This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCOMM.2020.3007744, IEEE Transactions on Communications

Slotted ALOHA with NOMA for the Next Generation IoT

Sotiris A. Tegos, *Student Member, IEEE,* Panagiotis D. Diamantoulakis, *Senior Member, IEEE,* Athanasios S. Lioumpas, Panagiotis G. Sarigannidis, *Member, IEEE,* and George K. Karagiannidis, *Fellow, IEEE*

***Abstract*—Random access (RA) has recently been revisited and considered as a key technology for the medium access control layer of the Internet of Things applications. Compared to other RA protocols, slotted ALOHA (SA) has the advantages of low complexity and elimination of partially overlapping transmissions, reducing the number of collisions, however it may suffer from congestion as the traffic load and the number of devices increase. To this end, two RA protocols based on SA and uplink non-orthogonal multiple access are proposed and applied to wireless sensor networks and wireless powered sensor networks. More specifically, to reduce the number of collisions and increase the throughput of SA, while maintaining low complexity, two detection techniques are used to mitigate the interference, when two sources transmit information at the same time slot, namely successive interference cancellation (SIC) with optimal decoding order policy and joint decoding (JD). To evaluate the performance of the proposed protocols, the outage probability of SIC and JD is derived, which is used to express the average throughput attained by each protocol in closed-form. Finally, both the analytical results and simulations verify that the proposed protocols substantially increase the throughput and the number of connected devices compared to SA.**

***Index Terms*—Random access, slotted ALOHA, uplink NOMA, energy harvesting, wireless power transfer, outage probability, wireless powered sensor network**

I. Introduction

With the development of the Internet of Things (IoT) a massive amount of wireless devices is expected to be used in IoT applications, creating several research, innovation and implementation challenges. The priorities of the European Union in the Next Generation Internet of Things (NGIoT) include the development of reliable, low-cost, sustainable and scalable wireless sensor networks (WSNs), IoT miniaturization, energy harvesting, and pervasiveness [1]. It should be highlighted that the performance of the IoT networks, their energy consumption, and the number of connected sensors are severely affected by the design of the utilized multiple access protocols, which is the main focus of this paper.

Multiple access can be achieved through either an organized and predetermined approach, which requires coordination among sources, such as time division multiple access (TDMA), or a different approach where sources share the medium in a random and distributed way. In WSNs for IoT applications, where sources with sparse activity are usually used, simpler protocols are more practical and, thus, the later approach is more useful. Therefore, random access (RA) has recently been revisited and considered as a key technology for the medium access control (MAC) layer of the IoT, due to offering many advantages, such as low latency for small payload transmissions, without requiring initial connection setup, dedicated resource allocation for connection maintenance, or signaling overhead for radio resources allocation. Compared to other RA protocols, e.g., pure ALOHA, slotted ALOHA (SA) [2] avoids collisions due to partially overlapping transmissions, while retaining low complexity. To this end, SA has received increased researcher's attention lately and constitutes one of the candidates of 5G RA protocol for machine-to-machine (M2M) communications [3], [4]. Moreover, SA has found several applications in different wireless communication setups, including existing and emerging technologies such as radio frequency identification (RFID) networks, Long-Term Evolution (LTE) networks [5], WSNs [6] and MTC [7]–[10]. However, despite its advantages, SA may suffer from congestion as the traffic load and the number of sources increase.

On the other hand, non-orthogonal multiple access (NOMA) besides increasing the spectral efficiency compared to orthogonal multiple access (OMA) schemes, e.g., TDMA, also facilitates massive connectivity, which is one of the main objectives in WSNs of the NGIoT ecosystem. It should be highlighted that although pure NOMA is a coordinated multiple access scheme [11]–[13], its principles can also be applied to RA schemes [14]. Since NOMA utilizes the power domain to achieve multiple access [15], multiuser detection techniques are required to retrieve the sources' signals at the receiver, such as successive interference cancellation (SIC) [16] or joint decoding (JD). In SIC, the signal of one source is decoded by treating the signals of other sources as interference, and subtracted from the received signals if successfully decoded. Therefore, SIC can mitigate interference, which is caused by the simultaneous utilization of the system resources. In JD,

S. A. Tegos, P. D. Diamantoulakis, and G. K. Karagiannidis are with Wireless Communication Systems Group (WCSG), Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54 124, Thessaloniki, Greece (e-mails: tegosoti@auth.gr, padiaman@ieee.org, geokarag@auth.gr).

A. S. Lioumpas is with the Forthnet S.A., Athens, Greece (e-mail: aliou@forthnet.gr).

P. G. Sarigiannidis is with Department of Informatics and Telecommunications Engineering, University of Western Macedonia, 501 00 Kozani, Greece (e-mail: psarigiannidis@uowm.gr).

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 833955.

The research work of S. A. Tegos was supported by the Hellenic Foundation for Research and Innovation (HFRI) under the HFRI PhD Fellowship grant (Fellowship Number: 1394).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCOMM.2020.3007744, IEEE Transactions on Communications

the received signals of all active sources are jointly decoded and the capacity region of both Gaussian and fading multiple access channel can be achieved [17], [18].

Moreover, WSNs can benefit significantly from energy harvesting (EH) [19], especially when replacing or recharging the batteries of the devices is inconvenient, costly or dangerous, such as in industrial or healthcare applications. The reliability of WSNs with EH can be increased when energy sources that intentionally generate energy, such as radio frequency (RF) signals, are used, which is the basis of wireless power transfer (WPT) [20]. Nevertheless, WPT creates unique challenges in the design of communication systems causing a tradeoff between information transmission and EH, since nodes can neither receive nor transmit information when harvesting energy [21]. To this end, simultaneous wireless information and power transfer (SWIPT), which aims at unifying the information and energy transmission, deals with this complication of the design of communication systems [22]. SWIPT enables wireless nodes to either use part of the received energy for EH when receiving information [23] or utilize the received energy to sequentially transmit their information using the harvest-then-transmit protocol [24]–[26], with the latter being considered in the present contribution.

A. Motivation

Taking into consideration the simplicity of ALOHA, as well as the superior throughput performance of NOMA and its ability to resolve collisions with the use of multiuser detection techniques, a hybrid ALOHA-NOMA scheme appears as an interesting alternative MAC protocol for low complexity IoT devices. It should be highlighted that the main disadvantages of ALOHA, i.e., the low throughput and the high collision rate, can be mitigated by NOMA, as it has been presented in the pioneering works [27] and [14]. More specifically, in [27], a NOMA-based RA scheme with multichannel ALOHA has been proposed, where sources can choose predetermined power levels to transmit their information. In this work, SIC with perfect channel state information (CSI) has been used with the assumption that each source knows its CSI. Furthermore, in [14], a layered RA scheme based on uplink NOMA and multichannel ALOHA has been studied, where SIC is used. However, the considered decoding order policy is suboptimal as proved in [28] and the derived expression for the throughput is an approximation. Moreover, predetermined power levels have also been used in a NOMA-based irregular repetition SA scheme for satellite networks [29], while in [30], a multichannel NOMA-ALOHA scheme is considered, where a game has been formulated when NOMA is applied to ALOHA to decide sources' access or transmission probabilities. Furthermore, in [31], a MAC protocol has been proposed incorporating pure ALOHA with NOMA in which the number of transmitters are not known a priori and estimated with multihypothesis testing. In [32], a non-orthogonal RA protocol has been proposed which integrates the arrival time-based multi-preamble detection and distance-based RA response reception schemes to effectively improve the preamble transmission success probability. Nevertheless, in the existing literature, closed-form expressions for the throughput of the considered NOMA-ALOHA schemes have not been derived. Moreover, only SIC is considered, while the effect of JD has not been investigated in such schemes. To this end, to extract a closed-form expression for the average throughput utilizing both SIC or JD, the expressions for the outage probability of these techniques are necessary. However, closed-form expressions for the outage probability of SIC with the optimal decoding order policy and JD in uplink NOMA, which are not a straightforward extension of the ones in downlink NOMA, have not been derived.

Moreover, applying a RA scheme, such as SA, in wireless powered sensor networks (WPSNs) has received researchers' attention recently, as EH sources have a limited and sporadic energy supply and, thus, cannot utilize complex communication protocols. More specifically, in [33], a SA-based EH MAC protocol has been proposed, where each source randomly selects one of the given time slots and continuously harvests the energy from the base station (BS) until the start of the chosen time slot. In [34], a wireless powered communication network (WPCN) where SA is employed has been studied, where sources harvest the broadcasted energy and use it to transmit information back to the BS with a specific rate. In [35], a WPCN similar to [34] has been considered, assuming that the BS is mounted on unmanned aerial vehicle (UAV). However, in the existing literature, a NOMA-based RA scheme has not been investigated in the context of WPSNs.

B. Contribution

In the present work, we propose two RA protocols based on SA and uplink NOMA utilizing both SIC with the optimal decoding order policy and JD. These protocols aim to reduce the number of collisions and increase throughput of SA, while maintaining low complexity. Compared to the SA scheme, the complexity increases solely at the BS's side where the superimposed signal is received and decoded and, thus, it does not affect the sources which transmit their signals as in the case of SA. The proposed protocols can be utilized in WSNs but their utilization can be extended to WPSNs. More specifically, the contributions of this work are listed below:

- We propose two RA protocols based on SA and uplink NOMA utilizing both SIC and JD, termed as SA-NOMA-SIC and SA-NOMA-JD, respectively, which are deployed in a WSN and in a WPSN. The proposed protocols are proved to always outperform SA in terms of average and sum throughput.
- We derive the average throughput of the proposed protocols. The expression for the average throughput requires the corresponding of the outage probability. To this end, we derive the outage probability of uplink NOMA with SIC with the optimal decoding order policy and JD, where two sources transmit information to the BS and the general case of Nakagami-m fading is assumed. The outage probability is also derived for the special case of Rayleigh fading where the expressions are simplified and the behavior in the high signal-to-noise ratio (SNR) regime is investigated and discussed.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCOMM.2020.3007744, IEEE Transactions on Communications

- We provide simulation results to compare the considered systems with the SA counterpart. These results demonstrate the substantial superiority of the proposed protocols, which can be utilized in a twofold way, i.e., either by increasing the throughput of the network or by increasing the number of the connected sources maintaining the throughput that can be achieved by each source with SA. Finally, regarding the comparison of the two proposed protocols, SA-NOMA-JD outperforms SA-NOMA-SIC in the medium and high SNR regime.

C. Structure

The rest of the paper is organized as follows: Section II describes the proposed protocols and the system model for both a WSN and a WPSN where the proposed protocols are deployed. In Section III, the outage probability when SIC with the optimal decoding order policy is used is derived and the corresponding average throughput for both considered networks. In Section IV, the previous analysis is performed for the case of JD. In Section V, simulation results are provided to corroborate the derived analytic results and to illustrate the performance of the proposed protocols. Finally, closing remarks and discussions are provided in Section VI.

II. Protocols Description and System Model

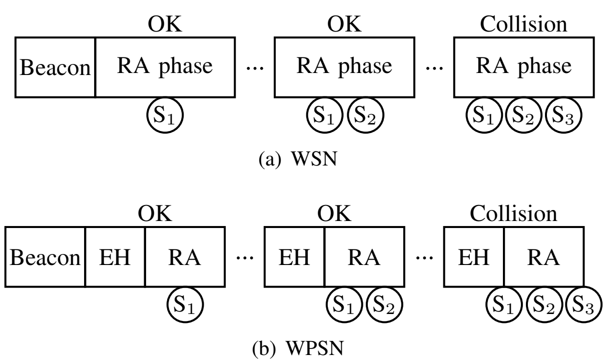

Fig. 1. The frame structure of the proposed protocols and examples of the multiuser access.

We consider a WSN consisting of a BS and N sources. It is assumed that all nodes are equipped with a single antenna and operate in half duplex mode. It is further assumed that the time is divided into frames and the BS has perfect CSI.

A. Proposed Protocols

At the beginning of the frame, the BS broadcasts the beacon packet for frame synchronization and to inform the sources about the number of RA slots in a specific frame. Each beacon is followed by M time slots used for information transmission from the sources. Each time slot has duration T.

We consider the random variable $I_i \in \{0,1\}$ which is defined as the outcome of a Bernoulli trial [34], i.e.,

$$I_i(t) = \begin{cases} 1, & \text{with probability } q_i \\ 0, & \text{with probability } 1-q_i. \end{cases} \tag{1}$$

The success probability of I_i, i.e., $\mathbb{E}[I_i] = q_i$ corresponds to two different but mathematically identical scenarios. More specifically:

- each source always has information to transmit and q_i determines the probability that the i-th source tries to access the channel in a specific time slot.
- each source does not always have information to transmit and q_i determines the joint probability that the i-th source has information to transmit and tries to access the channel in this time slot.

Regarding the scenario where the sources do not always have information to transmit, q_i depends on the traffic distribution and the use case. Practically, the source should estimate $\mathbb{E}[I_i]$ based on the actual traffic demands and feed the BS with this value. The accuracy of this information depends on various conditions, such as the statistics of the traffic pattern and it is out of the scope of this work. On the other hand, assuming that the sources have always information to transmit, q_i is determined by the BS and a scheduling algorithm can be used to calculate and, thus, optimize q_i subject to a specific performance metric, e.g., sum throughput. These values are transmitted by the BS to the sources in the beacon packet. This case has been taken into account in our simulations.

In order to reduce the number of collisions and increase the throughput of SA while maintaining low complexity, we propose two protocols based on the combination of SA and uplink NOMA, as shown in Fig. 1(a). More specifically, the use of either SIC or JD is proposed to mitigate the interference, when two sources transmit information in the same time slot and, thus, the proposed protocols are termed as SA-NOMA-SIC and SA-NOMA-JD, respectively. To this context, if two sources transmit information in the same time slot, a collision does not occur unlike the case of SA. It should be highlighted that scheduling two sources to perform NOMA is aligned with how NOMA is implemented in LTE Advanced [36] and also that in SA the probability that more than two sources transmit in the same time slot is significantly lower than that of the complementary event. More specifically, the probability that the number of sources K that access the channel in the same time slot is k results from the product of N Bernoulli trials and is given by the probability mass function of the Poisson's binomial distribution and can be written as [37]

$$\Pr(K=k) = \sum_{A \in F_k} \prod_{i \in A} q_i \prod_{j \in A^{\mathrm{c}}} (1-q_j), \tag{2}$$

where F_k is the set of all subsets of k integers that can be selected from $\{1, 2, ..., N\}$, A is an ordered subset of F_k whose elements are arranged in increasing order and A^{c} is the complement of A. If we consider $q_i = q$ for all sources, the probability in (2) is given by the probability mass function of the binomial distribution and can be written as

$$\Pr(K=k) = \binom{N}{k} q^k (1-q)^{N-k}. \tag{3}$$

For example, if we consider $N = 10$ sources and $q_i = \frac{1}{N}$, $\Pr(K=1) = 38.74\%$, $\Pr(K=2) = 19.37\%$ and $\Pr(K > 2) = 7.02\%$.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCOMM.2020.3007744, IEEE Transactions on Communications

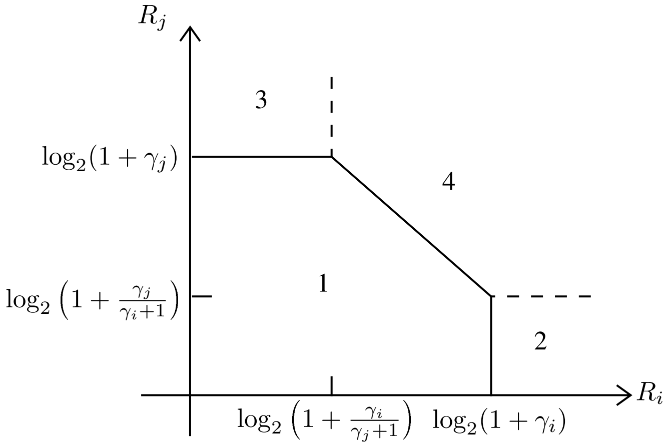

Fig. 2. Achievable rate region.

B. Achievable Rate

Assuming that only the i-th source accesses the channel in a time slot, the achievable rate of this source is given by

$$R_i = \log_2(1+\gamma_i) \tag{4}$$

with $\gamma_i = \frac{l_i |h_i|^2 p_i}{\sigma^2}$, where σ^2 denotes the variance of the ambient additive white Gaussian noise (AWGN) and h_i and p_i denote the small scale fading coefficient between the i-th source and the BS and the transmitted power of the i-th source, respectively. In this work, the channel between the i-th source and the BS is modeled as a quasi-static block fading channel, where each fading block coincides with a single time slot. The channel fading is assumed to be a stationary and ergodic random process, whose instantaneous channel realizations follow the Nakagami-m distribution with parameters (m_i, Ω_i). The Nakagami-m channel model is general enough to describe the typical wireless fading environments. In this case, γ_i follows the gamma distribution with parameters (m_i, b_i), where $b_i = \frac{\sigma^2 m_i}{l_i p_i \Omega_i}$. The special case of Rayleigh fading is also considered, in which γ_i follows the exponential distribution with rate parameter $b_i = \frac{\sigma^2}{l_i p_i \Omega_i}$.

When two sources access the channel in a time slot, two NOMA detection techniques are utilized, i.e., SIC and JD. When SIC is used, the achievable rate of the i-th source, if its message is decoded first, considering the interference from the j-th source's signal, is given by

$$R_{i,1} = \log_2\left(1+\frac{\gamma_i}{\gamma_j+1}\right). \tag{5}$$

If its message is decoded second, considering the decoding result of the j-th source's message, which is decoded first, the achievable rate is given by

$$R_{i,2} = \log_2\left(1+\frac{\gamma_i}{\epsilon\gamma_j+1}\right), \tag{6}$$

where $\epsilon \in \{0,1\}$ represents the decoding result of the source's message that is decoded first. When JD is utilized, the achievable rate region is defined by the inequalities

$$\begin{aligned} R_k &\leq \log_2(1+\gamma_k), \ k \in \{i,j\} \\ R_i + R_j &\leq \log_2(1+\gamma_i+\gamma_j). \end{aligned} \tag{7}$$

The above inequalities describe the pair of rates that can be achieved by both users (region 1 in Fig. 2). Moreover, region 2 indicates that R_i cannot be achieved and outage occurs in the i-th source while R_j is achievable if it is lower than or equal to $\log_2\left(1+\frac{\gamma_j}{\gamma_i+1}\right)$. Accordingly, region 3 indicates that outage occurs only in the j-th source. Finally, in region 4 neither R_i nor R_j is achievable.

C. Extension of the Proposed Protocols for WPSNs

The proposed protocols can be applied in WPSNs, by dividing each time slot into two phases of fixed duration, as shown in Fig. 1(b). Without loss of generality, it is assumed that the EH and the RA phase are of duration τT and $(1-\tau)T$, respectively, where $0 \leq \tau \leq 1$. During the EH phase, the BS broadcasts RF energy to the sources at fixed power p_{t} and all sources harvest part of the received energy. More specifically, the harvested energy by the i-th source is given by

$$E_i = \tau T \zeta_i l_i |\tilde{h}_i|^2 p_{\mathrm{t}}, \tag{8}$$

where $0 < \zeta_i \leq 1$ is the energy harvesting efficiency of the i-th source, while l_i and $\tilde{h}_i$ denote the path loss factor and the small scale fading coefficient between the BS and the i-th source, respectively.

Furthermore, each source is assumed to have a rechargeable battery, which stores the harvested energy. The rechargeable battery of the i-th source is modeled as an energy queue with unlimited energy storage capacity. The i-th source tries to access the channel in randomly selected time slots, i.e., when $I_i = 1$, thus it is possible that in a specific time slot the source does not have the required stored energy to transmit with the desired output power. In [38], it is proven under general conditions that if a source with infinite storage capacity employs a power allocation policy where the average harvested energy is larger than or equal to the average consumed energy, this source can transmit with its desired output power in almost all time slots, assuming a WPSN operating for infinitely long communication sessions over stationary fading channels, i.e., $M \to \infty$. In other words, the number of time slots in which the battery of the i-th source cannot provide the desired output power is negligible compared to the number of time slots in which the battery can supply with the desired output power. In this case, the considered EH network can be replaced with an equivalent non-EH network, where the average energy departure rate from the energy queue of the i-th source, $\mathbb{E}[(1-\tau)Tp_iI_i]$, is less than or equal to the average energy arrival rate at the energy queue of the i-th source, $\mathbb{E}[E_i]$, i.e.,

$$(1-\tau)p_i q_i \leq \tau \zeta_i l_i \Omega_i p_{\mathrm{t}}. \tag{9}$$

III. Protocol based on slotted ALOHA and NOMA with successive interference cancellation

In this section, we analyze the performance of SA-NOMA-SIC in terms of throughput for both WSNs and WPSNs, considering both Nakagami-m and Rayleigh fading. To this end, we first derive the outage probability, assuming that the optimal decoding order policy for SIC is used, which jointly minimizes the outage probabilities of both sources is identical

$$c_2 = \begin{cases} \sum_{n=0}^{m_j+l-1} \frac{n!}{\left(\frac{b_i}{\beta_j}+b_j\right)^{n+1}} \binom{m_j+l-1}{n} \left(e^{-\beta_j\left(\frac{b_i}{\beta_j}+b_j\right)} \beta_j^{m_j+l-1-n} - e^{-\left(\frac{b_i}{\beta_j}+b_j\right)\frac{(\beta_i+1)\beta_j}{1-\beta_i\beta_j}} \left(\frac{(\beta_i+1)\beta_j}{1-\beta_i\beta_j}\right)^{m_j+l-1-n} \right), & \beta_i\beta_j < 1 \\ \left(\frac{b_i}{\beta_j}+b_j\right)^{-m_j-l} \Gamma\left(m_j+l, \beta_j\left(\frac{b_i}{\beta_j}+b_j\right)\right), & \beta_i\beta_j \geq 1 \end{cases} \tag{13}$$

under the perfect, imperfect, and worst-case SIC assumptions and is given by [28]

$$\mathcal{S} = \begin{cases} (i,j), & \frac{\gamma_i}{\gamma_j+1} \geq \beta_i \ \& \ \frac{\gamma_j}{\gamma_i+1} < \beta_j \\ (j,i), & \frac{\gamma_i}{\gamma_j+1} < \beta_i \ \& \ \frac{\gamma_j}{\gamma_i+1} \geq \beta_j \\ (i,j) \text{ or } (j,i), & \text{otherwise,} \end{cases} \tag{10}$$

where $\mathcal{S} = (k,l)$ denotes the decoding order if the k-th source is decoded first and the l-th source is decoded second. Taking into account (10), it should be highlighted that the decoding order using the optimal policy depends on both the target rate and the channel conditions of the sources. This decoding order can be selected by the BS since it is assumed to have perfect CSI.

A. Performance Analysis for Nakagami-m Fading

Theorem 1: The outage probability of the i-th source, assuming that the i-th and the j-th sources access the channel in the same time slot, SIC with the optimal decoding order policy is used and m_k is an integer, is given by

$$\begin{aligned} P_{ij}^{\mathrm{s}} &= \frac{\gamma\left(m_j, b_j\beta_j\right)}{\Gamma(m_j)} - \frac{b_j^{m_j} e^{-b_i\beta_i}}{\Gamma(m_j)} \\ &\times \sum_{k=0}^{m_i-1}\sum_{l=0}^{k}\binom{k}{l}\frac{(b_i\beta_i)^k}{k!}(b_i\beta_i+b_j)^{-m_j-l}c_1 \\ &+ \frac{b_j^{m_j}e^{b_i}}{\Gamma(m_j)}\sum_{k=0}^{m_i-1}\sum_{l=0}^{k}\binom{k}{l}\frac{1}{k!}\left(\frac{b_i}{\beta_j}\right)^k(-\beta_j)^{k-l}c_2 \\ &+ \frac{b_i^{m_i}e^{-b_j\beta_j}}{\Gamma(m_i)}\sum_{k=0}^{m_j-1}\sum_{l=0}^{k}\binom{k}{l}\frac{(b_j\beta_j)^k}{k!}(b_j\beta_j+b_i)^{-m_i-l} \\ &\times \gamma\left(m_i+l, \beta_i\left(b_j\beta_j+b_i\right)\right), \end{aligned} \tag{11}$$

where $\beta_k = 2^{\hat{R}_k} - 1$ with $\hat{R}_k$ being the target rate of the k-th source,

$$c_1 = \begin{cases} \gamma\left(m_j+l, (b_i\beta_i+b_j)\frac{(\beta_i+1)\beta_j}{1-\beta_i\beta_j}\right), & \beta_i\beta_j < 1 \\ \Gamma\left(m_j+l\right), & \beta_i\beta_j \geq 1 \end{cases} \tag{12}$$

and c_2 is given in (13) at the top of the next page with $\Gamma(\cdot)$, $\gamma(\cdot,\cdot)$, and $\Gamma(\cdot,\cdot)$ being the gamma function, the lower incomplete gamma function, and the upper incomplete gamma function, respectively [39].

Proof: The proof is provided in Appendix A. ■

It should be highlighted that the expression of the outage probability depends on the sources' target rates, which implies that a fundamentally different behavior is expected when different combinations of target rates are used.

Utilizing the closed-form expressions for the outage probability with SIC derived in Theorem 1, the average throughput which is a useful metric to evaluate the performance of the proposed protocols can be derived.

Theorem 2: The average throughput of the i-th source during the RA phase for SA-NOMA-SIC in the considered WSN is given by

$$\begin{aligned} \tilde{R}_i^{\mathrm{s}} = \hat{R}_i q_i \Bigg(& \prod_{k\neq i}(1-q_k)(1-P_i^{\mathrm{o}}) \\ & + \sum_{j\neq i} q_j \prod_{k\neq i,j}(1-q_k)(1-P_{ij}^{\mathrm{s}}) \Bigg). \end{aligned} \tag{14}$$

Proof: The probability that only the i-th source accesses the channel in a specific time slot is described as the product of the probability that the i-th source accesses with the probability that none of the others accesses. When the i-th source is the only one that accesses the channel the outage probability is defined as

$$P_i^{\mathrm{o}} = \Pr\left(\gamma_i < \beta_i\right). \tag{15}$$

Considering that γ_i follows the gamma distribution with parameters (m_i, b_i), the outage probability is given by [34]

$$P_i^{\mathrm{o}} = \frac{1}{\Gamma(m_i)}\gamma\left(m_i, b_i\beta_i\right). \tag{16}$$

The probability that the i-th and the j-th source access the channel is described as the the product of the probability that the i-th and the j-th source access for all $j \neq i$ with the probability that none of the other sources accesses. Utilizing Theorem 1, the outage probabilities when SIC is used can be extracted. ■

Remark 1: It is obvious that SA-NOMA-SIC outperforms SA in terms of throughput, since a positive term is added in the expression for the average throughput of SA. Considering a network consisting of M sources where SA-NOMA-JD is utilized and a network consisting of N sources where SA is used and assuming that the rate threshold $\hat{R}_i$ and the channel access probability q_i are the same in both networks and do not depend on the number of sources, an $M \geq N$ exists so that the average throughput of the i-th source when SA-NOMA-SIC is utilized is greater than the corresponding one when SA is used. Therefore, the superiority of SA-NOMA-SIC compared to SA can be utilized in a twofold way, i.e., either by increasing the throughput of the network or by increasing the number of the connected sources maintaining the throughput that can be achieved by each source with SA.

B. Performance Analysis for Rayleigh Fading

At this point, it is useful to derive the outage probability for the special case of Rayleigh fading, as it can provide some

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCOMM.2020.3007744, IEEE Transactions on Communications

insights into the system performance, due to its simplicity compared to the case of Nakagami-m fading.

Proposition 1: The outage probability of the i-th source, assuming that the i-th and the j-th sources access the channel in the time slot and SIC is used, for the case of Rayleigh fading channel is given by

$$P_{ij}^{\mathrm{s}} = 1 - e^{-b_j\beta_j} - \frac{b_j e^{-b_i\beta_i}}{b_i\beta_i + b_j} c_4 + \frac{b_j e^{b_i}}{\frac{b_i}{\beta_j} + b_j} c_5 + \frac{b_i e^{-b_j\beta_j}}{b_j\beta_j + b_i}\left(1 - e^{-\beta_i(b_j\beta_j + b_i)}\right), \tag{17}$$

where

$$c_4 = \begin{cases} 1 - e^{-(b_i\beta_i + b_j)\frac{(\beta_i+1)\beta_j}{1-\beta_i\beta_j}}, & \beta_i\beta_j < 1 \\ 1, & \beta_i\beta_j \geq 1. \end{cases} \tag{18}$$

and

$$c_5 = \begin{cases} e^{-\beta_j\left(\frac{b_i}{\beta_j} + b_j\right)} - e^{-\left(\frac{b_i}{\beta_j} + b_j\right)\frac{(\beta_i+1)\beta_j}{1-\beta_i\beta_j}}, & \beta_i\beta_j < 1 \\ e^{-\beta_j\left(\frac{b_i}{\beta_j} + b_j\right)}, & \beta_i\beta_j \geq 1. \end{cases} \tag{19}$$

Proof: Setting $m_i = m_j = 1$ in (11), (17) is derived. ■

An important insight is the behavior of the outage probability in the high SNR regime, i.e., $\frac{p_k}{\sigma^2} \to \infty$.

Proposition 2: The outage probability of the i-th source, assuming that the i-th and the j-th source access the channel in the time slot and SIC is used, for the case of Rayleigh fading channel in the high SNR regime is given by

$$P_{ij}^{\mathrm{s},\infty} = \begin{cases} 0, & \beta_i\beta_j < 1 \\ \frac{l_i l_j \Omega_i \Omega_j (\beta_i\beta_j - 1)}{(l_i\Omega_i\beta_j + l_j\Omega_j)(l_j\Omega_j\beta_i + l_i\Omega_i)}, & \beta_i\beta_j \geq 1. \end{cases} \tag{20}$$

Proof: Considering that $\frac{p_k}{\sigma^2}$ is contained in the expression for b_k and calculating the limits, (20) is derived. ■

It is obvious that when $\beta_i\beta_j \geq 1$, there is a floor in the performance in terms of the outage probability, while there is no floor otherwise.

Using the expressions for the outage probability for the case of Rayleigh fading in (14), the corresponding expressions for the average throughput of the i-th source are extracted, considering that the outage probability when only the i-th source accesses the channel for Rayleigh fading is given by

$$P_i^{\mathrm{o}} = 1 - e^{-b_i\beta_i}. \tag{21}$$

Corollary 1: The improvement of the throughput of the i-th source when SA-NOMA-SIC is utilized compared to SA in the high SNR regime is given by

$$\mathrm{IR}_i^{\mathrm{s}} = \sum_{j\neq i} \frac{q_j P_{ij}^{\mathrm{s},\infty}}{1 - q_j}. \tag{22}$$

Proof: The improvement of SA-NOMA-SIC compared to SA is expressed as

$$\mathrm{IR}_i^{\mathrm{s}} = \frac{\tilde{R}_i^{\mathrm{s}} - \tilde{R}_i^{\mathrm{sa}}}{\tilde{R}_i^{\mathrm{sa}}}, \tag{23}$$

where $\tilde{R}_i^{\mathrm{sa}}$ is the throughput of the i-th source when SA is utilized and is given by

$$\tilde{R}_i^{\mathrm{sa}} = \hat{R}_i q_i \prod_{k\neq i}(1 - q_k)(1 - P_i^{\mathrm{o}}). \tag{24}$$

Considering that the outage probability P_i^{o} is equal to 0 in the high SNR regime, (22) is derived. ■

C. Throughput of Wireless Powered Sources

For the considered WPSN, the BS broadcasts RF energy to the sources and the sources utilize the harvested energy to transmit their signals. When SA-NOMA-SIC is deployed, it is assumed that the sources choose their transmitted power opportunistically, i.e., the strict equality is used in (9). In this case,

$$b_k = \frac{q_k \sigma^2 (1-\tau) m_k}{l_k^2 \zeta_k p_{\mathrm{t}} \tau \Omega_k^2} \tag{25}$$

is used in the expressions for P_i^{o} and P_{ij}^{s}. In the expression for b_k, the double near-far effect is reflected by the term l_k^2, which indicates that far users harvest less power, but they also need to transmit more power during the uplink. Considering (14) and the fact that the RA phase has duration $(1-\tau)T$, the throughput of the i-th source, SA-NOMA-SIC is utilized in a WPSN, is given by

$$\tilde{R}_i^{\mathrm{s}} = (1-\tau)\hat{R}_i q_i \left(\prod_{k\neq i}(1 - q_k)(1 - P_i^{\mathrm{o}}) + \sum_{j\neq i} q_j \prod_{k\neq i,j}(1 - q_k)(1 - P_{ij}^{\mathrm{s}})\right). \tag{26}$$

In (26), a tradeoff regarding τ can be observed. More specifically, it is obvious that the throughput of the i-th source increases with the decrease of τ due to the term $1-\tau$. However, considering (25) and the fact that the outage probabilities in (26) decrease with the decrease of b_k, the increase of τ is also desirable. Therefore, an optimal value of τ exists where the throughput of the i-th source is maximized.

IV. Protocol Based on Slotted ALOHA and NOMA with Joint Decoding

In this section, we analyze the performance of SA-NOMA, assuming that JD is used to detect the sources' messages at the BS, instead of SIC.

A. Performance Analysis for Nakagami-m Fading

Theorem 3: The outage probability of the i-th source, assuming that the i-th and the j-th sources access the channel in the time slot, JD is utilized and m_k is an integer, is given by

$$\begin{aligned} P_{ij}^{\mathrm{jd}} = 1 &- \frac{\Gamma(m_i, b_i\beta_i)}{\Gamma(m_i)} \frac{\Gamma(m_j, b_j(\beta_i+1)\beta_j)}{\Gamma(m_j)} \\ &- \frac{b_j^{m_j} e^{-b_i\beta_{ij}}}{\Gamma(m_j)} \sum_{k=0}^{m_i-1}\sum_{l=0}^{k}\binom{k}{l}\frac{b_i^k}{k!}\beta_{ij}^{k-l}(-1)^l c_6 \\ &- \frac{b_j^{m_j} e^{-b_i\beta_i}}{\Gamma(m_j)} \sum_{k=0}^{m_i-1}\sum_{l=0}^{k}\binom{k}{l}\frac{(b_i\beta_i)^k}{k!}(b_i\beta_i + b_j)^{-m_j-l} \\ &\times \gamma\left(m_j + l, \beta_j\left(b_i\beta_i + b_j\right)\right), \end{aligned} \tag{27}$$

$$c_6 = \begin{cases} \sum_{n=0}^{m_j+l-1} \frac{(-1)^n n!}{(b_i-b_j)^{n+1}} \binom{m_j+l-1}{n} \left(e^{(b_i-b_j)(\beta_i+1)\beta_j} \left((\beta_i+1)\beta_j\right)^{m_j+l-1-n} - e^{(b_i-b_j)\beta_j} \beta_j^{m_j+l-1-n} \right), & b_i \neq b_j \\ \frac{1}{m_j+l} \left(\left((\beta_i+1)\beta_j\right)^{m_j+l} - \beta_j^{m_j+l} \right), & b_i = b_j \end{cases} \quad (28)$$

where $\beta_{ij} = (\beta_i + 1)(\beta_j + 1) - 1$ and c_6 is given in (28) at the top of the next page.

Proof: The proof is provided in Appendix B. ∎

The average throughput of the i-th source, when SA-NOMA-JD is utilized in a WSN, is given by (14) replacing P_{ij}^{s} with P_{ij}^{jd}. It should be highlighted that Remark 1 also applies to SA-NOMA-JD.

B. Performance Analysis for Rayleigh Fading

Proposition 3: The outage probability of the i-th source, assuming that the i-th and the j-th sources access the channel in the time slot and JD is utilized, for the case of Rayleigh fading channel is given by

$$P_{ij}^{\mathrm{jd}} = 1 - e^{-b_i\beta_i} e^{-b_j(\beta_i+1)\beta_j} - b_j e^{-b_i\beta_{ij}} c_7 - \frac{b_j e^{-b_i\beta_i}}{b_i\beta_i + b_j} \left(1 - e^{-\beta_j(b_i\beta_i+b_j)}\right), \quad (29)$$

where

$$c_7 = \begin{cases} \frac{1}{b_i-b_j} \left(e^{(b_i-b_j)(\beta_i+1)\beta_j} - e^{(b_i-b_j)\beta_j} \right), & b_i \neq b_j \\ \beta_i\beta_j, & b_i = b_j. \end{cases} \quad (30)$$

Proof: Setting $m_i = m_j = 1$ in (27), (29) is derived. ∎

In the high SNR regime, when JD is utilized, the outage probability is zero, which can be proved by calculating the limit of (29) as $\frac{p_k}{\sigma^2} \to \infty$.

The average throughput of the i-th source for the case of Rayleigh fading is given by (14) replacing P_{ij}^{s} with P_{ij}^{jd} as described by (29).

Corollary 2: The improvement of the throughput of the i-th source when SA-NOMA-JD is utilized compared to SA in the high SNR regime is given by

$$\mathrm{IR}_i^{\mathrm{jd}} = \sum_{j\neq i} \frac{q_j}{1-q_j}. \quad (31)$$

Proof: The proof follows from Corollary 1. ∎

Remark 2: It should be highlighted that, if $q_i = \frac{1}{N}$ for all sources, $\mathrm{IR}_i^{\mathrm{jd}} = 1$ and, thus, SA-NOMA-JD exhibits 100% improvement compared to SA.

C. Throughput of Wireless Powered Sources

When JD is utilized, the system performance is maximized when all sources transmit with maximum power, as in this case the achievable rate region is maximized, and, thus, (9) is used with strict equality. The average throughput of the i-th source during the RA phase, when SA-NOMA-JD is utilized in a WPSN, is given by (26) replacing P_{ij}^{s} with P_{ij}^{jd} and using the b_k as described by (25).

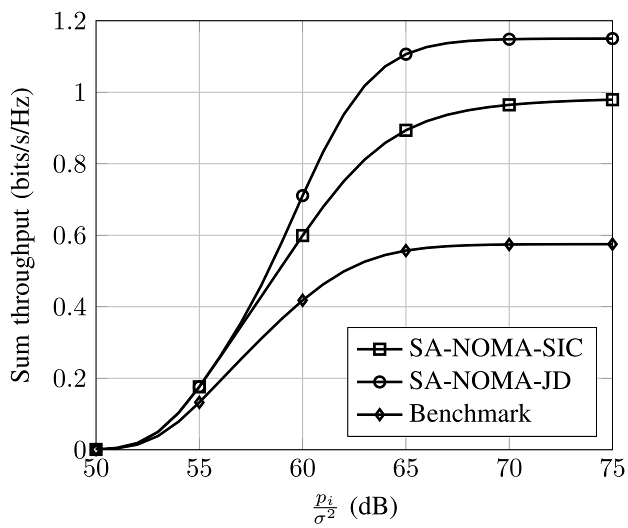

Fig. 3. Sum throughput versus transmitted SNR in the considered WSN.

V. Simulation and Discussion

In this section, we use simulation results to quantify the performance of the proposed protocols and validate the analytical results. We assume an even number of sources that are equally divided in two groups. The first group is placed on a circle of radius r_1 around the BS, while the second one on a concentric circle of radius r_2. The path loss factor of the i-th source is modeled as $l_i = 10^{-3} r_i^{-3}$ [34]. Moreover, without loss of generality and unless stated otherwise, it is assumed that $r_1 = 5$m, $r_2 = 10$m, $N = 10$, and $q_i = \frac{1}{N}$ for all sources. Also, we assume that the transmitted SNR is $\frac{p_i}{\sigma^2} = 65$dB, and $\frac{P}{\sigma^2} = 120$dB [34] when the WSN and the WPSN is considered, respectively, for all sources. For the case of the WPSN, the value of the SRN is higher, as the double near-far effect is considered. It should be highlighted that with the considered path loss for the WSN the average received SNR is 14dB for the first group and 5dB for the second group. Accordingly, for the WPSN the average received SNR is 18dB for the first group and 0dB for the second group. Furthermore, when a WPSN is considered, we set $\zeta_i = 0.815$ [23], [40] for all sources and $\tau = 0.4$. Regarding the channel fading, the Nakagami-m distribution with $m_i = 3$ and $\Omega_i = 1$ is considered for all sources. We use the variable $\tilde{\beta}_i = \frac{\mathbb{E}[\gamma_i]}{\beta_i}$, where the average received SNR of the i-th source at the BS $\mathbb{E}[\gamma_i]$ is calculated for the above setup. Unless stated otherwise, $\tilde{\beta}_i = 9$ and $\tilde{\beta}_i = 3$ for the first and the second group, respectively. In the following figures, the performance of the proposed protocols is compared with the case of SA which is considered in [34] and as benchmark in this work.

Fig. 3 illustrates the performance of the considered WSN with the increase of transmitted SNR which is assumed to be equal for all sources. It is observed that the sum throughput

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCOMM.2020.3007744, IEEE Transactions on Communications

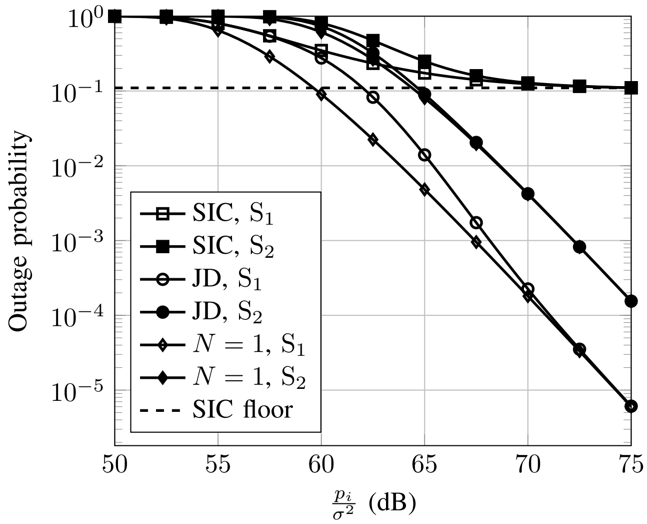

Fig. 4. Outage probability versus transmitted SNR in the considered WSN.

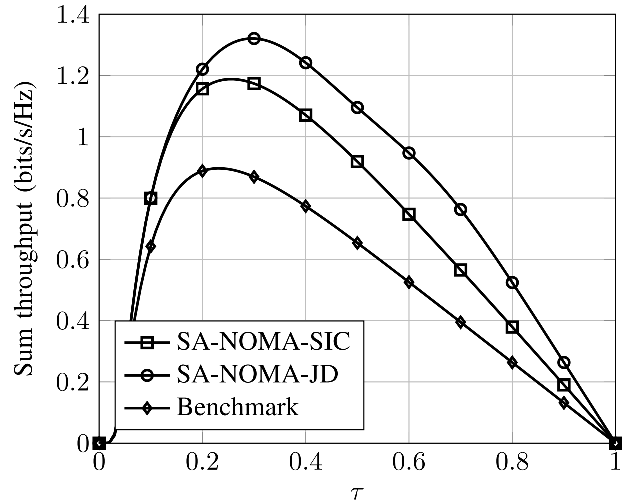

Fig. 6. Sum throughput versus portion of EH phase τ in the considered WPSN.

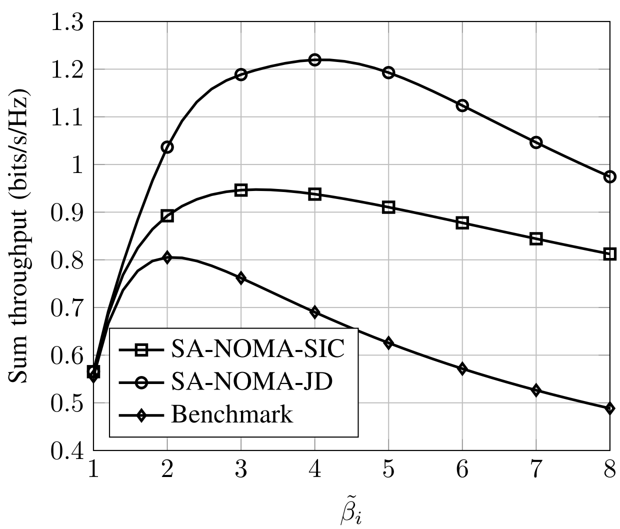

Fig. 5. Sum throughput versus threshold $\tilde{\beta}_i$ in the considered WSN.

initially increases exponentially and then is saturated for all considered protocols. Also, SA-NOMA-SIC and SA-NOMA-JD perform similarly for lower values of SNR, since the outage probability of each source exhibits similar behavior for this values of SNR. To provide further insights, in Fig. 4, the outage probability of a WSN with SIC or JD, is illustrated and compared with the one of the corresponding single source systems. The first group consists of the source S_1 and the second one consists of the source S_2. The single source lines can be considered as lower bounds, since these systems always outperform the NOMA counterparts where two sources share the same resources. Moreover, the floor of SIC is evident, which highlights the fact that JD outperforms SIC in the high SNR regime.

Fig. 5 illustrates the performance of the considered WSN in terms of sum throughput, for different values of the thresholds. The values of the thresholds is different in each of the two groups of sources, as they depend on the distance between each source and the BS. It can be observed that the performance of SA-NOMA-JD is maximized for a value of $\tilde{\beta}_i$ greater than the one that maximizes the performance of SA-NOMA-SIC. The performance of the benchmark protocol is maximized for the lowest value of $\tilde{\beta}_i$ compared with the proposed protocols. The optimal value of $\tilde{\beta}_i$ where the sum throughput is maximized is given by

$$\tilde{\beta}_i^{\,*} = \underset{\tilde{\beta}_i}{\operatorname{argmax}} \sum_i \tilde{R}_i^{\mathrm{pr}} \tag{32}$$

with $\mathrm{pr} = \{\mathrm{s}, \mathrm{jd}, \mathrm{sa}\}$ considering that β_i appears in the outage probabilities.

In Fig. 6, the sum throughput of the considered WPSN for the possible values of the portion of time slot τ allocated for the EH phase is demonstrated. We observe that the performance of SA-NOMA-JD is maximized for a value of τ greater than the one that maximizes the performance of both SA-NOMA-SIC and SA. Fig. 6 highlights the tradeoff between EH and RA. For the lower values of τ, the sum throughput increases, as the sources harvest more energy and, thus, they transmit more power. However, the term $1-\tau$ in the expression for the throughput leads to the decrease of the sum throughput, after it reaches its maximum value.

In Fig. 7, the sum throughput of the considered WPSN is plotted versus the channel access probability q which is assumed to be equal for all sources. After the sum throughput reaches its maximum value, it decreases, since the number of collisions and the outage probabilities increase, as q increases.

In Fig. 8, the sum throughput of the considered WPSN is plotted versus the number of sources of the network. It is observed that the value of the sum throughput when the proposed protocols are utilized is significantly higher than the one of the benchmark protocol, when the WPSN consists of two sources, since no collision occurs with the utilization of the proposed protocols. This is also the reason why for the case of SA-NOMA-SIC the sum throughput decreases when the number of sources increase from 2 to 4. When the number of sources increases, the sum throughput also increases, as the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCOMM.2020.3007744, IEEE Transactions on Communications

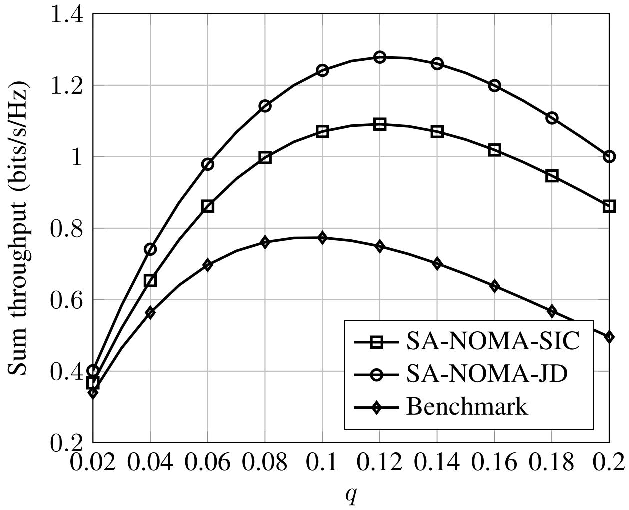

Fig. 7. Sum throughput versus success probability of each source q in the considered WPSN.

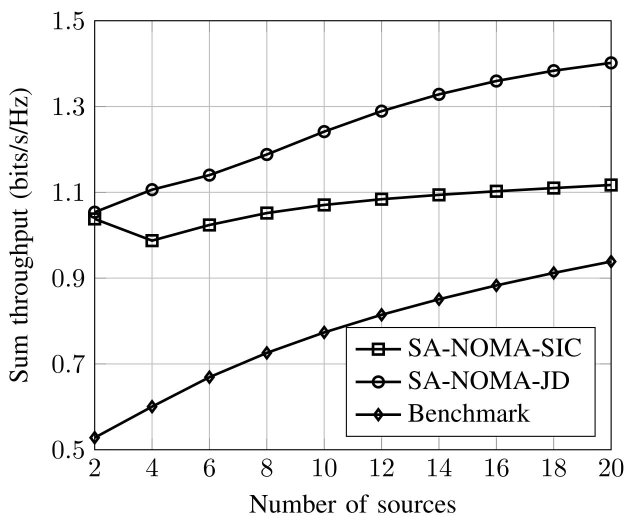

Fig. 8. Sum throughput versus number of sources in the considered WPSN.

decrease of the channel access probability of each source is significantly less than the fact that more sources are served.

In Fig. 9, the optimized throughput of the considered WSN which is obtained as

$$\tilde{R}^* = \max_{\frac{p_i}{\sigma^2}\leq\gamma^{\mathrm{t}},\ 0<q_i<1} \min \tilde{R}_i^{\mathrm{pr}}, \tag{33}$$

where γ^{t} denotes the transmitted SNR threshold and is set to 65dB, is plotted versus the number of sources of the network. In the considered optimization, the variables are the channel access probability q_i as described in Section II, which is assumed to be equal for all sources, and the transmitted power of each source p_i and they are derived with one-dimensional search. The optimization is solved by the BS considering the statistics of the channel, the distance and the number of the sources. It can be observed that the same value of the optimized throughput of SA can be achieved with SA-NOMA-SIC and especially with SA-NOMA-JD for a greater number of sources. For example, the value of the optimized throughput of SA with 8 sources can be achieved with 14 and 16 sources when SA-NOMA-SIC and SA-NOMA-JD are utilized, respectively. This observation highlights the fact that the proposed protocols increase the connectivity compared to the benchmark scheme without reducing the quality of service.

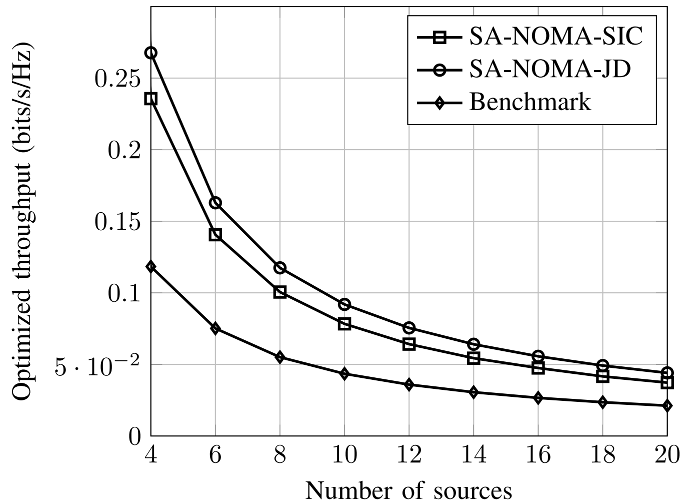

Fig. 9. Optimized throughput versus number of sources in the considered WSN.

In all figures where the performance of the proposed protocols in terms of throughput is illustrated, it is obvious that the proposed protocols substantially outperform the benchmark scheme. Furthermore, SA-NOMA-JD outperforms SA-NOMA-SIC, especially in the medium and high SNR regime, due to the superiority of JD, which extends the capacity region, compared to SIC.

VI. Conclusions

In this work two RA protocols based on SA and uplink NOMA have been proposed. Both SIC and JD have been considered and the corresponding outage probabilities have been derived for a system consisting of two sources. The expression for the average throughput has been extracted for the case of a WSN and a WPSN where the SA-NOMA-SIC and SA-NOMA-JD protocols are deployed. The performance of both considered networks has been investigated and it has been proved that the proposed protocols outperform SA in terms of throughput and also increase the number of sources that can be served with the same quality of service compared to SA, which has also been illustrated in the provided simulation results. Therefore, SA-NOMA-SIC and SA-NOMA-JD are promising multiple access protocols for the NGIoT. For the case of WPSNs the theoretical analysis with the assumptions in this paper can be considered as a benchmark for the evaluation of the performance of schemes with different assumptions such as nonlinear harvesting model or limited energy capacity batteries.

Appendix A
Proof of Theorem 1

Utilizing the optimal decoding order policy described in (10), outage occurs in the i-th source, regardless if outage occurs in the j-th source or not, thus the outage probability of the i-th source is given by [28]

$$P_{ij}^{\mathrm{s}} = \Pr\left(\frac{\gamma_i}{\gamma_j+1} < \beta_i, \frac{\gamma_j}{\gamma_i+1} < \beta_j\right) + \Pr\left(\frac{\gamma_j}{\gamma_i+1} \geq \beta_j, \gamma_i < \beta_i\right). \tag{34}$$

Using the random variables $X = \gamma_i$ and $Y = \gamma_j$, the first term in (34), termed as P_1^{s}, can be written as

$$P_1^{\mathrm{s}} = \Pr\left(\frac{Y}{\beta_j} - 1 < X < \beta_i\left(Y+1\right)\right). \tag{35}$$

Considering that the expressions $\frac{X}{Y+1} = \beta_i$ and $\frac{Y}{X+1} = \beta_j$ intersect at the point $\frac{(\beta_i+1)\beta_j}{1-\beta_i\beta_j}$ if $\beta_i\beta_j < 1$, and they do not intersect if $\beta_i\beta_j \geq 1$, and that X and Y are independent, (35) can be rewritten as

$$P_1^{\mathrm{s}} = \int_0^d \mathrm{F_X}\left(\beta_i\left(y+1\right)\right) f_Y(y)dy - \int_{\beta_j}^d \mathrm{F_X}\left(\frac{y}{\beta_j} - 1\right) f_Y(y)dy, \tag{36}$$

where

$$d = \begin{cases} \frac{(\beta_i+1)\beta_j}{1-\beta_i\beta_j}, & \beta_i\beta_j < 1 \\ \infty, & \beta_i\beta_j \geq 1. \end{cases} \tag{37}$$

Considering that both X and Y follow the gamma distribution with parameters (m_i, b_i) and (m_j, b_j), respectively, the first integral in (36), termed as P_{11}^{s}, can be written as

$$P_{11}^{\mathrm{s}} = \int_0^d \frac{1}{\Gamma(m_i)}\gamma\left(m_i, b_i\beta_i(y+1)\right)\frac{b_j^{m_j}}{\Gamma(m_j)}y^{m_j-1}e^{-b_jy}dy. \tag{38}$$

Assuming that m_i is a positive integer, (38) can be rewritten as

$$P_{11}^{\mathrm{s}} = \int_0^d \left(1 - e^{-b_i\beta_i(y+1)}\sum_{k=0}^{m_i-1}\frac{(b_i\beta_i(y+1))^k}{k!}\right) \times \frac{b_j^{m_j}}{\Gamma(m_j)}y^{m_j-1}e^{-b_jy}dy. \tag{39}$$

Using the binomial theorem, (39) can be rewritten as

$$P_{11}^{\mathrm{s}} = \mathrm{F_Y}(d) - \frac{b_j^{m_j}e^{-b_i\beta_i}}{\Gamma(m_j)}\sum_{k=0}^{m_i-1}\sum_{l=0}^{k}\binom{k}{l} \times \frac{(b_i\beta_i)^k}{k!}\int_0^d y^{l+m_j-1}e^{-(b_i\beta_i+b_j)y}dy. \tag{40}$$

Accordingly, the second integral in (36), termed as P_{12}^{s}, can be written as

$$P_{12}^{\mathrm{s}} = \int_{\beta_j}^d \frac{1}{\Gamma(m_i)}\gamma\left(m_i, b_i\left(\frac{y}{\beta_j} - 1\right)\right)\frac{b_j^{m_j}}{\Gamma(m_j)}y^{m_j-1}e^{-b_jy}dy. \tag{41}$$

Assuming that m_i is a positive integer, (41) can be rewritten as

$$P_{12}^{\mathrm{s}} = \int_{\beta_j}^d \left(1 - e^{-b_i\left(\frac{y}{\beta_j}-1\right)}\sum_{k=0}^{m_i-1}\frac{\left(b_i\left(\frac{y}{\beta_j}-1\right)\right)^k}{k!}\right) \times \frac{b_j^{m_j}}{\Gamma(m_j)}y^{m_j-1}e^{-b_jy}dy. \tag{42}$$

Using the binomial theorem, (42) can be rewritten as

$$P_{12}^{\mathrm{s}} = \mathrm{F_Y}(d) - \mathrm{F_Y}(\beta_j) - \frac{b_j^{m_j}e^{b_i}}{\Gamma(m_j)}\sum_{k=0}^{m_i-1}\sum_{l=0}^{k}\binom{k}{l} \times \frac{1}{k!}\left(\frac{b_i}{\beta_j}\right)^k(-\beta_j)^{k-l}\int_{\beta_j}^d y^{l+m_j-1}e^{-(\frac{b_i}{\beta_j}+b_j)y}dy. \tag{43}$$

Furthermore, the second term in (34), termed as P_2^{s}, can be written as

$$P_2^{\mathrm{s}} = \Pr\left(\frac{Y}{X+1} \geq \beta_j, X < \beta_i\right). \tag{44}$$

Considering that X and Y are independent, (44) can be rewritten as

$$P_2^{\mathrm{s}} = \int_0^{\beta_i}\left(1 - \mathrm{F_Y}\left(\beta_j(x+1)\right)\right)f_X(x)dx. \tag{45}$$

Considering that both X and Y follow the gamma distribution with parameters (m_i, b_i) and (m_j, b_j), respectively, (45) can be rewritten as

$$P_2^{\mathrm{s}} = \int_0^{\beta_i}\frac{1}{\Gamma(m_j)}\Gamma\left(m_j, b_j\beta_j(x+1)\right)\frac{b_i^{m_i}}{\Gamma(m_i)}x^{m_i-1}e^{-b_ix}dx. \tag{46}$$

Assuming that m_j is a positive integer, (46) can be rewritten as

$$P_2^{\mathrm{s}} = \int_0^{\beta_i} e^{-b_j\beta_j(x+1)}\sum_{k=0}^{m_j-1}\frac{(b_j\beta_j(x+1))^k}{k!} \times \frac{b_i^{m_i}}{\Gamma(m_i)}x^{m_i-1}e^{-b_ix}dx. \tag{47}$$

Using the binomial theorem, (47) can be rewritten as

$$P_2^{\mathrm{s}} = \frac{b_i^{m_i}e^{-b_j\beta_j}}{\Gamma(m_i)}\sum_{k=0}^{m_j-1}\sum_{l=0}^{k}\binom{k}{l} \times \frac{(b_j\beta_j)^k}{k!}\int_0^{\beta_i}x^{l+m_i-1}e^{-(b_j\beta_j+b_i)x}dx. \tag{48}$$

Using (40), (43), (48) and exploiting the definition of gamma function, lower and upper incomplete gamma functions and [39, eq.(2.321/2)], (11) can be derived.

Appendix B
Proof of Theorem 3

Utilizing JD, outage occurs in the i-th source, regardless if outage occurs in the j-th source or not, thus the outage probability of the i-th source is given by

$$P_{ij}^{\mathrm{jd}} = 1 - \Pr\left(\gamma_i \geq \beta_i, \gamma_j \geq \beta_j, \gamma_i + \gamma_j \geq \beta_{ij}\right) - \Pr\left(\frac{\gamma_i}{\gamma_j+1} \geq \theta_i, \gamma_j < \theta_j\right). \tag{49}$$

Using the random variables $X = \gamma_i$ and $Y = \gamma_j$ which are independent, the first two terms in (49), which are termed as P_1^{jd} and express the common outage probability, i.e., outage occurs in both sources, can be rewritten as

$$P_1^{\mathrm{jd}} = 1 - \int_{\beta_j}^{\infty}\Pr\left(X \geq \beta_i, X + y \geq \beta_{ij}\right)f_Y(y)dy. \tag{50}$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCOMM.2020.3007744, IEEE Transactions on Communications

In (50), the probability can be rewritten as

$$\Pr\left(X \geq \beta_i, X + y \geq \beta_{ij}\right) = 1 - F_X\left(\max\{\beta_i, \beta_{ij} - y\}\right), \tag{51}$$

where $\max$ denotes the maximum of the two elements. The second term in $\max$, $\beta_{ij} - y$, is greater than b_i, when $y < (\beta_i + 1)\beta_j$, thus (50) can be written as

$$\begin{aligned} P_1^{\mathrm{jd}} = 1 &- \int_{\beta_j}^{(\beta_i+1)\beta_j} \left(1 - F_X\left(\beta_{ij} - y\right)\right) f_Y(y) dy \\ &- \int_{(\beta_i+1)\beta_j}^{\infty} \left(1 - F_X\left(\beta_i\right)\right) f_Y(y) dy. \end{aligned} \tag{52}$$

Considering that both X and Y follow the gamma distribution with parameters (m_i, b_i) and (m_j, b_j), respectively, (52) can be rewritten as

$$\begin{aligned} P_1^{\mathrm{jd}} = 1 &- \frac{\Gamma\left(m_i, b_i\beta_i\right)}{\Gamma(m_i)} \frac{\Gamma\left(m_j, b_j(\beta_i+1)\beta_j\right)}{\Gamma(m_j)} \\ &- \int_{\beta_j}^{(\beta_i+1)\beta_j} \frac{\Gamma\left(m_i, b_i(\beta_{ij} - y)\right)}{\Gamma(m_i)} \frac{b_j^{m_j}}{\Gamma(m_j)} y^{m_j - 1} e^{-b_j y} dy. \end{aligned} \tag{53}$$

Assuming that m_i is a positive integer, (53) can be rewritten as

$$\begin{aligned} P_1^{\mathrm{jd}} = 1 &- \frac{\Gamma\left(m_i, b_i\beta_i\right)}{\Gamma(m_i)} \frac{\Gamma\left(m_j, b_j(\beta_i+1)\beta_j\right)}{\Gamma(m_j)} \\ &- \int_{\beta_j}^{(\beta_i+1)\beta_j} e^{-b_i(\beta_{ij} - y)} \\ &\times \sum_{k=0}^{m_i-1} \frac{\left(b_i(\beta_{ij} - y)\right)^k}{k!} \frac{b_j^{m_j}}{\Gamma(m_j)} y^{m_j - 1} e^{-b_j y} dy. \end{aligned} \tag{54}$$

Using the binomial theorem, (54) can be rewritten as

$$\begin{aligned} P_1^{\mathrm{jd}} = 1 &- \frac{\Gamma\left(m_i, b_i\beta_i\right)}{\Gamma(m_i)} \frac{\Gamma\left(m_j, b_j(\beta_i+1)\beta_j\right)}{\Gamma(m_j)} \\ &- \frac{b_j^{m_j} e^{-b_i\beta_{ij}}}{\Gamma(m_j)} \sum_{k=0}^{m_i-1} \sum_{l=0}^{k} \binom{k}{l} \frac{b_i^k}{k!} \beta_{ij}^{k-l} (-1)^l \\ &\times \int_{\beta_j}^{(\beta_i+1)\beta_j} y^{l + m_j - 1} e^{(b_i - b_j)y} dy. \end{aligned} \tag{55}$$

Accordingly, the third term in (49), termed as P_2^{jd}, can be written as

$$P_2^{\mathrm{jd}} = \Pr\left(X \geq \beta_i(Y + 1), Y < \beta_j\right). \tag{56}$$

Considering that X and Y are independent, (56) can be rewritten as

$$P_2^{\mathrm{jd}} = \int_0^{\beta_j} \left(1 - F_X\left(\beta_i(y + 1)\right)\right) f_Y(y) dy. \tag{57}$$

Using (54) and (57), exploiting [39, eq.(2.321/2)] and following similar steps as in the proof of Theorem 1, (27) can be derived.

REFERENCES

[1] A. Brékine *et al.*, "Building a Roadmap for the Next Generation Internet of Things. Research, Innovation and Implementation 2021 – 2027 (Scoping Paper)," M. Brynskov, F. M. Facca, and G. Hrasko, Eds., Sep. 2019.

[2] N. Abramson, "The Throughput of Packet Broadcasting Channels," *IEEE Trans. Commun.*, vol. 25, no. 1, pp. 117–128, Jan. 1977.

[3] T. Li, J. Yuan, and M. Torlak, "Network Throughput Optimization for Random Access Narrowband Cognitive Radio Internet of Things (NB-CR-IoT)," *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1436–1448, Jun. 2018.

[4] T. Akyildiz, U. Demirhan, and T. M. Duman, "Asymptotic Analysis of Contention Resolution ALOHA with Replica Concatenation," in *Proc. IEEE Int. Conf. Communications (ICC)*, Shanghai, China, May 2019, pp. 1–6.

[5] M. Hasan, E. Hossain, and D. Niyato, "Random Access for Machine-to-Machine Communication in LTE-Advanced Networks: Issues and Approaches," *IEEE Commun. Mag.*, vol. 51, no. 6, pp. 86–93, Jun. 2013.

[6] C. Psomas and I. Krikidis, "Backscatter Communications for Wireless Powered Sensor Networks with Collision Resolution," *IEEE Wireless Commun. Lett.*, vol. 6, no. 5, pp. 650–653, Oct. 2017.

[7] T. Taleb and A. Kunz, "Machine Type Communications in 3GPP Networks: Potential, Challenges, and Solutions," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 178–184, Mar. 2012.

[8] H. Shariatmadari, R. Ratasuk, S. Iraji, A. Laya, T. Taleb, R. Jäntti, and A. Ghosh, "Machine-Type Communications: Current Status and Future Perspectives toward 5G Systems," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 10–17, Sep. 2015.

[9] C. Bockelmann, N. Pratas, H. Nikopour, K. Au, T. Svensson, C. Stefanovic, P. Popovski, and A. Dekorsy, "Massive Machine-Type Communications in 5G: Physical and MAC-Layer Solutions," *IEEE Commun. Mag.*, vol. 54, no. 9, pp. 59–65, Sep. 2016.

[10] X. Jian, Y. Liu, Y. Wei, X. Zeng, and X. Tan, "Random Access Delay Distribution of Multichannel Slotted ALOHA with its Applications for Machine Type Communications," *IEEE Internet Things J.*, vol. 4, no. 1, pp. 21–28, Feb. 2017.

[11] P. D. Diamantoulakis, K. N. Pappi, Z. Ding, and G. K. Karagiannidis, "Wireless-Powered Communications with Non-Orthogonal Multiple Access," *IEEE Trans. Wireless Commun.*, vol. 15, no. 12, pp. 8422–8436, Dec. 2016.

[12] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, and V. K. Bhargava, "A Survey on Non-Orthogonal Multiple Access for 5G Networks: Research Challenges and Future Trends," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2181–2195, Oct. 2017.

[13] L. Xiao, Y. Li, C. Dai, H. Dai, and H. V. Poor, "Reinforcement Learning-Based NOMA Power Allocation in the Presence of Smart Jamming," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 3377–3389, 2018.

[14] J. Choi, "Layered Non-Orthogonal Random Access with SIC and Transmit Diversity for Reliable Transmissions," *IEEE Trans. Commun.*, vol. 66, no. 3, pp. 1262–1272, Mar. 2018.

[15] P. Wang, J. Xiao, and L. P, "Comparison of Orthogonal and Non-Orthogonal Approaches to Future Wireless Cellular Systems," *IEEE Veh. Technol. Mag.*, vol. 1, no. 3, pp. 4–11, Sep. 2006.

[16] M. Al-Imari, P. Xiao, M. A. Imran, and R. Tafazolli, "Uplink Non-Orthogonal Multiple Access for 5G Wireless Networks," in *Proc. 11th Int. Symp. Wireless Communications Systems (ISWCS)*, Barcelona, Spain, Aug. 2014, pp. 781–785.

[17] L. H. Ozarow, S. Shamai, and A. D. Wyner, "Information Theoretic Considerations for Cellular Mobile Radio," *IEEE Trans. Veh. Technol.*, vol. 43, no. 2, pp. 359–378, May 1994.

[18] D. N. C. Tse and S. V. Hanly, "Multiaccess Fading Channels. I. Polymatroid Structure, Optimal Resource Allocation and Throughput Capacities," *IEEE Trans. Inf. Theory*, vol. 44, no. 7, pp. 2796–2815, Nov. 1998.

[19] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng, and R. Schober, "Simultaneous Wireless Information and Power Transfer in Modern Communication Systems," *IEEE Commun. Mag.*, vol. 52, no. 11, pp. 104–110, Nov. 2014.

[20] P. Grover and A. Sahai, "Shannon Meets Tesla: Wireless Information and Power Transfer," in *Proc. IEEE Int. Symp. Information Theory*, Austin, TX, USA, Jun. 2010, pp. 2363–2367.

[21] C. Zhong, H. A. Suraweera, G. Zheng, I. Krikidis, and Z. Zhang, "Wireless Information and Power Transfer with Full Duplex Relaying," *IEEE Trans. Commun.*, vol. 62, no. 10, pp. 3447–3461, Oct. 2014.

[22] S. Bi, C. K. Ho, and R. Zhang, "Wireless Powered Communication: Opportunities and Challenges," *IEEE Commun. Mag.*, vol. 53, no. 4, pp. 117–125, Apr. 2015.

[23] S. A. Tegos, P. D. Diamantoulakis, K. N. Pappi, P. C. Sofotasios, S. Muhaidat, and G. K. Karagiannidis, "Toward Efficient Integration of Information and Energy Reception," *IEEE Trans. Commun.*, vol. 67, no. 9, pp. 6572–6585, Sep. 2019.

[24] H. Ju and R. Zhang, "Throughput Maximization in Wireless Powered Communication Networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 1, pp. 418–428, Jan. 2014.

[25] P. D. Diamantoulakis, K. N. Pappi, G. K. Karagiannidis, H. Xing, and A. Nallanathan, "Joint Downlink/Uplink Design for Wireless Powered Networks with Interference," *IEEE Access*, vol. 5, pp. 1534–1547, 2017.

[26] D. Li, W. Peng, and Y. Liang, "Hybrid Ambient Backscatter Communication Systems with Harvest-Then-Transmit Protocols," *IEEE Access*, vol. 6, pp. 45 288–45 298, 2018.

[27] J. Choi, "NOMA-Based Random Access with Multichannel ALOHA," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 12, pp. 2736–2743, 2017.

[28] M. Najafi, V. Jamali, P. D. Diamantoulakis, G. K. Karagiannidis, and R. Schober, "Non-Orthogonal Multiple Access for FSO Backhauling," in *Proc. IEEE Wireless Communications and Networking Conf. (WCNC)*, Barcelona, Spain, Apr. 2018, pp. 1–6.

[29] 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.

[30] J. Choi, "Multichannel NOMA-ALOHA Game with Fading," *IEEE Trans. Commun.*, vol. 66, no. 10, pp. 4997–5007, Oct. 2018.

[31] E. Balevi, F. T. A. Rabee, and R. D. Gitlin, "ALOHA-NOMA for Massive Machine-to-Machine IoT Communication," in *Proc. IEEE Int. Conf. Communications (ICC)*, Kansas City, MO, USA, May 2018, pp. 1–5.

[32] Y. Liang, X. Li, J. Zhang, and Z. Ding, "Non-Orthogonal Random Access for 5G Networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 7, pp. 4817–4831, Jul. 2017.

[33] H.-H. Choi and W. Shin, "Slotted ALOHA for Wireless Powered Communication Networks," *IEEE Access*, 2018.

[34] Z. Hadzi-Velkov, S. Pejoski, N. Zlatanov, and R. Schober, "Proportional Fairness in ALOHA Networks with RF Energy Harvesting," *IEEE Wireless Commun. Lett.*, vol. 8, no. 1, pp. 277–280, Feb. 2019.

[35] Z. Hadzi-Velkov, S. Pejoski, R. Schober, and N. Zlatanov, "Wireless Powered ALOHA Networks with UAV-Mounted Base Stations," *IEEE Wireless Commun. Lett.*, p. 1, 2019.

[36] 3GPP, "TP for Classification of MUST Schemes," Aug. 2015.

[37] Y. H. Wang, "On the Number of Successes in Independent Trials," *Statistica Sinica*, pp. 295–312, 1993.

[38] N. Zlatanov, R. Schober, and Z. Hadzi-Velkov, "Asymptotically Optimal Power Allocation for Energy Harvesting Communication Networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 7286–7301, Aug. 2017.

[39] I. S. Gradshteyn and I. M. Ryzhik, *Table of integrals, series, and products*. Academic press, 2014.

[40] J. Kang, I. Kim, and D. I. Kim, "Wireless information and power transfer: Rate-energy tradeoff for nonlinear energy harvesting," *IEEE Transactions on Wireless Communications*, vol. 17, no. 3, pp. 1966–1981, 2018.

Sotiris A. Tegos was born in Serres, Greece. He received the Diploma Degree (5 years) in Electrical and Computer Engineering from the Aristotle University of Thessaloniki (AUTH), Greece, in 2017, where he is currently pursuing his PhD with the Department of Electrical and Computer Engineering. Also, he is a member of the Wireless Communications Systems Group (WCSG). In 2018, he was a visitor researcher at the department of Electrical and Computer Engineering at Khalifa University, Abu Dhabi, UAE. His current research interests include resource allocation in wireless communications, wireless power transfer, optimization theory and applications, and probability theory. He was an exemplary reviewer in IEEE Communication Letters for 2019 (top 3% of reviewers).

Panagiotis D. Diamantoulakis is Senior Member IEEE. He received the Diploma (five years) and Ph.D. degrees from the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki (AUTH), Greece, in 2012 and 2017, respectively. From 2017 to 2019, he was a Visiting Post-Doctoral Researcher with the Key Laboratory of Information Coding and Transmission, Southwest Jiaotong University, China, and the Telecommunications Laboratory (LNT), Institute for Digital Communications (IDC), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Germany. Since 2017, he has been a Post-Doctoral Fellow with the Wireless Communications Systems Group (WCSG), AUTH. His current research interests include resource allocation in optical wireless communications, optimization theory and applications, game theory, non-orthogonal multiple access, and wireless power transfer. He serves as an Editor for IEEE Wireless Communications Letters, Physical Communications (Elsevier), IEEE Open Journal of the Communications Society, and Frontiers in Communications and Networks. He was also an Exemplary Reviewer of IEEE Communications Letters in 2014 and IEEE Transactions on Communications in 2017 and 2019 (top 3% of reviewers).

Athanasios S. Lioumpas received the B.Eng. (2005) and Ph.D. (2009) degrees from the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, with specialization in wireless digital communication systems. He has extensive experience (A.U.Th, University of Piraeus, N.T.U.A) as a researcher and coordinator of research projects funded by European or/and national funds, as well as broad experience in mobile and fixed telephony networks design, deployment and operation (Cyta Hellas, Nokia Networks, Forthnet). He previously worked as Network Design Engineer for Cyta Hellas, which launched the first full MVNO network in Greece. He was also responsible for the coordination of the company's research projects, related to 5G networks and the internet of things. Later, he worked for Nokia Networks as a Verification Engineer for cloud-based 4G/IMS e2e solutions. Currently, he is with Forthnet Group, as a Senior Telecommunications Engineer. Dr. Lioumpas was awarded by the Greek Ministry of Education, Lifelong Learning and Religious Affairs for contributing to the academic and scientific excellence (2012) and by the Aristotle University of Thessaloniki for his patent being selected by the Greek Patent Office, as a candidate for the European inventor awards 2016. He is co-author of a scientific paper that received the best paper award at the Wireless Communications Symposium of the IEEE ICC 2007. He also served as an Associate Editor for IEEE Communications Letters (2013-2017). His scientific contributions include more than 50 papers in international refereed journals, peer-reviewed conferences and chapters in books, while he holds 5 patents.

Dr. Panagiotis G. Sarigiannidis is an Assistant Professor in the Department of Electrical and Computer Engineering in the University of Western Macedonia, Kozani, Greece since 2016. He received the B.Sc. and Ph.D. degrees in computer science from the Aristotle University of Thessaloniki, Thessaloniki, Greece, in 2001 and 2007, respectively. He has published over 170 papers in international journals, conferences and book chapters, including IEEE Communications Surveys and Tutorials, IEEE Internet of Things, IEEE Transactions on Broadcasting, IEEE Systems Journal, IEEE Wireless Communications Magazine, IEEE/OSA Journal of Lightwave Technology, IEEE Access, and Computer Networks. He has been involved in several national, European and international projects. He is currently the project coordinator of three H2020 projects, namely a) H2020-DS-SC7-2017 (DS-07-2017), SPEAR: Secure and PrivatE smArt gRid, b) H2020-LC-SC3-EE-2020-1 (LC-SC3-EC-4-2020), EVIDENT: bEhaVioral Insgihts anD Effective eNergy policy acTions, and H2020-ICT-2020-1 (ICT-56-2020), c) TERMINET: nexT gEneRation sMart INterconnectEd ioT, while he coordinates the Operational Program MARS: sMart fArming with dRoneS (Competitiveness, Entrepreneurship, and Innovation). He also serves as a principal investigator in the H2020-SU-DS-2018 (SU-DS04-2018-2020), SDN-microSENSE: SDN-microgrid reSilient Electrical eNergy SystEm and in the Erasmus+ KA2 ARRANGE-ICT: pArtneRship foR AddressiNG mEgatrends in ICT (Cooperation for Innovation and the Exchange of Good Practices). His research interests include telecommunication networks, internet of things and network security. He is an IEEE member and participates in the Editorial Boards of various journals, including International Journal of Communication Systems and EURASIP Journal on Wireless Communications and Networking.

George K. Karagiannidis (M'96-SM'03-F'14) was born in Pithagorion, Samos Island, Greece. He received the University Diploma (5 years) and PhD degree, both in electrical and computer engineering from the University of Patras, in 1987 and 1999, respectively. From 2000 to 2004, he was a Senior Researcher at the Institute for Space Applications and Remote Sensing, National Observatory of Athens, Greece. In June 2004, he joined the faculty of Aristotle University of Thessaloniki, Greece where he is currently Professor in the Electrical & Computer Engineering Dept. and Head of Wireless Communications Systems Group (WCSG). He is also Honorary Professor at South West Jiaotong University, Chengdu, China. His research interests are in the broad area of Digital Communications Systems and Signal processing, with emphasis on Wireless Communications, Optical Wireless Communications, Wireless Power Transfer and Applications and Communications & Signal Processing for Biomedical Engineering. Dr. Karagiannidis has been involved as General Chair, Technical Program Chair and member of Technical Program Committees in several IEEE and non-IEEE conferences. In the past, he was Editor in several IEEE journals and from 2012 to 2015 he was the Editor-in Chief of IEEE Communications Letters. Currently, he serves as Associate Editor-in Chief of IEEE Open Journal of Communications Society. Dr. Karagiannidis is one of the highly-cited authors across all areas of Electrical Engineering, recognized from Clarivate Analytics as Web-of-Science Highly-Cited Researcher in the five consecutive years 2015-2019.