Hybrid resource allocation for millimeter wave NOMA

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Abstract: Future generation of cellular mobile networks are requested to connect an increased number of devices with different connectivity requirements. While some of these devices have no capability to perform advanced signal processing algorithms, others will. This opens the possibility to use non-orthogonal multiple access (NOMA) schemes in future radio access networks. In these schemes the users are multiplexed in power domain in the transmitter and de-multiplexed using successive interference cancellation in the receiver. In this work we propose hybrid resource allocation of orthogonal and non-orthogonal radio resources and determine the improvements on cell capacity achieved in single cell millimeter wave scenarios.

Introduction

ITU vision for 5G [1] establishes capacity goals and indicates several enhancements of key performance indicators with respect to IMT-Advanced. Among them, the area traffic capacity should improve 100x, to support 10x higher connection density and 10x user experienced data rates. These goals are also in line with the vision from industrial fora like 5GPP [2] and NGMN [3] and standardization bodies like 3GPP [4].

In the last few years new players have emerged in the telecom business value chain, which are not properly addressed by the mobile industry, most notably the over-the-top (OTT) and vertical players. Current vision in 5G PPP is that 5G mobile networks have to be capable to implement services that are to be delivered by the mobile network operator (MNO) itself, by over-the-top (OTT) companies, by verticals, or, most probably, by a dynamic and heterogeneous combination of them. The huge diversity of services that might be required to be provided, demands that 5G networks are much more flexible than in previous mobile generations.

The trend to deploy different services using the mobile network, and higher spectrum bands, will continue in the future. In fact, we think that the investments made in the densification of the mobile network, and the adoption of millimeter wave, will result in the establishment of telecommunication infrastructures with enough capacity to provide other wireless services to the users (e.g. M2M, broadcasting, PPDR, ITS, …) in addition to telephony and broadband. In addition, given the technical advances in computing, storage and display technologies, we envision that in the near future, the same terminal will be capable to support all these services.

In cellular mobile networks, the design of proper radio access network is important to improve overall system capacity. Traditionally orthogonal multiple access schemes have been used to allow efficient communication using simpler receivers. However, non-orthogonal multiple access schemes which multiplex the several cell users in power domain and de-multiplex them using successive interference cancellation (SIC), have been shown to be achieve the optimum multiuser capacity in the downlink [5][6] as well as in the uplink [7].

The rest of the paper is organized as follows: in the next section we provide state-of-the-art in NOMA, then we highlight the standardization efforts of NOMA-like technologies in 3GPP, and present NOMA basics. The core of this work is presented in the next section where we investigated different ways of using simultaneously OFDMA and NOMA in single cell scenarios, after which we list the lessons learned from these investigations. The paper end with a description of the extensions of this work to more realistic scenarios.

State of the art

In [8] it is shown that OFDMA and NOMA can achieve similar maximum cell throughputs in downlink as well as in the uplink, although in the case of OFDMA this is achieved by allocating most of the resources (power and bandwidth) just to one user, i.e. to the one possessing better channel conditions, while the others are left almost with no resources. On the other hand, NOMA allows to reach the maximum cell throughput when the resources are fairly distributed among the several users in the cell, even when some of them have poor channel conditions. In the cellular case, this is especially important as the increased cell throughput should not be achieved at the expense of having poorer performance at the cell-edge.

In what concerns the use of NOMA with multiple antennas, it was verified that for SISO and SIMO cases, superposition coding and dirty paper coding were equivalent and provided optimum cell throughput results. For the MIMO case, dirty paper coding has to be mandatorily used, if optimum results are required [6]. However, dirty paper coding is very demanding in respect of delay and accuracy of the channel state information that has to be feedback from the receiver to the transmitter.

As a result, sub-optimum, less complex and more reliable multiple antenna NOMA schemes were proposed for downlink. In [9] a solution employing intra-beam superposition coding in the transmitter, and SIC in the receivers is proposed. In this solution, several transmitter precoders are used to create multiple beams, and, within each beam, several users are superposition coded. In the receiver the received signals start by being spatially filtered to remove inter-beam interference, after which they suffer successive interference cancellation for intra-beam interference cancellation. Regarding resource allocation, [9] assumes NOMA is exclusively used. Then, in downlink the users to be scheduled, and their respective powers, are jointly selected in order to maximize a scheduling metric that takes into account both the user fairness and throughput maximization, while in uplink the power allocated to each user may be independently selected.

In the literature, resource allocation methods assume that NOMA is exclusively used [9], or that the system may switch between OFDMA and NOMA from time transmission interval (TTI) to time transmission interval [10][11]. In this regard, and to the authors' knowledge, this work provides a novel contribution, since it proposes the allocation of both orthogonal and non-orthogonal OFDM downlink subcarriers to several mobile terminals within the same TTI.

Standardization

In 3GPP, non-orthogonal multiple access scheme that multiplexes users in power domain is a technology studied for inclusion in 3GPP Release 13, under the name ”multi-user superposition transmission (MUST)” [12]. In MUST, the base station multiplexes in power domain the signals intended to different mobile terminals, using the same precoding but different power levels. The signal aiming at the far UE receives more power to compensate the poor cell-edge performance, while the closer UE is allocated less power due to reduced propagation losses. In addition, the closer UE also decodes the signal aiming to the other terminal and subtracts it from the received signal in order to get a signal clean from interference.

MUST admits three different superposition categories [12], according to the selection, or not, of adaptive power allocation on component signal constellations and/or Gray encoding in the composite constellation. MUST Category 1, is essentially similar to NOMA, as it superimposes the signals using adaptive power allocation on component signal constellations and do not uses Gray encoding in the composite constellation.

Standardization [12] also focused on the identification of the most suitable MUST receiver schemes for UEs near-base-station and for UEs far-from-base-station. For the UEs closer to the base station the study focused on Maximum Likelihood (ML) and Reduced complexity maximum likelihood (R-ML) receivers, Symbol Level Interference Cancellation (SLIC) receiver and Linear Code Word level successive Interference Cancellation (L-CWIC) receiver. For far-from-the-base-station UEs the studied receivers were Linear Minimum Mean Square Error with Interference Rejection Combining (LMMSE-IRC), Maximum Likelihood (ML) and Reduced complexity Maximum Likelihood (R-ML) receivers, as well as Symbol Level Interference Cancellation (SLIC) receiver.

The performance of MUST using the above receiver types were evaluated through system simulations on three different network scenarios:

- Homogeneous macro cellular network
- Heterogeneous network composed by macro cells and small cells uniformly distributed within the macro cell, but using different channel frequencies
- Heterogeneous network composed by macro cells and small cells uniformly distributed within the macro cell and using the same frequencies as the macro cell.

The study concluded that MUST can increase network capacity, being specially tailored for those situations where the network is heavily loaded and uses wideband scheduling, while it can also improve user perceived throughput of cell-edge users.

NOMA basics

Traditional cellular mobile systems use orthogonal radio resources in order to minimize interference between signals from/to different mobile terminals, so they can be recovered with low probability of error using receivers not excessively complex. However, even using orthogonal OFDM subcarriers, multipath propagation and terminal velocity originates inter-symbol and inter-carrier interference, which require careful design of cyclic prefix and subcarrier spacing, as well as the adoption of equalizers at the receiver.

With advances in integrated circuit technology there are already available signal processors with enough computational power and reduced power consumption that turns possible to implement interference cancellation algorithms in mobile terminals. So, instead of fighting interference from all possible means, solutions capable of living with interference are starting to be proposed. Non-orthogonal multiple access (NOMA), is a multiple access scheme that proposes to deliberately superimpose in the transmitter the signals targeting *K* different mobile terminals, so the transmitted y(t) signal is of the form

$$y(t) = \sqrt{p_1}x_1(t) + \sqrt{p_2}x_2(t) + \cdots + \sqrt{p_K}x_K(t)$$

where the power allocated to the K mobiles is constrained not to exceed the transmitter maximum output, i.e. $p_1 + p_2 + \cdots + p_K \leq P_T$. These $x_1(t)$…$x_K(t)$ signals will interfere among them, however, under certain circumstances, the interference could be reliably removed at the mobile receiver. When signals propagate through the air, they suffer losses which increase with the distance between transmitter and receiver. A transmitter employing NOMA, assigns higher powers to the mobiles located far away from the base station, and lower powers to closer mobiles [10]. When the power allocated to the far away mobiles is enough for them to decode reliably their own signal, it will be also possible to the closer mobiles to decode it. Therefore, the closer mobiles can subtract the signals targeting the other mobiles from the received signal in order to get their own signal with reduced interference. By proceeding this way, the same radio resources could be simultaneously used to communicate more mobiles, increasing the traffic capacity of the cell [10].

If we assume a single cell, single antenna at both the base station and the mobile terminal, and an additive white Gaussian noise channel between them, from [13] the capacity of the channel is given by $C = B \cdot \log_2(1 + SINR)$. In NOMA, the ability to cancel the interference at the receivers closer to the base station results in their SINR not to degrade excessively. At the same time, the several signals may use, simultaneously all the channel bandwidth. The net effect is that the capacity of channel using non-orthogonal access schemes like NOMA, can be much higher than what is achievable using orthogonal schemes like OFDMA.

In Figure 1, we compare the capacity of a single cell operating in the millimeter wave band (73GHz), when employing OFDMA and NOMA. For simplicity reasons, we consider there are only two mobile users sharing the radio resources at a given time transmit interval (TTI). The remaining assumptions are described in Table 1.

Carrier frequency	73 GHz
Channel bandwidth	800 MHz
Transmission power output	15 dBm
Transmission mode	SISO
Base station antenna gain	37 dBi
Path loss model [14]	PL = 69.8 + 33 log(d), (dB)
Mobile terminal antenna gain	0 dBi
Mobile terminal noise figure	6 dB

Table 1 – Parameters that are common to all scenarios

To get results with some adherence to a real situation, SINR values used in capacity evaluations were obtained through LTE-Advanced link level simulations considering 73GHz channel model [14].

Regarding the power allocation strategy followed in NOMA, we adopted the algorithm proposed in [15]. This algorithm starts by making pairs of users. Then for each pair, it allocates power levels to the users constrained to the fact that the user closer to the cell border may not experience reduced capacity in NOMA compared to the capacity it would experience if using OFDMA. Therefore, the power level of the cell edge user will be increased while the power level of the user placed closer to the base station will be reduced, as indicated by the following expressions, where UE1 refers to the user closer to the base station and UE2 refers to the user near the cell-edge.

$$P_{UE1} = \frac{\sqrt{1 + SNR(UE2)} - 1}{SNR(UE2)} P_{TOTAL}$$

$$P_{UE2} = P_{TOTAL} - P_{UE1}$$

We then calculated the sum-capacity when one of the mobiles (UE1) is moving from the cell center to the border, while the other (UE2) remains at the cell border, assuming UE1 is capable of performing ideal cancellation of UE2 interference.

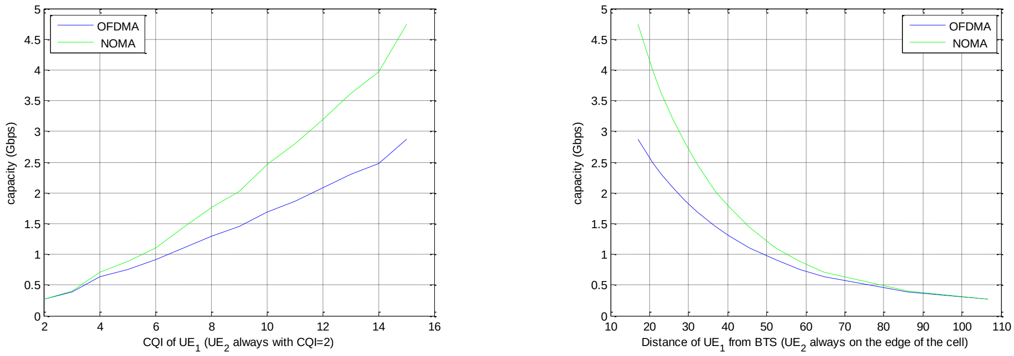


Figure 1 – Comparison of the capacity achieved by OFDMA and NOMA, considering a single cell using millimeter wave band (73GHz).

Under the considered scenario, Figure 1 clearly illustrates that NOMA allows to achieve higher cell capacities than OFMA. The cell capacity is similar when both terminals are in the cell border, but NOMA brings increased capacity gains as one of the users moves to the cell center, reaching 60.8% more capacity than OFDMA in this situation. As expected [10], Figure 1, allows us to conclude that NOMA is especially suited for scenarios where the users sharing the resources have different channel losses.

Proposed hybrid resource allocation scheme

Figure 1 illustrates the fact that using NOMA instead of OFDMA can induce capacity gains in single cell scenarios. However, there may be situations where the cell cannot completely switch from OFDMA to NOMA and vice-versa, e.g. when newer powerful terminals have to coexist with less capable legacy terminals. Therefore we are proposing a system model which will analyze the scenario where NOMA and OFDMA can co-exist, rather than just apply NOMA in overall system, as proposed in previous NOMA literature [8]-[11].

To quantify the potential benefits achieved by the simultaneous use of OFDMA and NOMA within the same time (at same TTI), and to compare them with the situations where there is exclusive use of OFDMA or NOMA in each TTI, we are going to derive the capacity of five ideal single cell scenarios. In all these four downlink scenarios, we consider that 73GHz millimeter wave (mmWave) band has to be allocated to four mobile terminals located at different distances from the base station, although the way the mmWave band is torn apart among the several mobiles changes from scenario to scenario.

To place the mobiles in different cell zones we assumed the SINR values indicated in Table 2, which allow to achieve a block error level (BLER) of 10% assuming LTE-Advanced technology operating in the 73GHz mmWave band.

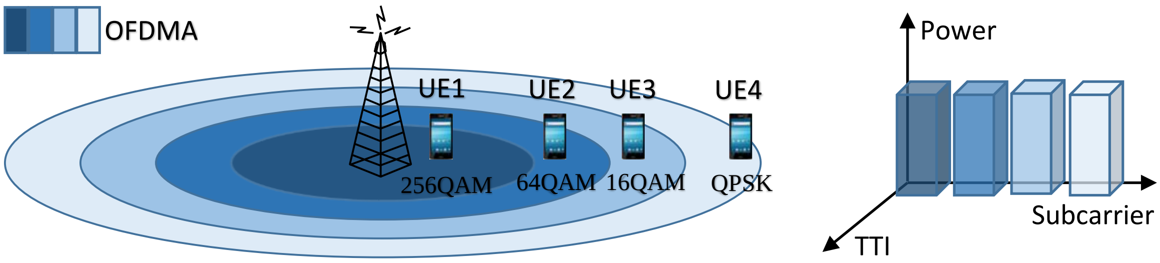
	UE1	UE2	UE3	UE4
CQI	15	11	6	2
Modulation	256-QAM	64-QAM	16-QAM	QPSK
SINR (dB)	20.55	12.82	4.48	-5.75
Distance from base station	17.0 m	29.2 m	52.2 m	106.6 m

Table 2 – Placement of the 4 mobile terminals in the cell, based on LTE-Advanced SINR for 10% BLER at 73GHz

The parameters that remain unchanged in all scenarios are indicated in Table 1.

Case 1: OFDMA in single cell

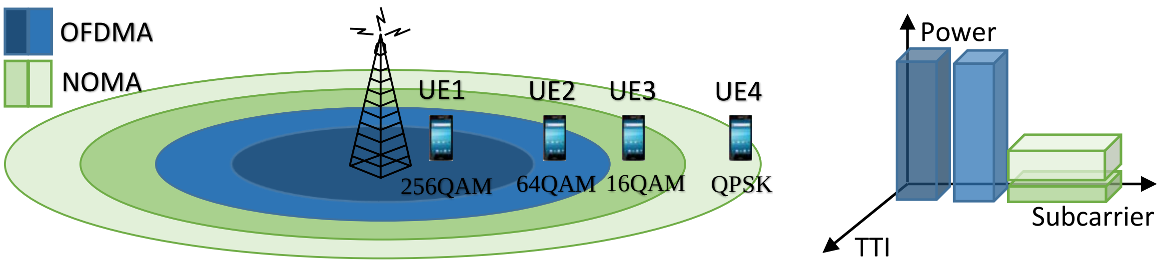
The first scenario is proposed for benchmarking purposes. It consists in the conventional OFDMA situation, where the 4 UEs are allocated the same number of orthogonal subcarriers, and are transmitted at the full power.



In this scenario, when considering AWGN channels between the base station and the mobiles, there will be no interference among the UEs. Using the path losses computed according to the millimeter wave channel model indicated in Table 1, we reached a sum-capacity of 2.69 Gbps.

Case 2: OFDMA / NOMA in single cell

In the first scenario that mixes OFDMA and NOMA, we use OFDMA for the two UE closer to the base station, and NOMA for the two UE that are more faraway. Downlink signals targeting UE1 and UE2 do not interfere with any signal, but those aiming at UE3 and UE4 will interfere with each other. As UE3 is closer to the base station, it will be able to cancel interference caused by the signal aimed at UE4, while the UE4 will not be capable to cancel interference produced by the signal to UE3.



In this scenario we investigated three different ways to split the power among the OFDMA and NOMA pairs of users:

i) half of the total power to each pair;
ii) one third of the total power to OFDMA pair and two thirds to the NOMA pair,
iii) two thirds of the total power to OFDMA pair and one third for NOMA pair.

The sum-capacity of these three scenario variants is, respectively, 2.79Gbps, 2.68Gbps and 2.81Gbps. This means that assigning more power to the pair closer to the base station, i.e. the OFDMA pair, seems to be the better choice, as this will lead to reduced power to UE3, and thus to reduced interference over UE4.

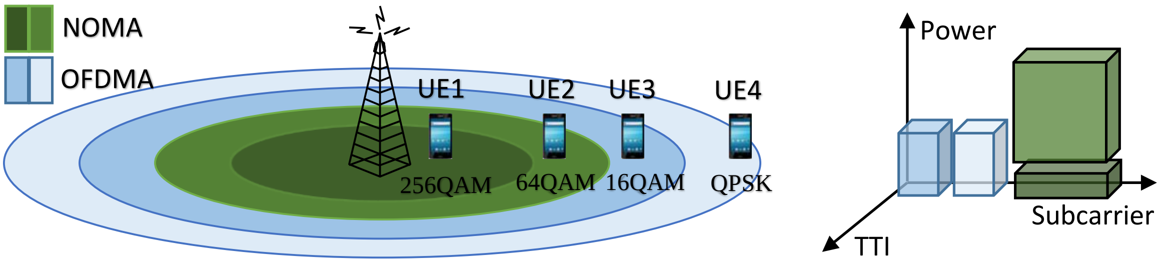
These results seem to indicate this scenario can achieve slightly higher capacities than OFDMA alone.

Please bear in mind this is a theoretical upper bound which, to be obtained, require optimum source and channel coding algorithms, which may be different from the ones implemented in LTE-Advanced.

Case 3: NOMA / OFDMA in single cell

In the next scenario we use NOMA for the users UE1 and UE2 which are closer to the base station, and OFDMA for users UE3 and UE4 which are near the cell edge. In this situation UE1 and UE2 will interfere with each other, while UE3 and UE4 will not interfere with anyone else.

As UE1 is closer to the base station, it will be able to cancel the interference caused by the downlink signal to UE2, while UE2 will not be capable to cancel interference caused by the signal to UE1.



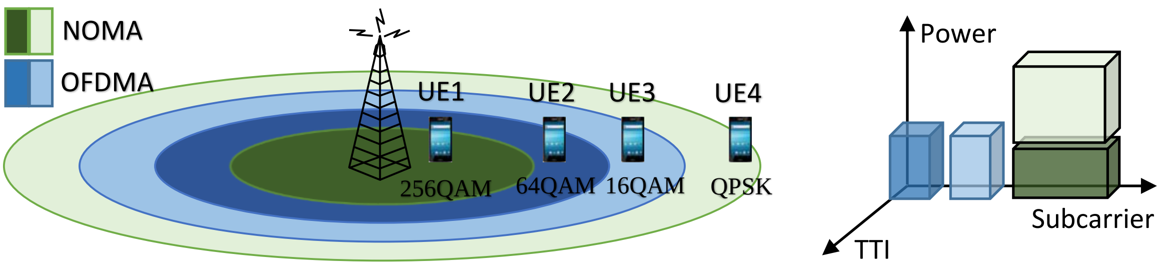
We also tested in this scenario the same variants of power distributions as in the previous scenario. The three variants, achieved respectively a sum-capacity of 3.10Gbps, 2.91Gbps and 3.18 Gbps. Once again, this indicates that it is better to allocate more power to the pair of pair of users that is closer to the base station, although they are now using NOMA.

This happens because the selected power allocation strategy used for NOMA [15] will allocate to UE1 much less power than for UE2, which means that UE1 causes much less interference in UE2, than the opposite. However, the enhanced interference of UE2 over UE1 can be cancelled and, as such, does not degrade performance.

Case 4: NOMA / OFDMA / OFDMA / NOMA in single cell

As indicated in the section on NOMA basics, NOMA brings more increase in capacity when the channel gains associated with the mobiles are as different as possible. This conclusion motivated a new scenario, where we use NOMA to combine the two users that are closer (UE1) and faraway (UE2) from the base station. The remainder users (UE2 and UE3) will be connected using OFDMA.

In this scenario, signals to UE1 and UE4 will interfere with each other, while signals to UE2 and UE3 will not interfere with anyone else. As UE1 is closer to the base station, it will be able to cancel interference from UE4, but UE4 will not be capable to remove interference of UE1.



The same three different power distributions between the pairs of users using OFDMA and OMA were analyzed. They reached a capacity of, respectively, 3.63 Gbps, 3.62 Gbps, and 3.52

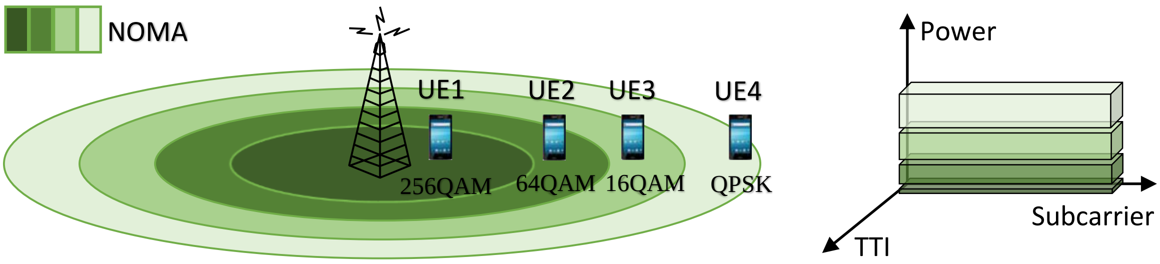
Gbps. This means that allocating identical power to the OFDMA and NOMA pairs, or, in alternative, allocating more power to the NOMA pair than to the OFDMA pair, will be similar good options. This happens because, as SINR4 is very low, the selected power allocation algorithm [15] will assign similar values to P1 and P4. As interference of the signal to UE4 over the signal to UE1 can be cancelled, the interference that will impact on the capacity is the interference from the signal to UE1 over the signal to UE4. However, when using millimeter wave frequencies, the coupling loss between UE1 and UE4 is so high, that increasing moderately the power of the signal to UE1 will have reduced effects in the interference captured in UE4.

Case 5: NOMA in single cell

The last scenario considers the situation where all the 4 users support NOMA.

Now every signal interferes with all the others. To allow that every UE, with exception of UE4, is capable of cancelling the interference from the other users, we created two pairs of NOMA users: first pair is associated with UE1 and UE2, while the second pair is formed by UE3 and UE4. Then, we assigned two thirds of the total power to the pair closer to the base station, i.e. UE1-UE2, and one third of the total power to the pair UE3-UE4. This will make possible to have P1 < P2 < P3 < P4, and by that reason, cancel higher levels of interference

- UE1 can cancel interference from the signals aimed to UE2-UE3-UE4,
- UE2 will be capable of cancel interference from the signals to UE3 and UE4 but not to UE1,
- UE3 will be able to cancel interference from the signal to UE4, but not to UE2-UE1,
- UE4 will not cancel interference caused by any signal.



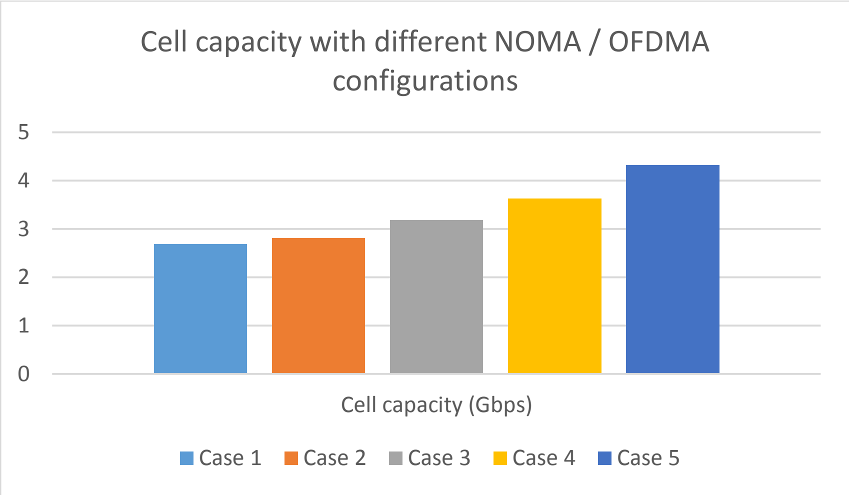
Using this pairing scheme, and power distribution among the pairs, allowed to reach a sum capacity of 4.32 Gbps, reasonably higher than all the other scenarios previously considered.

Lessons learned (from single cell results)

The study of the scenarios presented above allowed to conclude that, under the assumption of single cell configurations, AWGN channels, and ideal interference cancellation, the introduction of NOMA will always bring additional capacity to the cell, when compared with the OFDMA only situation.

The scenario with major capacity increase potential is to completely substitute OFDMA by NOMA. However, there might be situations where such radical change is not possible, e.g. when the cell has to support M2M and IoT low complex equipment, or old-fashioned legacy terminals, in addition to have to high performant receivers within higher-end smartphones. In such situations, the cell should be able to support a mix of OFDMA and NOMA. Depending on the location of the NOMA capable receivers within the cell, the following decisions should be made:

- NOMA should substitute OFDMA in the higher extent possible;
- When NOMA may only be used in part of the cell, the users that should be using NOMA are the ones closer and farther away from the base station;
- When NOMA may only be used in a contiguous part of the cell, it is preferable to use NOMA in the region closer to the base station, than in the region closer to the cell edge. In both situations, a greater amount of the total power should be assigned to the users closer to the base station than to the users placed faraway.
- Mixed OFDMA/NOMA will have higher capacity potential than OFDMA only scenarios, and less capacity potential than NOMA only scenarios.



Further work

By considering single cell scenarios, AWGN channels, and ideal interference cancellation, this work constitutes a first step to understand the best way to exploit NOMA potentialities to the greatest extent possible, under realistic conditions.

Further work is needed to evaluate the robustness of NOMA under inter-cell interference, with and without inter-cell coordination, as well the impact of partial interference cancelation caused by imperfect channel estimation.

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