$$

$$R_2 = C(\frac{(1-\gamma)I_2}{\gamma I_2 + 1}). \tag{4}$$

C. IC-based NOMA

By defining $a = I_1/S_2$ and $b = I_2/S_1$ as the channel coefficients of the standard form [15], four different classes of interference channels can be identified according to how a and b compare to unity:

1) Strong IC: $a \geq 1$, $b \geq 1$: In strong interference channels, the interference is such that users start by removing their respective interfering signals through SIC and then proceed to decode their own signals. The communication channel reduces to a compound multiple-access (MAC) channel. Also, in addition to the individual user rate bounds $R_1 \leq C(S_1)$ and $R_2 \leq C(S_2)$ common to all interference classes, the inequality defining the capacity region is given by [16]:

$$R_1 + R_2 \leq \min\{C(S_1 + I_1), C(S_2 + I_2)\}. \tag{5}$$

The strong IC case is the only case for which the capacity is perfectly known for interference channels. For the remaining classes, the best achievable estimate known to date is provided by Han and Kobayashi [12]. The idea resides in splitting the messages of every user into a common part which is to be decoded by both users, and a private part to be decoded only by the intended user. The common and the private messages of every user are then transmitted using superposition coding. Through this scheme, part of the interference can be canceled while the interference relative to the private message part of the other user is treated as noise. This scheme allows for flexibility in the splits of each user's common and private parts, as well as for flexibility in the power allocation and time sharing, resulting in a somewhat difficult region to characterize. However, more recent advances employing generalized degrees of freedom [13] enabled the formulation of upper and lower bounds for the Gaussian IC achievable within half a bit per dimension. Hence, in the following, the bounds of [13] are used to characterize the capacity region of the remaining IC classes.

2) Weak IC: $a < 1$, $b < 1$: The upper and lower bounds for the weak interference channel are given by

$$\begin{aligned} R_1 + R_2 \leq \min\{&C(S_1) + C(\frac{S_2}{1+I_2}), C(S_2) + C(\frac{S_1}{1+I_1}), \\ &C(I_1 + \frac{S_1}{1+I_2}) + C(I_2 + \frac{S_2}{1+I_1})\}, \\ 2R_1 + R_2 \leq\ &C(I_1 + S_1) + C(I_2 + \frac{S_2}{1+I_1}) + C(\frac{S_1 - I_2}{1+I_2}), \\ R_1 + 2R_2 \leq\ &C(I_2 + S_2) + C(I_1 + \frac{S_1}{1+I_2}) + C(\frac{S_2 - I_1}{1+I_1}). \end{aligned} \tag{6}$$

3) Mixed IC, type 1: $b < 1$, $a \geq 1$: For the moderate or mixed interference channel 1, the bounds on the capacity region are as follows:

$$\begin{aligned} &R_1 + R_2 \leq C(S_2) + C(\frac{S_1}{1+I_1}), \\ &R_1 + R_2 \leq C(S_2 + I_2), \\ &R_1 + 2R_2 \leq C(S_1 + I_1) + C(I_2 + \frac{S_2}{1+I_1}) + C(\frac{S_1}{1+I_2}). \end{aligned} \tag{7}$$

4) Mixed IC, type 2: $b \geq 1$, $a < 1$*:* For the moderate or mixed interference channel 2, the bounds on the capacity region are obtained by

$$\begin{aligned} &R_1 + R_2 \leq C(S_1) + C(\frac{S_2}{1+I_2}), \\ &R_1 + R_2 \leq C(S_1 + I_1), \\ &R_1 + 2R_2 \leq C(S_2 + I_2) + C(I_1 + \frac{S_1}{1+I_2}) + C(\frac{S_2}{1+I_1}). \end{aligned} \tag{8}$$

The shapes of the capacity regions for every class of IC are depicted in Fig. 2.

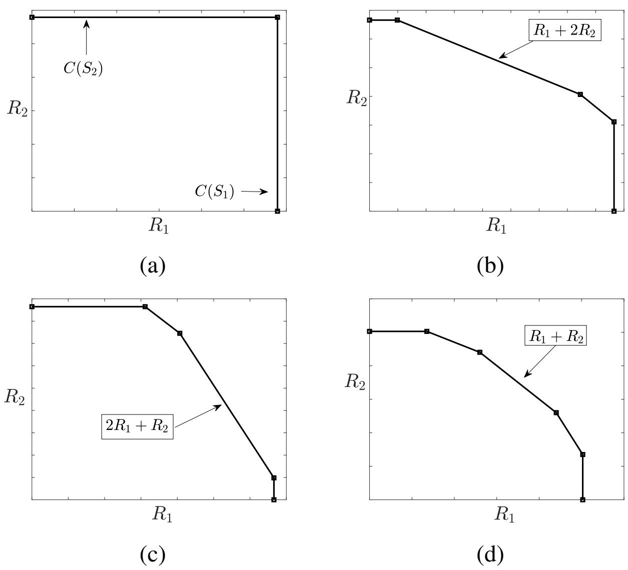


Fig. 2: Schematics of achievable capacity regions for strong IC (a), mixed IC 1 (b), mixed IC 2 (c), and weak IC (d).

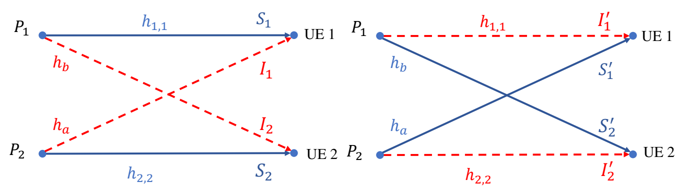
III. Proposed Antenna Switching Scheme

The study of interference channels in information theory assumes no cooperation between transmitters. In a wireless network, this can correspond to two adjacent cells serving independently their respective users on the same time/frequency resource in the uplink or downlink. Assuming a DAS setup within the same cell for the downlink channel as in Fig. 1, coordination between serving antennas becomes possible, altering thereby the interference channel model and leading to a new larger capacity if exploited properly. Out of the many possible levels of coordination between the transmitting antennas – which vary in complexity – one of the simplest coordination schemes is to swap the user-antenna association with potential benefits on system performance. Next, we propose the antenna switching (AS) scheme to aggregate the capacities of the two possible user-association schemes, resulting in an increased achievable capacity from the perspective of MA techniques. The impact of AS on two-user IC is also analyzed.

From an information theoretic perspective, the different associations between the transmitter-receiver pairs of Fig. 1 constitute separate interference channels. In the following, the IC-direct user-antenna association refers to serving user i from antenna i as shown in Fig. 3a, while the IC-switched association refers to the other scenario shown in Fig. 3b. After switching the serving antennas, the interfering signal at the level of user 1 (resp. user 2) originates from antenna 1 (resp. antenna 2) and experiences the newly interfering link $h_{1,1}$ (resp. $h_{2,2}$) while the useful signal is transmitted from antenna 2 (resp. antenna 1), experiencing the newly direct link h_a (resp. h_b). Therefore, the new SNRs and INRs of Fig. 3b ($S_1^{'}, I_1^{'}, S_1^{'}, I_2^{'}$) are obtained from the previous SNRs and INRs of Fig. 3a as follows:

$$\begin{aligned} S_1^{'} = I_1, \quad S_2^{'} = I_2, \\ I_1^{'} = S_1, \quad I_2^{'} = S_2. \end{aligned} \tag{9}$$

Based on these new SNRs and INRs, the interference class of the newly obtained IC may differ from the initial one. If we let $\alpha = I_1^{'}/S_2^{'}$ et $\beta = I_2^{'}/S_1^{'}$ be the standard form channel coefficients of the switched scenario, then we have $\alpha = 1/b$ and $\beta = 1/a$. This means that an initially strong IC yields a weak IC after AS, and similarly, an initially weak IC yields a strong IC after AS.



(a) Direct (b) Switched

Fig. 3: Interference channel for: (a) a direct user-antenna association, (b) a switched user-antenna association.

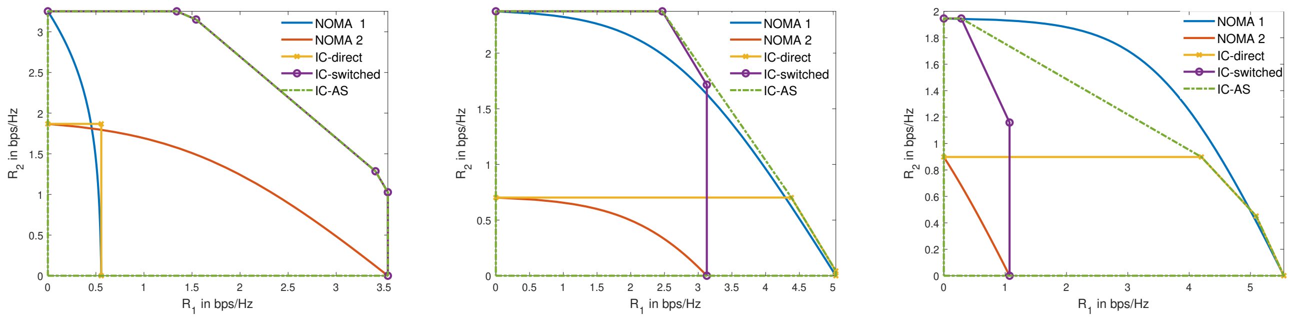
However, for type 1 and type 2 mixed ICs, one can check that the interference class remains unchanged after AS. This being said, the obtained mixed IC still differs significantly from the original one since it has quite different standard form channel coefficients ($\alpha \neq a$ and $\beta \neq b$). In other words, although the IC class is unchanged, the corresponding capacity regions are significantly impacted.

Having determined the interference class of the new IC and the expressions of the SNRs and INRs, the corresponding set of upper and lower bounds ((5), (6), (7) or (8)) is then applied to determine the capacity region of the swapped channel. From herein after, IC-AS designates the aggregation of IC-direct and IC-switched setups through time sharing, which results in its capacity region being the convex hull of the two ICs. Hence, IC-AS presents a larger capacity region than both scenarios. Finally, note that the counterpart of AS in the classical (single antenna) NOMA scheme (NOMA-AS) resides in switching the powering antenna of both superimposed user signals from antenna 1, referred to as NOMA 1, to antenna 2 (NOMA 2) and vice-versa.

IV. Case studies

The first step in comparing classical NOMA to IC-based NOMA with and without AS resides in analyzing the achievable capacity regions for each MA scheme. For that matter, special cases are selected in this section that best depict the properties of AS-enabled IC-based NOMA.

Fig. 4a superposes the capacity region of a strong IC (IC-direct curve) to its weak counterpart after AS (IC-switched), and



(a) (b) (c)

Fig. 4: IC capacity region for: (a) $S_1 = 0.7$ dB, $S_2 = 11$ dB, $I_1 = 21$ dB, $I_2 = 20$ dB, (b) $S_1 = 30$ dB, $S_2 = 2$ dB, $I_1 = 19$ dB, $I_2 = 14$ dB, (c) $S_1 = 33$ dB, $S_2 = 4$ dB, $I_1 = 5$ dB, $I_2 = 11$ dB

to classical NOMA regions when powering the signals from the first antenna (NOMA 1) or the second antenna (NOMA 2). As shown in the figure, the weak IC presents a significant increase in the capacity region compared to the initial strong IC. The interference cancellation capabilities available for the case of strong IC come at the cost of having the interfering signal more powerful than the actual information signal, resulting in a larger capacity region for weak IC. In fact, it can be shown through mathematical manipulations of the corresponding capacity region equations that the achievable sum-capacity of the weak IC (derived from a strong IC) is always larger than the sum-capacity of strong IC and that of NOMA 1 and 2. A more intuitive explanation is that interference avoidance (through treating interference as noise) should be privileged over interference cancellation by systematically adopting the user-antenna setup yielding a weak IC. Note that the underlying reason for resorting to mere comparisons of the capacity regions of different IC classes is that both strong and weak ICs originate from the same physical channel but with different user-antenna setups.

In Fig. 4b, the capacity regions of a mixed IC type 1 is depicted. As opposed to the case of strong IC, the sum-capacity of mixed IC scenarios (type 1 and 2) is not necessarily larger after swapping the antennas serving the users. For the conditions of Fig. 4b, switching the antennas results in a decrease of the sum-capacity from 5.1 bps/Hz to 4.8 bps/Hz. Nonetheless, the achievable capacity region of the aggregated IC-AS is still larger than the original IC thanks to the convex hull operation. Note that the IC-AS capacity region, may include that of classical NOMA, as in Figs. 4a and 4b, or not, as in Fig. 4c. It can therefore be concluded that the potential gains and drawbacks of IC over classical NOMA cannot be merely accounted for by the achievable sum-capacity obtained over a particular time/frequency/space resource. Indeed, other indicators are needed to further assess and quantify their differences in broader MA system level simulations, since they do provide different trade-offs for the resource allocation scheduler compared to the case without AS. Consequently, we propose next to evaluate the classical and distributed NOMA for the proportional fairness (PF) scheduler [17], using the key performance indicators (KPIs) consisting of the achieved total throughput and the Jain fairness index [18] (higher is better with the best case value equal to one).

V. System Level Simulations

A. Proportional Fairness Scheduler

The PF scheduler [17] is selected in this work because it provides a good trade-off between user fairness and total throughput. For NOMA systems, it takes into account the historic user rates to allocate each non-orthogonally multiplexed time/frequency resource or subcarrier to the user pair that maximizes the PF metric given by:

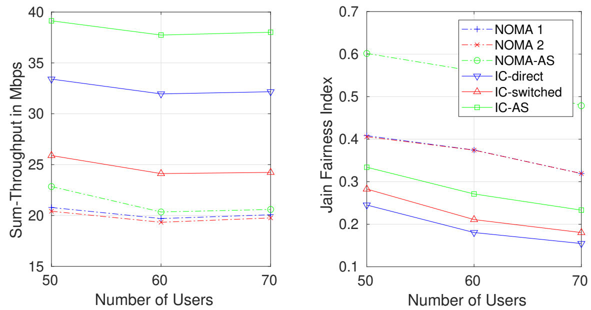
$$U_s = \arg\max_{U} \sum_{k\in U} \frac{R_{k,s}(t)}{T_k(t)}, \tag{10}$$

where U is the set of all possible user pairs, $R_{k,s}(t)$ the throughput that would be achieved by users $k \in U$ if paired on subcarrier s at time slot t, and $T_k(t)$ the historic rate of k at time slot t (i.e. the mean rate of user k until time slot t).

An equal power distribution is applied for inter-subcarrier power allocation for both classical and IC-based NOMA. In classical NOMA, a single antenna is used to transmit the signals of both users over a sub-carrier, therefore the operating point of the capacity region is determined by the intra-subcarrier power allocation. Differently, in IC-based NOMA, each user signal is powered independently from one antenna, hence the operating point of the capacity region is selected through rate allocation. For classical NOMA, the power allocation proposed in [19] that accounts for the user channel gains and their historic rates to maximize the PF metric is adopted. Therefore, the proposed rate allocation for IC-based NOMA follows the same idea by selecting the corner point of the capacity region maximizing the PF metric.

B. Simulation Results

The system depicted in Fig. 1 is applied in a single circular cell of radius 500 m. The two RRHs are deployed in a diametrically opposed manner, 250 m away from the cell-center, with 1 W of total transmit power each. For NOMA 1 and 2, the other antenna is switched off and the active antenna power is set to 2 W for a fair comparison. The propagation model includes large-scale fading and is given by $p_{los}[dB] = 128 + 37.\times \log(d[km]) + \delta$, with δ representing the lognormal shadowing of variance of 8 dB. The Gaussian noise power spectral density is of -150 dBm/Hz. A 10 MHz system bandwidth divided into 128 subcarriers to serve randomly spread users throughout the cell is considered. The results are averaged over 100 simulations of user dispositions, for which the PF scheduler is run each time for 50 timeslots.



(a) Throughput (b) Fairness

Fig. 5: KPIs of the PF scheduler for classical NOMA and IC-based NOMA as a function of the number of users.

In Fig. 5a, the achieved system throughput is presented as a function of the number of users. Starting with the schemes without AS, we observe that IC-based NOMA schemes, both direct and switched, provide a clearly higher throughput than the proposed power allocation in NOMA 1 and 2. The same observations can be made with IC-AS yielding significantly more throughput than NOMA-AS (38 vs. 20.5 Mbps). However, when comparing IC-AS and NOMA-AS in terms of system fairness, we can see from Fig. 5b that NOMA-AS delivers better fairness than IC-AS, which underlies a tradeoff to be made when selecting IC-based NOMA over classical NOMA. The key to understanding these results for classical NOMA and IC-based NOMA resides in the comparison of their achievable capacity regions provided in Fig. 4c. There, it can be seen that, for each subcarrier allocation, neither NOMA nor IC strategies can be designated as the best solution because their capacity regions can overlap without inclusion. Therefore, the better scheme for a given scenario comes down to which of the two capacity regions can provide a *better* operating point. Criteria for selecting the operating point are yet to be defined according to the framework of the study or the constraints of the underlying target application. They could span a wide range of requirements such as system power minimization, system latency reduction, maximizing the number of connected devices, etc. Therefore, the absence of a clear winning scheme in our system simulations is only a reflection of the non-inclusion between the capacity regions of IC and NOMA, at a system level scale. To select the scheme to employ, network designers and operators should first define their target throughput/fairness trade-off, then apply the same type of capacity region and system-level evaluation for their system model. This highlights the importance of the proposed new perspective and framework.

VI. Conclusion

In this letter, we have proposed a new form of NOMA with two transmitters, relying on two-user interference channels from information theory. Taking advantage of the centralization of network architectures, we proposed a simple but effective AS scheme to further increase the achievable capacity region and sum-capacity of two-user NOMA. The conducted simulations validated the idea of using IC as a valuable tool to be adopted by network operators for the evaluation of different NOMA variants with and without the proposed antenna switching scheme. Indeed, corresponding throughput/fairness trade-offs can be clearly determined, identifying the most suitable variant for the considered system or scenario. Interesting future work directions include the identification of the conditions where AS delivers increased capacity regions and sum-capacity and the conditions where the capacity region of classical NOMA is not encompassed by the one of IC. Indeed, with a deeper understanding of the interplay between classical NOMA and IC-based NOMA, more efficient resource allocation policies could be proposed to tackle all sorts of deployment scenarios.

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