Energy-Constrained NOMA with Packet Diversity for Slotted Aloha Systems

F. Babich, G. Buttazzoni, F. Vatta, and M. Comisso
Department of Engineering and Architecture
University of Trieste, Via A. Valerio 10, 34127 Trieste, Italy
E-mail: {babich,gbuttazzoni,vatta,mcomisso}@units.it

Abstract— **Random access algorithms are fundamental mechanisms for managing multiple uncoordinated transmissions towards a common receiver. For such a scenario, which includes satellite and cellular systems, several Non-Orthogonal Multiple Access (NOMA) techniques and different repetition-based strategies have been separately developed. However, few studies jointly analyze the two solutions and propose combined schemes. Purpose of this paper is to fairly compare the actual performance of the two approaches by imposing suitable energy and complexity constraints. The final aim is to explore the benefits provided by the joint adoption of power and packet diversity in a slotted Aloha scheme implementing interference cancellation, focusing on the impact of the energy levels and of the number of packet replicas.**

Index Terms— **Random access; non-orthogonal multiple access; slotted Aloha; packet diversity; energy constraints.**

I. Introduction

Uncoordinated random access represents an important issue to be solved in many wireless networks that cannot rely on a centralized authority, or that have to sustain irregular traffic loads sent by spread transmitters towards a common receiver [1]–[5]. For managing these scenarios, the Slotted Aloha (SA) protocol represents a suitable solution, which is usually adopted in satellite networks and cellular systems. Recently, the SA performance has been significantly improved by jointly introducing energy diversity and Interference Cancellation (IC), whose combination has enabled the design of several Non-Orthogonal Multiple Access (NOMA) schemes [6]. In particular, the NOMA concept allows independent users, adopting the same modulation and the same code rate, to select different energy levels chosen in a set of L elements. The levels are commonly chosen so that, if a group of at most L users select different energy levels in the same slot, all of them may be correctly received by using successive IC. More precisely, successive IC consists of the successive decoding of the user signals. The decoded signals are in fact subtracted from the received one before the decoding of the next signal, so that it can benefit from the removal of the already acquired ones. The process continues until there is a signal with a power level sufficient to guarantee a correct decoding, under the interference coming from the remaining, not already removed signals. Beside NOMA, another alternative strategy has been conceived for improving the SA performance. This strategy consists in combining packet diversity and IC, hence exploiting the transmission of a certain number M of replicas of a packet. In this case, two fixed repetitions may be adopted, according to the Contention Resolution Diversity SA (CRDSA) protocol [7], or a random number of them may be considered, according to the Irregular Repetition SA (IRSA) scheme [8]. This latter algorithm can be further optimized by adding prioritization strategies [9]. Differently, code diversity is adopted by the Coded SA (CSA) scheme [10], in which the packets, instead of being simply repeated, are firstly subdivided into segments and then encoded.

Most of the above cited access schemes are tested assuming an erasure channel model, in which each transmitted packet is individually encoded and its correct reception is established by just considering its decoding in an uncollided or in a cleaned (after IC) slot. Hence, in the erasure scenario, all the collided transmissions not resolved after IC are discarded and cannot be used for improving the packet success probability. On the other hand, in all SA schemes using packet diversity,

[1]This work is partly supported by the Italian Ministry of University and Research within project FRA 2018 (Univ. of Trieste, Italy) "UBER-5G: Cubesat 5G networks - Access layer analysis and antenna system development."

each replica must include a header specifying the number of repetitions referred to a given packet and their position within the frame [7]–[9]. In this way, all the corresponding replicas can be removed from the frame itself, in the case that one of them is correctly decoded. This implies that, when the position of the replicas is known, the content of the collided transmissions might be exploited to improve the success probability through Chase combing, if the individual transmissions are repetitions of the same packet, or through the combination of incremental redundancy and joint decoding [11]–[16]. However, to properly exploit Chase combining or joint decoding, a more robust header encoding is required to increase the probability that at least one among the M headers be correctly received. This strategy results more sensitive to the size of the header, but fosters the subsequent decoding of the entire packet [17].

Some further proposals have investigated the possibility to combine NOMA and packet repetition to jointly exploit the advantages of energy and packet diversity [18]–[20]. These studies have interestingly put into evidence the capability of this combined strategy to solve much more collisions with respect to the sole NOMA or repetition-based schemes. However, two main aspects should be deepened to better understand the reciprocal benefits among the two approaches. Firstly, a common basis for their performance evaluation, which cannot neglect the importance of the energy constraints that unavoidably affect any transmission system. Secondly, the adoption of a reception criterion more evolved than that based on the erasure model and capable to account for the capture effect [21], [22]. In real receivers, this effect may often occur even in the presence of not resolved collisions, whenever the reception power of a packet results sufficiently higher than the overall interference due to the other colliding ones.

To address these two issues, this paper investigates the actual benefits of the joint adoption of NOMA and packet diversity by comparing their performance on the basis of suitable energy constraints, which are used to determine the NOMA energy levels and the transmission power of each packet replica. This evaluation is carried out by firstly employing the erasure model, in order to relate the results to the existing literature, and by subsequently considering Chase combining and joint packet decoding, in order to provide a more practical view of the achievable performance.

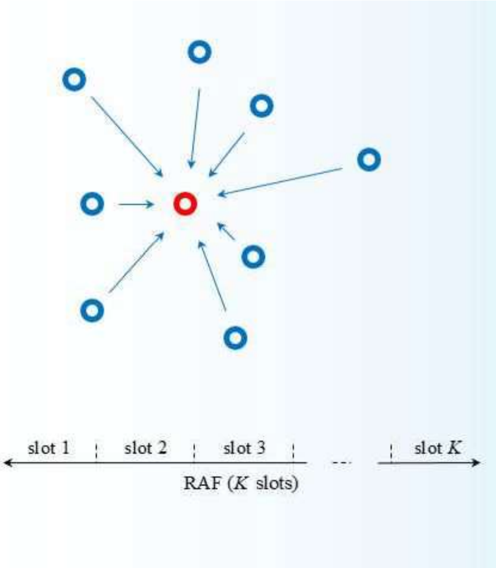

Fig. 1. Network Scenario.

The paper is organized as follows. Section II introduces the addressed scenario. Section III describes the energy model. Section IV presents the obtained results and discusses the interaction among NOMA and packet diversity. Finally, Section V summarizes the main conclusions.

II. Scenario

Consider a network scenario where a certain number of uncoordinated users transmit packets towards a common receiver. Assume to adopt a time division multiple access technique in which the time domain is subdivided into Random Access Frames (RAFs), each of which is in turn subdivided into K slots of identical duration (Fig. 1). In each RAF, a generic transmitter sends at most one packet that can be repeated M times or encoded in M segments. The term 'segment' is here used in general to identify the possibility of adopting either repetition or incremental redundancy, in which the content of a slot may be designed to be individually decodable. Identify by R the transmission rate of the packet. When repetition is not used, and hence just basic NOMA is adopted, the subdivision in RAFs is not necessary and just $M = 1$ segments are present.When, instead, a repetition-based scheme is used, $M = 2$ segments are present for CRDSA,while, for IRSA, the number of segments M becomes a random variable (r.v.) whose possible optimized probability density functions have been determined by density evolution in [20]. Observe that the IRSA parameters have been determined theoretically

L	M			
	2	3	4	8
1	0.5112	0.2660		0.2228
2	0.6607	0.1605		0.1788
3	0.7439	0.0906	0.0156	0.1499
4	0.7947	0.0470		0.1583
5	0.8370			0.1630

TABLE I

IRSA: PROBABILITY OF SELECTING M SEGMENTS AS A FUNCTION OF THE NUMBER L OF ENERGY LEVELS.

by assuming the erasure channel model. Different detection methods might lead to different parameters, whose evaluation is much more involved and out of the scope of this paper.

The performance of each scheme is derived in terms of the throughput S, which is measured as the number of information bits per transmission that are correctly decoded at the common receiver. More precisely, the throughput is expressed as:

$$S = GP_sR, \tag{1}$$

where G is the total offered load (in packets per slot), which represents the rate of the transmitted packets, and P_s is the success probability, which identifies the probability that a packet is successfully received after completing the IC process (in a single slot when repetition is not adopted, or, otherwise, in a RAF). In the first part of this paper, we consider the joint utilization of NOMA and repetition (CRDSA or IRSA) by adopting an erasure model. More precisely, when the erasure channel is assumed, at least one of the M segments has to be correctly received to identify a correct packet reception. In the second part, instead, the joint utilization of the M segments with Chase combining or joint decoding, is taken into consideration. In particular, joint decoding is examined for CRDSA only, in which the full packet, of overall rate R, consists of two segments, whose position, similarly to Chase combining with repetition coding, can be assumed known at the receiver. All tested scenarios are investigated under perfect IC conditions.

III. ENERGY MODEL

Assuming a bi-dimensional modulation and the adoption of the Shannon bound, the minimum Signal to Interference plus Noise Ratio (SINR) required for the correct reception of a packet in the presence of a selected rate R is given by:

$$\alpha = 2^R - 1, \tag{2}$$

which derives from the inversion of the Shannon formula. Identify by L the total number of available power levels and define as E_l/N_0 the energy E_l used by the l-th ($l = 1, ..., L$) NOMA level normalized to the noise spectral density N_0. Observe that R represents the adopted modulation/code pair and may be seen as a further constraint on the receiver complexity. For allowing the correct detection of a packet when all transmitters use different energy levels, the following constraint must be met [6]:

$$\frac{E_l/N_0}{1+\sum_{i=1}^{l-1} E_i/N_0} \geq \alpha, \quad l = 1, ..., L. \tag{3}$$

It may be shown that (3) is satisfied when the l-th normalized energy level is given by:

$$E_l/N_0 = \alpha_1 \ (1+\alpha_1)^{l-1}, \quad l = 1, ..., L, \tag{4}$$

where $\alpha_1 = m_f \alpha$ accounts for a possible margin $m_f (\geq 1)$. Assuming, for simplicity, that all the energy levels are equally likely, the normalized average energy can be expressed as:

$$E_{\text{av}}/N_0 = \frac{(1+\alpha_1)^L - 1}{L} \, \mathrm{E}[M], \tag{5}$$

in which $\mathrm{E}[M]$ is the average number of repetitions. For a proper comparison among the different access techniques, the normalized average energy should be set to a desired value. Thus, recalling (5), the number of levels must satisfy the following constraint:

$$\frac{(1+\alpha)^L - 1}{L} \leq \frac{(1+\alpha_1)^L - 1}{L} = \frac{E_{\text{av}}/N_0}{\mathrm{E}[M]}. \tag{6}$$

In the IRSA case, M is a r.v. that depends on the number of levels, whose the probabilities, selected according to [20, Tab. I], are summarized in Table I. Using these values and fixing L, $\mathrm{E}[M]$, and E_{av}/N_0, the minimum normalized average energies (i.e., the SINR thresholds) required for the correct reception of a segment can be obtained (Table II).

IV. PERFORMANCE EVALUATION

This section is organized in three parts. The first part presents the capture probability evaluated at the first round of capture, that is, when IC has not been even applied to the RAF. The second one discusses the performance for the erasure channel model, while the third part extends the considerations to the case where the contributions of the different segments are combined.

	NOMA		CRDSA		IRSA	
L	M	$E_{\rm av}/N_0$ [dB]	M	$E_{\rm av}/N_0$ [dB]	E[M]	$E_{\rm av}/N_0$ [dB]
1	1	3.74	2	6.75	3.60	9.30
2	1	7.12	2	10.13	3.23	12.22
3	1	10.92	2	13.93	3.02	15.72
4	1	15.02	2	18.03	3.00	19.78
5	1	19.34	2	22.35	2.98	24.08

TABLE II

$E_{\rm av}/N_0$ THRESHOLDS FOR $R = 7/4$ INFORMATION BITS/SYMBOL.

A. Capture probability

The evaluation of the capture probability at the first round of capture is a useful indicator to compare the different reception schemes and underline the influence of the different L values. Observe that, by construction, all packets are captured when all transmitters use different energy levels, while, when some lower energy levels are used by more than one transmitter, the capture of the higher energy packets depend on the actually used energies. In this case, to determine the capture probability p_c, it is necessary to first determine the cumulative density function of the SINR for the best user in a slot, given the number of transmitters (i.e.. the interference context of the best user). In this way, p_c can be determined as a function of rate R. In particular, for $M > 1$, the combined effect of the M segments can be evaluated accounting for three possibilities: the maximum SINR (erasure channel), the total SINR (Chase combing), and the average sustainable rate (code combining) for efficient coding techniques [23]–[25]. More precisely, consider, for the erasure channel, a single slot transmission (i.e., the scenario with $M = 1$) with $N + 1$ transmitters, where the generic n-th transmitter uses an energy level E_{l_n}. Denoting as E_{l_0} the level of the possibly successful transmitter and assuming that the remaining energy levels are organized in non-increasing order, that is, $E_{l_0} > E_{l_1} \geq ... \geq E_{l_N}$, the success condition is given by:

$$\frac{\alpha_1 \left(1+\alpha_1\right)^{l_0-1}}{1+\alpha_1 \left[\sum_{n=1}^{N} \left(1+\alpha_1\right)^{l_n-1}\right]} \geq \alpha. \tag{7}$$

From (7), we obtain the condition that should be met by the user with the lowest energy level:

$$l_N \leq \frac{\log\left[\frac{(1+\alpha_1)^{l_0-1}}{\alpha} - \frac{1}{\alpha_1} - \sum_{n=1}^{N-1} (1+\alpha_1)^{l_n-1}\right]}{\log\left(\alpha_1+1\right)} + 1, \tag{8}$$

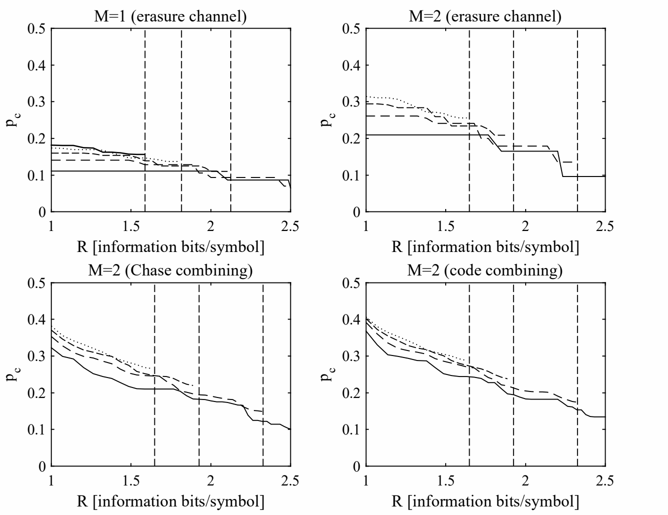

Fig. 2. Capture probability as a function of the rate for $N = 4$, $E_{\rm av}/N_0 =$ 25 dB, and different L values: $L = 3$ (solid thin line), $L = 4$ (dashed line), $L = 5$ (dash-dotted line), $L = 6$ (dotted line), $L = 7$ (solid thick line). The vertical dash-dotted lines denote the limiting rates for $L = 5, 6, 7$ when $M = 1$ (first subfigure) and for $L = 4, 5, 6$ when $M = 2$ (other three subfigures).

in which the log arguments are positive just when the interference context enables the successful reception. Observe that condition (7) is always met when $N + 1 \leq L$ and the levels are strictly decreasing. For the erasure channel, the extension to the case $M = 2$ with repetition is immediate, since it is sufficient that at least one of the replicas is successfully received, while the extension to the combining techniques is slightly more complex. An example for a given N value is reported in Fig. 2. In this figure, the capture probability given the interference context is obtained taking into account the number of levels that comply with (3). In particular, for basic NOMA ($M = 1$) with $E_{\rm av}/N_0 = 25$ dB, the preferable choices are: $L \leq 7$ for $R < 1.58$, $L \leq 6$ for $R < 1.81$, and $L \leq 5$ for $R < 2.12$. Despite the specific choices, however, it is worth to observe that, in almost all conditions, the maximum value of L ensures the maximum capture probability given the interference context, and, in turn, the maximum throughput.

B. Erasure model

Let us now examine the throughput and the success probability of the different schemes as a function of the average energy adopting the well established erasure model. The performance of the investigated schemes, which are implemented in Matlab, is evaluated through Monte Carlo simulations by averaging the results over 1000 realizations. Fig. 3 shows the

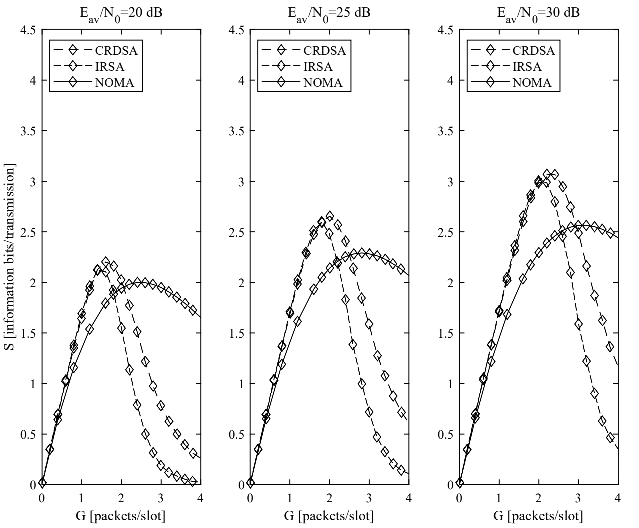

Fig. 3. Throughput as a function of the offered load for $R = 7/4$ information bits/symbol and $K = 20$ using the erasure model and considering different energy values: basic NOMA (solid line), CRDSA/NOMA (dashed line), IRSA/NOMA (dash-dotted line).

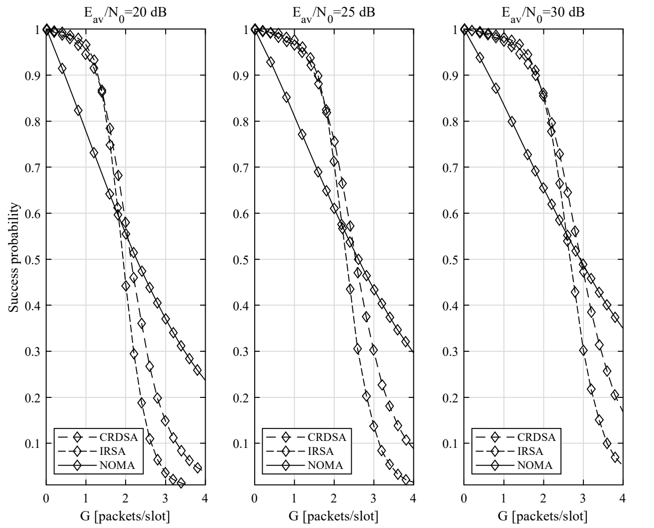

Fig. 4. Success rate as a function of the offered load for $R = 7/4$ information bits/symbol and $K = 20$ using the erasure model and considering different energy values: basic NOMA (solid line), CRDSA/NOMA (dashed line), IRSA/NOMA (dash-dotted line).

throughput of basic NOMA ($M = 1$), and of CRDSA ($M = 2$) and IRSA (M r.v.) combined with NOMA. The curves are derived for $K = 20$ and $R = 7/4$ information bits/symbol, considering three values of $E_{\rm av}/N_0$, corresponding to 20, 25, and 30 dB. The figure puts into evidence that CRDSA and IRSA slightly outperform the basic NOMA at low loads, while the basic NOMA is more robust against possible overloads. The figure also shows that CRDSA and IRSA are more sensitive to the available energy level than basic NOMA, and that a sufficiently high average energy is necessary to obtain significant advantages. Fig. 4 shows the success probability of the techniques under evaluations in the same conditions. The figure reveals that CRDSA and IRSA allow a significant increment of the success probability at low to moderate loads, making retransmissions unnecessary. This may be considered as the most important benefit obtained by adopting packet repetition in the erasure channel.

Let us now fix the energy value and observe the effects of the frame length on the derived performance. Figs. 5 and 6 respectively report the throughput and the success probability of basic NOMA, and of CRDSA and IRSA combined with NOMA, for $R = 7/4$ information bits/symbol, $E_{\rm av}/N_0 = 25$ dB, and selecting $K = 20, 50, 100$ slots. These figures show that CRDSA and IRSA both benefit from the increase of the RAF duration and that this effect is more evident for IRSA, which, however, is less robust to the overload. As a final situation for the erasure model, consider the effects of the code rate on the performance. To this aim, Figs. 7 and 8 respectively investigate the throughput and the success probability of basic NOMA, NOMA/CRDSA, and NOMA/IRSA for $E_{\rm av}/N_0 = 25$ dB and $K = 20$ by choosing $R = 2, 7/4, 3/2$ information bits/symbol. This latter result clarifies that the usefulness of the lower rates consists in the achievement of a higher success probability at low loads.

In summary, the presented results prove that, for the erasure channel model, CRDSA and IRSA with NOMA both outperform basic NOMA at low loads, provided that a sufficiently high number of slots and a sufficient amount of energy are available. This suggests that CRDSA/NOMA and IRSA/NOMA may be specifically suitable for delay-tolerant network scenarios and high-power transmission systems. The overall advantages become more evident when, beside the throughput, also the success probability is considered. Basic NOMA, instead, remains the most robust alternative at high channel loads.

C. *Chase and code combining*

Let us now move from the erasure model to more advanced decoding strategies that take into account the contributions deriving from all the received replicas or segments. To this

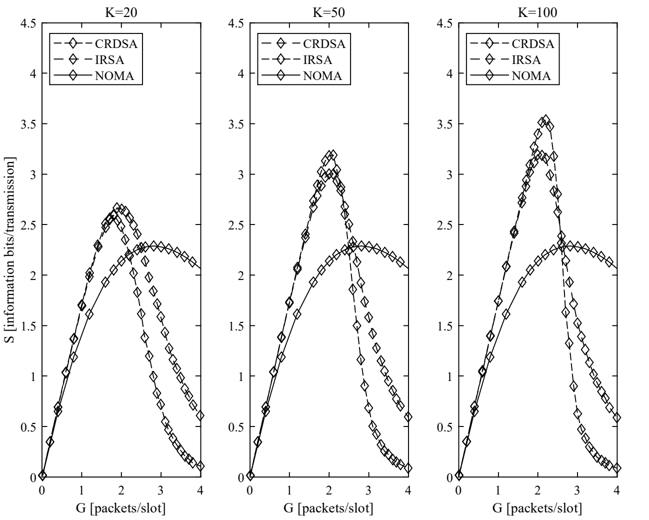

Fig. 5. Throughput as a function of the offered load for $R = 7/4$ information bits/symbol and $E_{\rm av}/N_0 = 25$ dB using the erasure model and considering different RAF durations: basic NOMA (solid line), CRDSA/NOMA (dashed line), IRSA/NOMA (dash-dotted line).

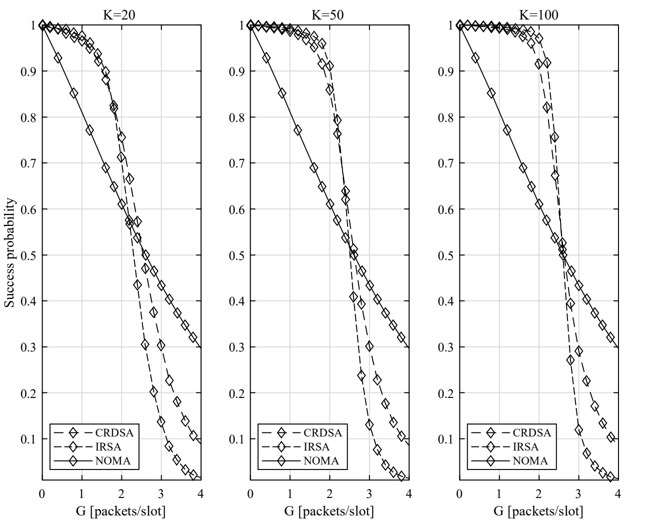

Fig. 6. Success rate as a function of the offered load for $R = 7/4$ information bits/symbol and $E_{\rm av}/N_0 = 25$ dB using the erasure model and considering different RAF durations: basic NOMA (solid line), CRDSA/NOMA (dashed line), IRSA/NOMA (dash-dotted line).

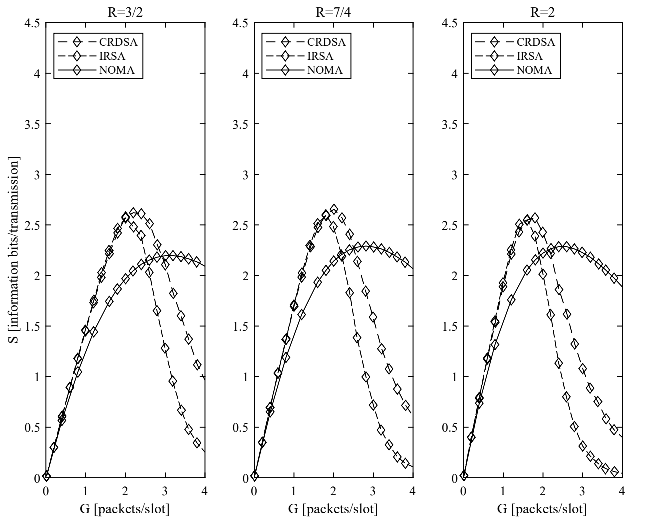

Fig. 7. Throughput as a function of the offered load for $E_{\rm av}/N_0 = 25$ dB and $K = 20$ using the erasure model and considering different transmission rates: basic NOMA (solid line), CRDSA/NOMA (dashed line), IRSA/NOMA (dash-dotted line).

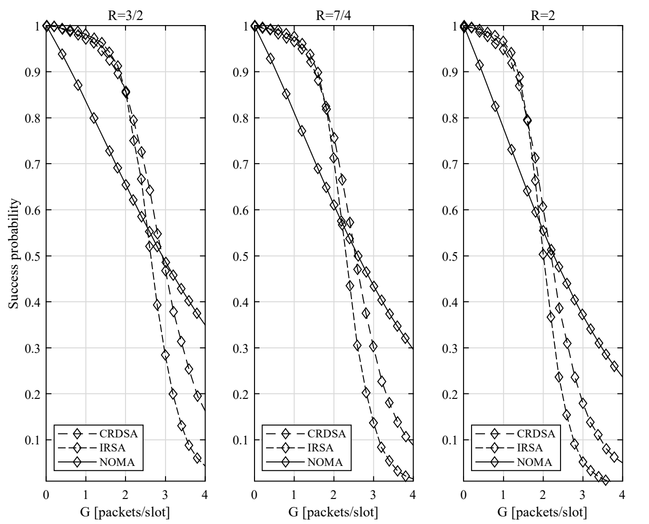

Fig. 8. Success rate as a function of the offered load for $E_{\rm av}/N_0 = 25$ dB and $K = 20$ using the erasure model and considering different transmission rates: basic NOMA (solid line), CRDSA/NOMA (dashed line), IRSA/NOMA (dash-dotted line).

purpose, Figs. 9 to 12 describe the combined effect of the transmission rate and of the reception model for $E_{\rm av}/N_0 = 25$ dB, for a number of slots $K = 20$, and selecting $R = 2, 7/4, 3/2$ information bits/symbol. In particular, Figs. 9 and 10 are derived adopting Chase combining for the two combined schemes (CRDSA/NOMA and IRSA/NOMA), while Figs. 11 and 12 are obtained using joint decoding for the sole CRDSA/NOMA scheme. In all figures, the performance of basic NOMA is also shown for comparison purposes.

This last set of results reveals that the advantages achievable by decreasing the transmission rate are more significant when the content of all the received replicas is exploited. Besides, the presented curves confirm that IRSA/NOMA, given the larger amount of packet diversity of some transmissions (corresponding to the higher random M values), may benefit more from the use of packet combining. As expected, joint packet

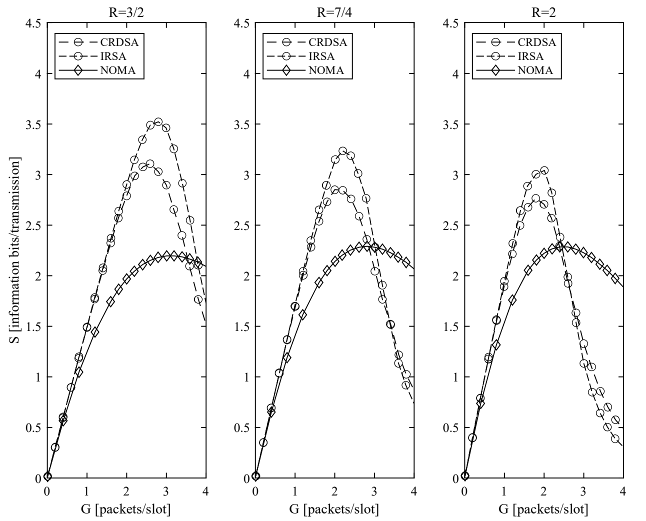

Fig. 9. Throughput as a function of the offered load for $E_{\rm av}/N_0 = 25$ dB and $K = 20$ using Chase combining and considering different transmission rates: basic NOMA (solid line), CRDSA/NOMA (dashed line), IRSA/NOMA (dash-dotted line).

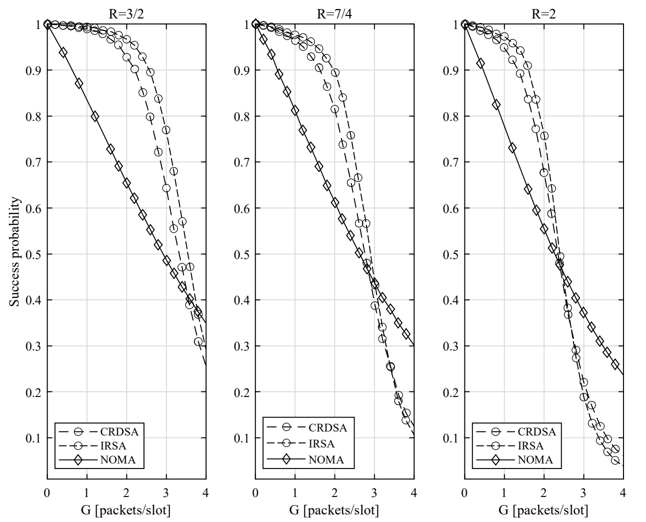

Fig. 10. Success rate as a function of the offered load for $E_{\rm av}/N_0 = 25$ dB and $K = 20$ using Chase combining and considering different transmission rates: basic NOMA (solid line), CRDSA/NOMA (dashed line), IRSA/NOMA (dash-dotted line).

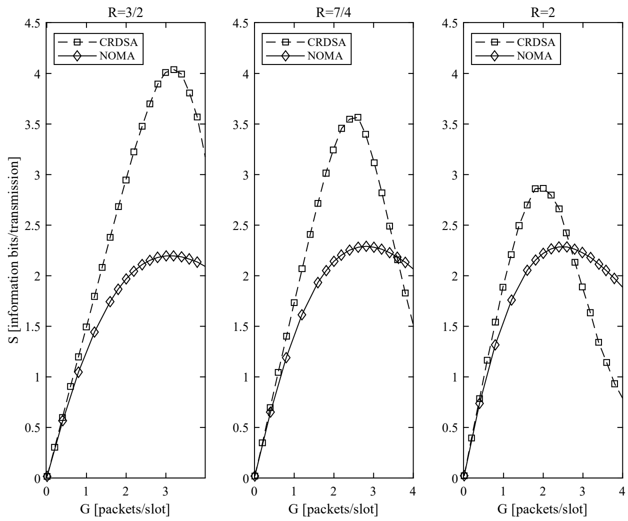

Fig. 11. Throughput as a function of the offered load for $E_{\rm av}/N_0 = 25$ dB and $K = 20$ using incremental redundancy with joint decoding and considering different transmission rates: basic NOMA (solid line), CRDSA/NOMA (dashed line).

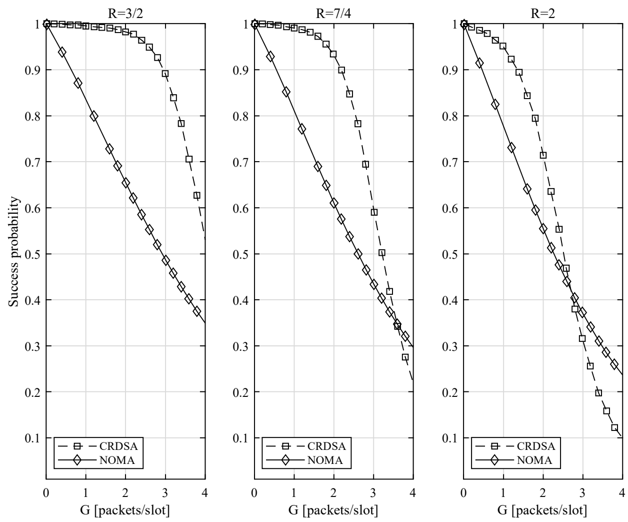

Fig. 12. Success rate as a function of the offered load for $E_{\rm av}/N_0 = 25$ dB and $K = 20$ using incremental redundancy with joint decoding and considering different transmission rates: basic NOMA (solid line), CRDSA/NOMA (dashed line).

decoding enables to better exploit the different energy levels when a low rate is selected. This benefit is however acquired at the expense of an increased decoding complexity.

V. Conclusions

Wireless networks must sustain an increasing amount of traffic, part of which derives from uncoordinated sources that attempt to access to a common receiver. This scenario urges the researchers and the standard developers to define efficient random access techniques able to handle these irregular conditions. Moving from the basic SA algorithm, adopted by many common networks, NOMA and packet diversity schemes may allow significant performance improvements. In this context, this paper has tested the joint adoption of NOMA and repetition-based strategies by assuming suitable and complexity energy constraints. The results have shown that the combined CRDSA/NOMA and IRSA/NOMA schemes benefit from an increased availability of energy and from a longer frame duration (that is, from an increased acceptable delay). Furthermore, CRDSA and IRSA allow a significant increment of the success probability at low to moderate loads, making retransmissions substantially unnecessary. Further improvements and deeper views of the actual performance have been observed by adopting reception criteria more advanced than the widely used erasure model. These criteria, which are able to model the capture effect, have been successfully applied to understand that the throughput of a combined scheme benefits from the exploitation of the content of all the received replicas or segments.

As a final consideration, it is worth to remark that, to properly exploit Chase or code combining, a suitable self-decodable pointer should be added to each segment or replica. Current research efforts aim to deepen this latter aspect by moving from the initial study in [17]. Further investigations are devoted to extend the formulated considerations on power diversity (NOMA), packet diversity (CRDSA and IRSA), and code diversity (IRSA) to other forms of diversity, including those provided by the random channel fluctuations, such as multipath-fading and shadowing.

REFERENCES

[1] A.S. Lalos, M. Di Renzo, L. Alonso, and C. Verikoukis, "Impact of correlated log-normal shadowing on two-way network coded cooperative wireless networks," *IEEE Commun. Lett.*, vol. 17, no. 9, pp. 1738–1741, Sep. 2013.

[2] F. Babich, M. Comisso, and A. Dorni, "A novel SIR-based access scheme for multi-packet communication in 802.11 networks," in *IEEE ICC*, 2012.

[3] A. Antonopoulos, A.S. Lalos, M. Di Renzo, and C. Verikoukis, "Cross-layer theoretical analysis of NC-aided cooperative ARQ protocols in correlated shadowed environments," *IEEE Trans. Veh. Technol.*, vol. 64, no. 9, pp. 4074–4087, Sep. 2015.

[4] M. Di Renzo, "Stochastic geometry modeling and analysis of multi-tier millimeter wave cellular networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 9, pp. 5038–5057, Sep. 2015.

[5] F. Babich and M. Comisso, "Including the angular domain in the analysis of finite multi-packet peer-to-peer networks with uniformly distributed sources," *IEEE Trans. Commun.*, vol. 64, no. 6, pp. 2494–2510, June 2016.

[6] C. Xu, L. Ping, P. Wang, S. Chan, and X. Lin, "Decentralized power control for random access with successive interference cancellation," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 11, pp. 2387–2395, Sep. 2013.

[7] E. Casini, R. De Gaudenzi, and O. del Rio Herrero, "Contention resolution diversity slotted ALOHA (CRDSA): An enhanced random access scheme for satellite access packet networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 4, pp. 1408–1419, Apr. 2007.

[8] G. Liva, "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA," *IEEE Trans. Commun.*, vol. 59, no. 2, pp. 477–487, Feb. 2011.

[9] L. Toni and P. Frossard, "Prioritized random MAC optimization via graph-based analysis," *IEEE Trans. Commun.*, vol. 63, no. 12, pp. 5002–5013, Dec. 2015.

[10] E. Paolini, G. Liva, and M. Chiani, "Coded slotted ALOHA: A graph-based method for uncoordinated multiple access," *IEEE Trans. Inf. Theory*, vol. 61, no. 12, pp. 6815–6832, Dec. 2015.

[11] F. Clazzer, E. Paolini, I. Mambelli, and Č. Stefanović, "Irregular repetition slotted ALOHA over the Rayleigh block fading channel with capture," in *IEEE ICC*, 2017.

[12] F. Clazzer , C. Kissling, and M. Marchese, "Enhancing contention resolution ALOHA using combining techniques," *IEEE Trans. Commun.*, vol. 66, no. 6, pp. 2576–2587, June 2018.

[13] F. Babich and M. Comisso, "Segmented framed slotted Aloha (SFSA) with capture and interference cancellation," in *IEEE VTC-Spring*, 2018.

[14] F. Babich and M. Comisso, "Impact of segmentation and capture on slotted Aloha systems exploiting interference cancellation," *IEEE Trans. Veh. Technol.*, vol. 68, no. 3, pp. 3613–3627, Mar. 2019.

[15] A. Mengali, R. De Gaudenzi, and Č. Stefanović, "On the modeling and performance assessment of random access with SIC," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 2, pp. 292–303, Feb. 2018.

[16] A. Mengali, R. De Gaudenzi, and P. D. Arapoglou, "Enhancing the physical layer of contention resolution diversity slotted ALOHA," *IEEE Trans. Commun.*, vol. 65, no. 10, pp. 4295–4308, Oct. 2017.

[17] F. Babich and M. Comisso "Impact of header on coded slotted Aloha with capture," *IEEE ISCC*, 2019.

[18] J. Choi, "NOMA-based random access with multichannel ALOHA," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 12, pp. 2736–2743, Dec. 2017.

[19] S. Alvi, S. Durrani, and X. Zhou, "Enhancing CRDSA with transmit power diversity for machine-type communication," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 7790–7794, Aug. 2018.

[20] X. Shao, Z. Sun, M. Yang, S. Gu, and Q. Guo, "NOMA-based irregular repetition slotted ALOHA for satellite networks," *IEEE Commun. Lett.*, vol. 23, no. 4, pp. 624–627, Apr. 2019.

[21] M. Comisso and F. Babich, "Coverage analysis for 2D/3D millimeter wave peer-to-peer networks," *IEEE Trans. Wireless Commun.*, vol. 18, no. 7, pp. 3613–3627, July 2019.

[22] T. Bai and R.W. Heath Jr., "Coverage and rate analysis for millimeter-wave cellular networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 2, pp. 1100–1114, Feb. 2015.

[23] F. Babich and A. Crismani, "Cooperative coding schemes: Design and performance evaluation," *IEEE Trans. Wireless Commun.*, vol. 11, no. 1, pp. 222–235, Jan. 2012.

[24] P. Kota and C. Schlegel, "A wireless packet multiple access method exploiting joint detection," in *IEEE ICC*, 2003.

[25] F. Vatta, A. Soranzo, and F. Babich, "More accurate analysis of sum-product decoding of LDPC codes using a Gaussian approximation," *IEEE Commun. Lett.*, vol. 23, no. 2, pp. 230–233, Feb. 2019.