Flexible Multiple Access Enabling Low-Latency Communications: Introducing NOMA-R

Mouktar Bello, Wenjuan Yu, Mylene Pischella, Arsenia Chorti, Inbar Fijalkow, Leila Musavian

I. INTRODUCTION

Various verticals in 5G and beyond (B5G) networks require very stringent latency guarantees, while at the same time envisioning massive connectivity. As a result, choosing the optimal multiple access (MA) technique to achieve low latency is a key enabler of B5G. In particular, this issue is more acute in uplink transmissions due to the potentially high number of collisions. On this premise, in the present contribution we discuss the issue of delay-sensitive uplink connectivity using optimized MA techniques; to this end, we perform a comparative analysis of various MA approaches with respect to the achievable effective capacity (EC). As opposed to standard rate (PHY) or throughput (MAC) analyses, we propose the concept of the effective capacity as a suitable metric for characterizing jointly PHY-MAC layer delays.

The palette of investigated MA approaches includes standard orthogonal MA (OMA) and power domain non orthogonal MA (NOMA) in uplink scenarios, both considering random pairing and optimized pairing alternatives. It further extends to encompass a recently proposed third alternative, referred to as NOMA-Relevant (NOMA-R), which extends OMA and NOMA approaches by flexibly selecting the MA technique. We show that optimizing both user pairing and MA selection increases the network EC, especially when stringent delay constraints are in place; thus a flexible MA is a potentially preferable strategy for future low latency applications.

II. LOW LATENCY B5G LANDSCAPE

Future communication networks will not only support an evolution of traditional communication services, but also address novel verticals where real-time response is critical, e.g., autonomous vehicles or industry 4.0 [4], [9]. While for these types of services, 5G and beyond (B5G) networks are targeting very stringent latency guarantees, e.g., between 1 and 10 ms, the network is required to provide other key performance indicators (KPIs) as well, for example, to provide high throughput in the context of ultra high speed low latency communications (uHSLLC), or to provide ultra reliability in the context of ultra reliable low latency communications (URLLC) [9]. Meeting these conflicting requirements is a key to open up new business opportunities and benefit a number of novel use cases including remote surgery, self-driving vehicles and tactile Internet.

Recently, rich research interest has concentrated on these topics, as enabling true real-time connectivity seems to be among the tallest hurdles in B5G fulfillment. So far, major efforts in addressing low latency requirements have been channeled to the empowerment of edge and fog computing on one hand, and, network slicing on the other, while in parallel novel radio access and scheduling approaches at the MAC sub-layer are actively studied, under the umbrella of flexible numerology [4].

A. Which delay metric to use?

In this context, an interesting question arises with respect to characterizing delays jointly at the radio (PHY) and MAC layers. In fact, in B5G, quality of service (QoS) according to the class based system of the differentiated services (DiffServ) paradigm will be in place everywhere – even for low-end Internet of things (IoT) sensors. In particular, in the first [6G white paper] it is noted that: “6G needs an upgraded networking paradigm moving from best effort to differentiated service quality”. At the same time, considerable amounts of traffic will be placed on the wireless edge (e.g., “M2M connections will be more than half of the global connected devices and connections by 2022” as projected in the Cisco Visual Networking Index: Forecast and Trends, 2017–2022 White Paper).

In the late nineties, delays were explicitly characterised in asynchronous transfer mode (ATM) wired networks that employed integrated services (IntServ) QoS by using the concept of the effective bandwidth [11] (later extending to cover DiffServ). In the wireless MAC however, due to small scale fading and shadowing, it is inherently impossible to provide hard delay guarantees. Additionally, DiffServ QoS, by design, can only provide statistical delay guarantees due to the absence of resource reservations with the exception of the network edges.

In wireless networks, to provide statistical delay guarantees the concept of the effective capacity (EC) [12], can be employed. It has been recently proven that a delay bound and a maximal tolerable delay bound violation probability can only be jointly satisfied if the effective capacity exceeds the effective bandwidth [10], for compactness, in the rest of this discussion we only consider the former metric.
B. Which multiple access technique to use?

Regarding the choice of the multiple access (MA) technology itself, faced with the scarcity of resources – at least until mmWave technologies become commonplace – the suitable radio MA arises as a stressing issue, particularly in the uplink under massive connectivity. Among the various proposed PHY solutions to increase throughput (and consequently decrease latency), e.g., [6], the exploitation of non-orthogonal multiple access (NOMA) technologies, which until recently have largely remained an information theoretic niche topic, seems the most promising [1].

In power domain NOMA (referred to as NOMA henceforth), several users can use the same resource blocks (RBs) simultaneously by employing superposition coding at the transmitter and successive interference cancellation (SIC) at the receiver, as illustrated in Figure 2. On the contrary, orthogonal MA (OMA) techniques such as time division MA (TDMA) allow only a single user to be served within the same time (or frequency) RB. NOMA has been shown to outperform OMA and other alternatives in terms of spectral efficiency, cell-edge throughput, energy efficiency and achievable secrecy rates [2], [14]. A natural question that arises is whether the supremacy of NOMA over OMA holds for the case of delay sensitive applications, with a particular focus on scenarios with users of varying QoS delay requirements.

In this study, we shed light to this question by utilizing the concept of the effective capacity in an uplink network and study OMA / NOMA with or without user pairing. Finally, we take a further step by discussing a novel, flexible MA technique that allows harnessing the benefits of both NOMA and OMA, particularly when users that experience favorable channel conditions require delay sensitive services.

III. EFFECTIVE CAPACITY IN WIRELESS NETWORKS

As mentioned above, it is inherently impossible to provide deterministic delay guarantees in radio access due to the random channel variations experienced in the form of small-scale fading and shadowing; intuitively, this is the consequence of the impossibility of a strictly zero outage probability, irrespective of the diversity order employed.

Hence, in this paper, we focus on statistical delay QoS guarantees and employ the theory of EC as a suitable performance metric to confine the delay violation probability below a required threshold. As a dual of the effective bandwidth that was extensively studied for wired networks, the theory of EC was proposed in [12]; EC denotes the maximum constant arrival rate that can be supported by a given service process (over wireless channels), on the condition that a target statistical delay QoS requirement is satisfied. Arguably, in most services a variable arrival rate is typical. This issue can be resolved by lower-bounding the EC by the effective bandwidth, as shown in [10]. In the following, we assume that this requirement holds in all cases without providing further details for the sake of simplicity.

To illustrate the concept of EC, as in Figure 1, let us assume a dynamic queueing system with an unconstrained buffer in which the queue length has already converged to a steady state. The probability that the delay experienced by a packet of user $k$ exceeds a maximum delay bound $D_{\text{max}}^k$ has been shown to decay exponentially with the product of three quantities: i) $D_{\text{max}}^k$, ii) the EC, and, iii) the QoS delay exponent, denoted by $\theta_k$ [12], i.e.,

$$P_{\text{out}}^\text{delay} = \Pr\{D_k(t) > D_{\text{max}}^k\} \approx \Pr\{q_k(t) > 0\} e^{-\theta_k E_k^k D_{\text{max}}^k},$$

where $E_k^k$ denotes the EC of user $k$, $P_{\text{out}}^\text{delay}$ is the delay-outage probability limit for user $k$, $D_{\text{max}}^k$ denotes a maximum tolerable delay and (in units of symbol periods), $\Pr\{q_k(t) > 0\}$ denotes the probability of a non-empty buffer at time $t$, and $\theta_k$ is referred
to as the delay QoS exponent. The delay exponent $\theta_k$ ($\theta_k > 0$) captures how stringent the delay constraint is. A smaller $\theta_k$ indicates that the user can tolerate a loose delay QoS guarantee (delay tolerant applications), while a larger $\theta_k$ corresponds to a system with more stringent delay QoS requirements (delay sensitive) \cite{12}, \cite{15}.

In order to satisfy a target delay-violation probability limit, a source needs to limit its maximum constant arrival rate to $E_C$ \cite{12}. Remarkably, applying the theory of large deviations under the assumption that the G"artner-Ellis limit exists, allows us to derive in closed form the expression for the EC of user $k$ in a block-fading additive white Gaussian noise (BF-AWGN) channel, expressed as \cite{15}

$$E_c^k = \frac{1}{\beta_k} \ln \left( \mathbb{E} \left[ e^{\beta_k R_k} \right] \right) \text{ (b/s/Hz)},$$

(2)

where $\mathbb{E} [\cdot]$ denotes expectation over the channel gains, $\beta_k = -\theta_k T_f B$, denotes the (negative) delay exponent, $T_f$ is the frame duration of the fading-block, $B$ is the bandwidth and $R_k$ is the achievable rate. From the above discussion, it is apparent that the EC is not only a suitable, but also a flexible metric which can represent various latency requirements.

IV. NOMA AND OMA UNDER DELAY CONSTRAINTS

In this Section, we discuss the performance of NOMA in low-latency communications, captured by small negative delay exponents. Comparative studies between NOMA and the conventional OMA will reveal that NOMA is more advantageous in terms of the total EC, but is not always superior to OMA in terms of individual ECs. As a result, it is possible that the use of...
NOMA can penalise a user of a delay sensitive application, a fact that needs to be explicitly accounted for when selecting the MA technique.

A. Two user baseline scenario

Assume a two-user NOMA uplink network with users $U_1$ and $U_2$ in a Rayleigh BF-AWGN propagation channel, with respective channel gains during a transmission block denoted by $|h_1|^2 < |h_2|^2$, as shown in Figure 2. In the following, user $U_1$ will be referred to as the weak user and $U_2$ as the strong user. The users transmit corresponding symbols with power $P_1$ and $P_2$ respectively, according to the NOMA uplink principle which imposes $P_1 \leq P_2$ [13]. The receiver (base station) will first decode the symbol of the strong user treating the signal of the weak user as interference. After decoding it, the receiver will suppress it before decoding the signal of the weak user. Following the SIC principle and denoting by $\rho$ the transmit signal-to-noise ratio (SNR), the achievable rate, in b/s/Hz, for user $U_i$, $i = 1, 2$, is expressed as

$$R_i = \log_2 \left[ 1 + \frac{\rho P_i |h_i|^2}{1 + \rho \sum_{l=1}^{i-1} P_l |h_l|^2} \right].$$

On the other hand, the achievable rate in OMA follows the standard time sharing principle. Furthermore, with respect to the allocation of the RBs, amongst various approaches, when fairness is the prevalent criterion, it is commonplace to assume that $U_1$ and $U_2$ utilize half of the available resources each when using OMA but have access to double the power (same energy expenditure per RB) [3]. As a result, their achievable rates are capped to half their respective Shannon capacities over the totality of the resources assuming twice the power budget.

The ECs of either user in either MA approach are evaluated by inserting the respective achievable rates into equation (2). A detailed illustration of our comparative findings is given below.

B. Comparison between NOMA and OMA

It is known that NOMA outperforms OMA in terms of the sum spectral efficiency. However, it is not clear how the two MA schemes compare when statistical delay QoS are in place. To address this question, we begin by analyzing the ECs of the two users as a function of the transmit SNR, depicted in Figure 3 for a fixed common negative delay exponent $\beta = -5$ for both users and $P_1 = 0.2$, $P_2 = 0.8$. We notice that for the strong user, NOMA achieves higher EC than OMA at low SNRs, while OMA is more advantageous than NOMA at high SNRs. On the other hand, for the weak user, NOMA seems to be better than OMA at both low and high transmit SNR. This reveals that NOMA does not always outperform OMA in terms of individual ECs. We also notice that the EC for the strong user reaches a plateau at high SNRs, due to the interference from the weak user, i.e., the MA scheme is interference limited for users with more favourable channel conditions.

Furthermore, to study the performance of NOMA in various delay scenarios, we plot Figure 4. In the upper sub-figure, the difference of the ECs achieved with NOMA and OMA, denoted by $\Delta E_c$, is depicted for $U_1$ and, respectively, in the lower sub-figure for $U_2$, for varying delay exponents. It is shown that for the weak user, as the delay requirement becomes more

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3}
\caption{NOMA versus OMA comparison for $\beta = -5$.}
\end{figure}
stringent, NOMA always outperforms OMA. In contrast, the strong user observes a phase transition in medium SNRs; in low SNRs, NOMA outperforms OMA while in high SNRs the opposite is true. As the negative delay exponent decreases, i.e., the delay constraints become more stringent, NOMA outperforms OMA in terms of EC over a larger range of SNRs. However, the gap in the ECs between NOMA and OMA decreases as the latency becomes more stringent. On the other hand, there is a clear penalty in EC at high SNRs when using NOMA; this penalty decreases with decreasing negative delay exponents, i.e., as the delay constraints become stringer.

The impact of this initial analysis is worth examining more closely in potential 5G scenarios. As an example, assume a high SNR delay sensitive user of a NOMA network, in which it plays the role of the strong user; in that case, the use of NOMA will result in penalties in terms of the service rate that would be compatible with the statistical delay QoS guarantees. As a result, the interplay between latency and throughput can be accentuated by the choice of MA. As the NOMA objective is to

\[ A \text{ high SNR is prerequisite to reach the target low BER for ultra reliability in URLLC, for example.} \]
Table I: Recommended MA techniques for various scenarios

| Scenarios          | Low latency service | Transmit SNR | Recommended MA techniques                                      |
|--------------------|---------------------|--------------|----------------------------------------------------------------|
|                    | Weak user           | High         | NOMA-R (optimal pairing) or NOMA (optimal pairing)              |
| Strong user        | ✓                   | ✓            | NOMA-R (optimal pairing) or OMA                                |
| High               | ✓                   | ✓            | NOMA-R (optimal pairing) or NOMA (optimal pairing)              |
| Low                | ✓                   | ✓            | NOMA (optimal pairing)                                          |
|                    | ✓                   | ✓            | NOMA-R (optimal pairing) or NOMA (optimal pairing)              |
|                    | ✓                   | ✓            | NOMA-R (optimal pairing) or NOMA (optimal pairing)              |
|                    | ✓                   | ✓            | NOMA-R (optimal pairing) or NOMA (optimal pairing)              |

outperform conventional MA methods, it is natural to ask whether it is possible to improve the performance of NOMA compared to OMA in regions where the latter does better than the former when accounting for statistical delay constraints. To address this question, we first explore user-pairing with NOMA, discussed next, and we subsequently introduce a novel scheme, referred to as NOMA-R.

C. Impact of user pairing

In larger networks with $M > 2$, although in terms of the sum EC it is beneficial to superimpose as many users as possible [3], with respect to the individual ECs this may not be the case. Furthermore, there are practical limitations in the number of users that can be superimposed. Firstly, performing several SICs in series at the receiver may lead to additional processing delay and thus increase the end-to-end (E2E) latency, especially for the weaker users (note that in the uplink the weak users are bound to lower transmit power, which in turn already penalizes their respective rates). Additionally, error propagation can severely impact the system performance in the case of imperfect SIC decoding [7].

An alternative MA approach, referred to as user-paired NOMA, has been proposed due to its advantages in terms of practical implementation. This MA approach is in essence a hybrid of OMA and NOMA; the users are split into a small number of groups that share between them the RBs according to OMA, while within each group the users are superimposed according to NOMA. It is known that pairing does not bring an improvement with respect to sum rates compared to full NOMA. Perhaps one should rather say, that it is a compromise between a variety of conflicting requirements: (a) for weak(er) users to decrease complexity and increase reliability by reducing the SIC layers, at the expense of a reduction in the achievable rate and by consequence in the EC; and (b) for strong(er) users to decrease interference and potentially increase their achievable rates and respective ECs, at the expense of lower sum rates and sum ECs in the network.

Studying the impact of user pairing, in Figure 5 we depict the gap in the sum ECs (denoted by $\Delta \text{Sum}E_C$) when using NOMA – with various pairing approaches – and OMA, in a $M = 4$ user network. Clearly, full NOMA with all users superimposed can in theory outperform all other approaches. However, as argued before, multi-layer SIC can severely compromise reliability due to error propagation. Alternatively, NOMA with optimal user pairing provides a reasonable compromise between performance, complexity and feasibility.

For the user-paired NOMA, it is well established that the pairing strategy has a great impact on the system performance. With respect to sum rates, optimal pairing entails grouping the strongest (user 1 in Figure 5) with the weakest user (user 4 in Figure 5), the second strongest (user 2 in Figure 5) with the second weakest (user 3 in Figure 5), and so on [3]. The same optimal pairing strategy $(1, 4), (2, 3)$ achieves also a considerable gain in terms of $\Delta \text{Sum}E_C$, compared to the worst pairing strategy which is sequential (users are paired in decreasing order).

A larger SNR gap is beneficial in terms of the sum ECs, confirming relevant prior results for the case of the achievable rates. Although the user-paired NOMA may achieve a lower sum EC than the full NOMA, it limits the experienced interference at the strong user, as the strong user needs to be decoded first with the weak users’ signals are treated as interference.

This inspires us to focus on the user-paired NOMA with the optimal pairing strategy. These results do not account for the individual ECs. We next investigate in further detail this issue and move on to propose a flexible MA strategy which can switch from user-paired NOMA to OMA when the former penalizes the EC of the stronger users.

V. NOMA-R STRATEGY FOR NETWORKS WITH STRONG LOW LATENCY USERS

As previously seen, OMA may outperform NOMA in terms of EC for the strong user at high SNRs due to large interference, which can be an issue when the strong user receives low latency services. Furthermore, overall, the achievable rates of strong
users can have a greater impact on the total rate performance, as we noticed in [15]. In order to avoid the interference limitation and to achieve better performance in networks with strong low latency users, a flexible MA strategy, referred to as NOMA-R was proposed in [8]. With NOMA-R, the MA technique that maximizes the achievable rate of the strong user is selected flexibly.

It can be shown that the probability of choosing NOMA over OMA in NOMA-R, tends to unity in low SNRs and becomes negligible in high SNRs, in accordance to intuition gained from the initial discussion around Figure 2. The EC in NOMA-R can be obtained from the instantaneous NOMA-R rate, evaluated using a time sharing strategy with weights equal to the corresponding probabilities of choosing NOMA or OMA. The EC of the strong user is always superior with the NOMA-R strategy compared to both NOMA and OMA, whereas the EC of the weak user with NOMA-R is larger than that with OMA, but lower than that with NOMA, as expected.

**NOMA-R in a two user baseline network**

The influence of the delay QoS exponent parameters $\beta_1$ and $\beta_2$ is represented in Figure 6, where the transmit SNR is set to 20 dB and $P_1 = 0.2$, $P_2 = 0.8$. NOMA-R is well-suited for stringent target delay-bound violation probabilities, that is, when $\beta_1$ and $\beta_2$ decrease. Adapting the MA strategy in order to avoid interference-limited situations for the strong user allows to better fulfill delay constraints. The proposed NOMA-R flexible MA selection strategy may consequently be a strong candidate...
A. NOMA-R in a multi-user network

Moreover, users pairing can be optimized according to the NOMA-R criterion. Users are paired in order to maximize the the signal to interference and noise ratio of the strongest user. This heuristic MA strategy aims at increasing the probability to select NOMA with NOMA-R for the users that are likely to have the largest ECs.

The obtained sum EC with NOMA-R, NOMA and OMA with either random or optimized pairing when $P_1 = 0.2$, $P_2 = 0.8$ and $\beta_1 = \beta_2 = -5$ is represented in Figure[7]. NOMA-R is the best technique with optimized pairing at large SNRs, while NOMA is shown to be particularly inefficient with random pairing due to large interference at the strong user. Combining NOMA-R with optimized pairing therefore provides the largest sum EC.

Finally, the influence of $\beta_1$ and $\beta_2$ on the EC with the same parameters as before is depicted in Figure[8]. A comparative analysis of Figures[8] and [6] shows that the $\beta$ region where NOMA-R outperforms NOMA in terms of sum EC increases thanks to pairing. Please notice that the z axis on Figures[8] and [6] differs and that the achieved data rate with 4 users pairing is more than twice that with 2 users. The sum EC is lower with NOMA-R than with NOMA with increasing $\beta_2$, i.e., as the strong user tends to receive a delay tolerant service.

The recommended MA techniques for various scenarios (depending on the existence of low latency service for each user and the value of transmit SNR) are summarized in Table[1]. Different latency scenarios are discussed: 1) when both users require low latency services; 2) when only one user has low latency requirements; 3) when both users are delay tolerant. We can conclude that when both users require low latency services, NOMA-R serves as the best MA technique, no matter whether the transmit SNR is high or low.

VI. Conclusion

In B5G, delay constraints emerge as a topic of particular interest, e.g., for uHSLLC and URLLC services such as autonomous vehicles, enhanced reality, factory automation, etc. In this context, novel MA techniques from the realm of NOMA have attracted a lot of attention in recent years. In this contribution, we provide a comparative performance analysis for the uplink of networks with different MA strategies, when statistical delay QoS constraints are in place. The latter are captured through each user’s effective capacity, a MAC layer rate metric that accounts for QoS delay exponents.

The first outcome of our analysis shows that in the high SNR region, “strong” NOMA users are interference limited, which translates in plateaus in their ECs. We further show that the inverse conclusions hold for the weak users. The second conclusion reached concerns the impact of user pairing or grouping and its impact on the ECs. Due to practical considerations, particularly in view of imperfect SIC, it is indicated that NOMA with optimal user pairing is a promising implementation approach for NOMA as it provides a good compromise between performance and feasibility.

Finally, in networks with users of varying delay QoS requirements, it is probable that the strong users are recipients of low latency services, e.g., they are URLLC users. In this scenarios we propose a flexible MA strategy, referred to as NOMA-R, in which NOMA is only adopted when it benefits the strong users. Our numerical results show that NOMA-R offers concrete benefits even in terms of sum ECs, particularly when the strong user has stringent delay QoS constraints.
REFERENCES

[1] 3GPP. Study on non-orthogonal multiple access (NOMA) for NR. In Specification 38.812v1.0.0 Rel-65.
[2] A. Chorti and H. V. Poor. Faster than Nyquist interference assisted secret communication for ofdm systems. In in Proc. 45th Asilomar Conf. Signals, Systems and Computers (ASILOMAR), pages 183–187, 2011.
[3] Z. Ding, P. Fan, and H. V. Poor. Impact of user pairing on 5G nonorthogonal multiple-access downlink transmissions. IEEE Trans. Vehic. Techn., 65(8):6010–6023, 2016.
[4] D. Feng, C. She, K. Ying, L. Lai, Z. Hou, T. Q. S. Quek, Y. Li, and B. Vucetic. Toward ultra-reliable low-latency communications: Typical scenarios, possible solutions, and open issues. IEEE Veh. Technol. Mag., 14(2):94–102, June 2019.
[5] SM Riazul Islam, , Nurilla Avazov, Octavia A Dobre, and Kyung-Sup Kwak. Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges. IEEE Commun. Surv, & Tut., 19(2):721–742, 2016.
[6] Y. Kanaras, A. Chorti, M. Rodrigues, and I. Darwazeh. A near optimum detection for a spectrally efficient non orthogonal FDM system. In Proc. IEEE 13th Int. OFDM Workshop, pages 65–69, 2008.
[7] M. Liu, T. Song, and G. Gui. Deep cognitive perspective: Resource allocation for NOMA-based heterogeneous IoT with imperfect SIC. IEEE Internet Things J., 6(2):2885–2894, 2019.
[8] M. Pischella and D. Le Ruyet. NOMA-Related clustering and resource allocation for proportional fair uplink communications. IEEE Wireless Commun. L., 8(3):873–876, June 2019.
[9] P. Popovski, J. J. Nielsen, C. Stefanovic, E. d. Carvalho, E. Strom, K. F. Trillingsgaard, A. Bana, D. M. Kim, R. Kotaba, J. Park, and R. B. Sorensen. Wireless access for ultra-reliable low-latency communication: Principles and building blocks. IEEE Network, 32(2):16–23, March 2018.
[10] Changyang She, Rui Dong, Wibowo Hardjawana, Yonghui Li, and Branka Vucetic. Optimizing resource allocation for 5G services with diverse quality-of-service requirements. In Proc. IEEE Global Commun. Conf. (GLOBECOM), 2019.
[11] D.N.C. Tse and S.V. Hanly. Linear multiuser receivers: effective interference, effective bandwidth and user capacity. IEEE Trans. Inf. Theory, 45(2):6010–6023, 1999.
[12] D. Wu and R. Negi. Effective capacity: a wireless link model for support of quality of service. IEEE Trans. Wireless Commun., 2(4):630–643, 2003.
[13] Zheng Yang, Zhiguo Ding, Pingzhi Fan, and Naofal Al-Dhahir. A general power allocation scheme to guarantee quality of service in downlink and uplink NOMA systems. IEEE Trans. Wireless Commun., 15(11):7244–7257, 2016.
[14] W. Yu, A. Chorti, L. Musavian, H. Vincent Poor, and Q. Ni. Effective secrecy rate for a downlink NOMA network. IEEE Trans. Wireless Commun., 18(12):5673–5690, Dec 2019.
[15] Wenjuan Yu, Leila Musavian, and Qiang Ni. Link-layer capacity of NOMA under statistical delay QoS guarantees. IEEE Trans. Commun., 66(10):4907–4922, 2018.