2023 IEEE International Mediterranean Conference on Communications and Networking (MeditCom) | 979-8-3503-3373-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/MeditCom58224.2023.10266655

Slotted ALOHA with Code Combining for IoT Networks

Dimitrios Tyrovolas*†, Athanasios Chrysologou*, Georgios Chondrogiannis*, Sotiris Tegos*, Prodromos-Vasileios Mekikis*, Panagiotis Diamantoulakis*, Sotiris Ioannidis†, Christos Liaskos‡, Nestor Chatzidiamantis*, George Karagiannidis*§

*Dept. of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece
e-mail: {tyrovolas, chrysolog, gchondro, tegosoti, vmekikis, padiaman, nestoras, geokarag}@auth.gr
† Dept. of Electrical and Computer Engineering, Technical University of Chania, Chania, Greece
e-mail: sotiris@ece.tuc.gr
‡Computer Science Engineering Department, University of Ioannina, Ioannina, Greece.
e-mail: cliaskos@ics.forth.gr
§Cyber Security Systems and Applied AI Research Center, Lebanese American University (LAU), Lebanon

***Abstract*—Internet of Things (IoT) networks are expected to be a key enabler technology for smart cities, due to their ability to offer real-time monitoring. In this work, we propose a novel medium access control (MAC) protocol, inspired by the synergy of slotted ALOHA and hybrid automatic repeat request with code combining (HARQ-CC), termed as code combining slotted ALOHA (CCSA), to improve the performance of IoT networks with multiple randomly deployed sensors. Specifically, we provide analytical closed-form expressions for the network's outage probability as well as for its average throughput when CCSA is applied. Finally, we provide simulation results that reveal the authenticity of the derived expressions and reveal the capabilities of HARQ-CC to significantly improve the network's performance when the sensors' access is based on a random access scheme.**

***Index Terms*—Hybrid automatic repeat request (HARQ), IoT networks, Random access, Stochastic geometry, Wireless sensor networks**

I. Introduction

Internet of Things (IoT) networks are foreseen as an integral part of future digital societies, due to their capabilities to sense the physical environment through a massive number of sensor nodes [1]. However, to enhance the IoT networks' maintainability, it is of significant importance to reduce the sensors' energy consumption, without degrading the network's performance. Therefore, novel communication methods can be proposed that assist in successful data reception from a large area of randomly deployed sensors that transmit with as low power as possible.

The quality of service (QoS) of an IoT network can be significantly enhanced in an energy-efficient manner through error control protocols. In this direction, the hybrid automatic repeat request protocol with code combining (HARQ-CC) is able to achieve reliable data transmission by exploiting retransmissions and frame combining [2]. Considering the capabilities of HARQ-CC in IoT networking, the authors in [3] optimized the performance of a HARQ-CC-enabled single-sensor network in the context of short-packet communication with energy constraints. Furthermore, in [4], the outage performance as well as the average throughput of a single-sensor scenario supported by a UAV-mounted reconfigurable intelligent surface (RIS) has been examined, while the authors in [5] characterized the age-energy trade-off for a single-sensor IoT monitoring system that applies HARQ. Nevertheless, the above works provide insights only for the case where the sensors are orchestrated to transmit in an orthogonal way, which is quite unrealistic as it requires accurate coordination among many randomly deployed sensors [6]. To this end, random access (RA) and especially slotted ALOHA (SA) have been proposed as a more appropriate way for multiple access in IoT networks, as it provides low latency communications with reduced need of accurate orchestration of the sensors' transmission process [6]. However, to the best of the authors' knowledge, no work exists that investigates the performance of a HARQ-CC assisted IoT network that applies a random access protocol for the sensors' access.

In this work, we quantify the performance of an IoT network that consists of multiple sensors that are randomly deployed within a circular disk. In particular, after providing closed-form expressions for the outage performance of a single randomly distributed sensor that employs HARQ-CC, we investigate the performance of a network of multiple sensors that applies a HARQ-CC-based SA (CCSA) protocol. The performance of the considered network is assessed in terms of both outage probability and average throughput. Simulations illustrate that HARQ-CC is able to significantly enhance the network's performance, when a RA protocol is applied.

II. System model

A. IoT Network Overview

We consider a set of S single-antenna IoT sensors that are uniformly distributed within a disk of radius R and an access point (AP) located at the disk's center, that collects the sensors' data. To increase the maintainability of the IoT network by expanding the sensors' lifetime, it is assumed that they use ultra-low power P_t for their transmissions. Hence, the received signal Y at the AP can be modelled as

$$Y = \sqrt{l_p G P_t} h x + w, \tag{1}$$

where x is the transmitted signal whose energy is assumed to be equal to one, i.e., $\mathbb{E}[x^2] = 1$ with $\mathbb{E}[\cdot]$ denoting the expectation of a complex number, and w is the additive white Gaussian noise with zero mean and variance σ^2. Moreover, $G = G_t G_r$ is the product of the AP and the sensors antenna gains, h corresponds to the complex coefficient of the n-th sensor-AP channel, and l describes the channel's path loss which can be expressed as $l_p = C_0 {d_0}^a d^{-a}$, where C_0 denotes the path loss at the reference distance d_0, d is the distance between the n-th sensor and the AP, and a is the path loss exponent. Additionally, by taking into account that the sensors are uniformly distributed within a disk with radius R, it is assumed that d is a random variable (RV) with probability density function (PDF) equal to $f_d(x) = \frac{2x}{R^2}$ [7]. We also assume that $|h|$ is an RV following the Nakagami-m distribution with shape parameter m and spread parameter Ω. Therefore, the instantaneous received SNR γ_r for the presented communication scenario can be described as $\gamma_r = \gamma_t \, G \, C_0 \, {d_0}^a \, d^{-a} \, |h|^2$ with $\gamma_t = \frac{P_t}{\sigma^2}$ denoting the transmit SNR and the RV $|h|^2$ following the gamma distribution with shape parameter $k = m$ and scale parameter $\theta = \frac{\Omega}{m}$ [8].

B. HARQ-Code Combining (HARQ-CC)

Given that sensor placements are unpredictable and they work as minimal power emitters, we need new strategies for dependable links to a vast number of randomly deployed IoT nodes. In this direction, by applying HARQ-CC, after a failed transmission attempt, the AP can store the erroneous decoded frame and send a non-acknowledgment (NACK) message to the transmitting sensor. After the reception of the NACK message, the sensor will retransmit its frame instead of dropping it. Once the frame is retransmitted, the AP can combine it with the stored one through maximum ratio combining (MRC) and then attempts to decode the combined frame. Hence, for the case where HARQ-CC is applied, the instantaneous received SNR after l transmission rounds is given as

$$\gamma_r = \Phi d^{-a} \sum_{i=1}^{l} |h_i|^2, \tag{2}$$

where we define $\Phi = \gamma_t G C_0 {d_0}^a$ and $|h_i|^2$ is the i-th transmission round channel gain. It is important to acknowledge that, for a given message, the quantity of transmissions is bounded by a pre-established maximum value. This limitation is implemented to ensure that the IoT network maintains an acceptable level of latency. Furthermore, channel coefficients h_i are assumed to be independent and identically distributed.

C. Code Combining Slotted ALOHA (CCSA) Protocol

A popular RA protocol that has been proposed for future machine-to-machine communications is SA, which is characterized by extremely low complexity [6], [9]. In SA, the following characteristics are observed: fixed-length packets are transmitted, the transmissions are synchronized at the initiation of each slot, and the duration of the slots is determined by the transmission time of the packets. However, when two sensors try to access the same slot, a collision event occurs, resulting in the system's outage. To this end, by taking into consideration the capabilities of HARQ-CC, we propose the CCSA protocol to devise a novel multiple access scheme that enjoys an increased probability of successful decoding due to packet retransmissions. In more detail, during any time slot of CCSA, each device can be in: i) the idle state, which describes the state when the device has no package for transmission, ii) the transmission state, denoting the active transmission of a packet by a device, regardless of whether the transmission is successful or unsuccessful, and iii) the retransmission state wherein a device awaits the opportunity for packet retransmission in a subsequent time slot. It should be mentioned that we assume that no erroneous transmissions of NACK messages occur, the number of transmission round cannot exceed a predefined threshold l, and for the case where $l = 1$, then CCSA coincides with SA.

III. Performance Analysis

In this section, we present closed-form analytical expressions that provide meaningful insights for IoT networks implementing CCSA. We assess three crucial performance indicators for the IoT network in question: i) the outage probability for a random sensor using HARQ-CC, ii) the overall network's outage probability, and iii) the average network throughput.

A. Outage probability of a single-sensor scenario with HARQ-CC

As aforementioned, an efficient way to reduce the outage events that occur within a communication network is through HARQ-CC. Specifically, to maintain an acceptable latency, the truncated version of HARQ-CC is considered, i.e., the number of retransmissions is limited to a maximum of l.

Proposition 1: The outage probability $P_{o,l}$ after l HARQ-CC transmission rounds of a single-sensor scenario where the sensor are assumed to be uniformly distributed within a disk of radius R can be expressed as

$$P_{o,l} = 1 - \frac{2}{aR^2} \left(\frac{\theta}{\tilde{\Phi}}\right)^{\frac{2}{a}} \sum_{i=1}^{m_l - 1} \frac{\gamma(i + \frac{2}{a}, \frac{\tilde{\Phi} R^a}{\theta})}{i!}, \tag{3}$$

where $m_l = ml$, $\tilde{\Phi} = \frac{\gamma_{\text{thr}}}{\Phi}$ with γ_{thr} being the SNR threshold for successful decoding and $\gamma(\cdot,\cdot)$ denoted the lower incomplete gamma function [10].

Proof: The outage probability after l HARQ-CC rounds can be evaluated as

$$P_{o,l} = \Pr\left(\Phi d^{-a} \sum_{i=1}^{l} |h_i|^2 \leq \gamma_{\text{thr}}\right), \tag{4}$$

By invoking the results provided in [8], $\sum_{i=1}^{l} |h_i|^2$ follows the gamma distribution with scale parameter θ and shape parameter $k_s = m_l$. Thus, by taking into consideration the cumulative density function (CDF) of gamma distribution that is equal to $F_g(x) = \frac{\gamma(k, \frac{x}{\theta})}{\Gamma(k)}$, and the PDF of the RV d, then (4) can be rewritten as

$$P_{o,l} = \int_0^R \frac{\gamma(m_l, \frac{\tilde{\Phi} y^a}{\theta})}{\Gamma(m_l)} \frac{2y}{R^2} dy, \tag{5}$$

where $\Gamma(\cdot)$ is the Gamma function. Additionally, assuming that $m \in \mathbb{Z}$, it holds that $m_l \in \mathbb{Z}$, since $l \in \mathbb{Z}$ by definition and,

$$P_{s,j} = \frac{2\theta^{\frac{2}{a}}}{aR^2\tilde{\Phi}^{\frac{2}{a}}}\left(\sum_{j_1=0}^{m-1}\frac{\gamma\left(j_1+\frac{2}{a},\frac{\tilde{\Phi}R^a}{\theta}\right)}{j_1!} - \sum_{j_2=0}^{m_j-1}\frac{\gamma\left(j_2+\frac{2}{a},\frac{\tilde{\Phi}R^a}{\theta}\right)}{j_2!} + \frac{1}{\Gamma(m)}\sum_{j_3=0}^{m_j-1}\sum_{j_4=0}^{j_3}\binom{j_3}{j_4}\frac{(-1)^{j_4}\gamma\left(j_3+m+\frac{2}{a},\frac{\tilde{\Phi}R^a}{\theta}\right)}{(j_4+m)j_3!}\right) \quad (9)$$

thus, the lower incomplete gamma function can be written as [10]

$$\gamma(m_l, \frac{\tilde{\Phi}y^a}{\theta}) = \Gamma(m_l)\left(1 - e^{-\frac{\tilde{\Phi}y^a}{\theta}}\sum_{i=0}^{m_l-1}\frac{\tilde{\Phi}^i y^{ai}}{\theta^i i!}\right). \quad (6)$$

Hence, by substituting (6) in (5), $P_{o,l}$ can be written as

$$P_{o,l} = \frac{2}{R^2}\left(\int_0^R y dy - \sum_{i=0}^{m_l-1}\frac{\tilde{\Phi}^i}{\theta^i i!}\int_0^R y^{ai+1}e^{-\frac{\tilde{\Phi}y^a}{\theta}}dy\right). \quad (7)$$

By performing some manipulations, (3) can be extracted. This concludes the proof. ■

B. Outage probability of an IoT network with CCSA

To accurately investigate the performance gains of HARQ-CC in IoT wireless networks where multiple sensors access the medium in a random manner, it is imperative to include any collision events in the outage probability expression, as they can lead to unsuccessful packet decoding, even if the channel conditions are favorable. Thus, to deduce the outage probability when CCSA is applied, it is required to describe all the causes that can lead to outage.

Proposition 2: The outage probability of an IoT network, that applies CCSA of l rounds and consists of S uniformly distributed sensors within a disk of radius R is given as

$$P_{O,l} = 1 - \sum_{i=1}^{l}\sum_{j=1}^{i}\left[1-(1-q)^{S-1}\right]^{i-j}(1-q)^{j(S-1)}P_{s,j}, \quad (8)$$

where q is the probability of each sensor to access the channel in a specific time slot, and $P_{s,j}$ is the probability of successful decoding at the j-th round, which is provided at the top of the page as (9), where $m_j = (j-1)m$.

Proof: The outage probability of the examined IoT network can be calculated as the complementary probability of successful data reception $P_{\text{suc},l}$ after l CCSA rounds. Thus, to determine the value of $P_{\text{suc},l}$, it is necessary to account for all possible combinations of collision events and channel conditions that led to unsuccessful packet delivery in previous rounds, along with the successful reception of data in the current round. Specifically, in the initial CCSA round, the probability of successful reception is calculated as $(1-q)^{(S-1)}P_{s,1}$, i.e., no collision occurs and the packet is successfully decoded at the first CCSA round. However, in the case where the packet is successfully decoded in the second round, we need to take into account the possible events that lead to the second CCSA round, i.e., the communication was unsuccessful in the first round due to collision or unfavorable channel conditions. Hence, successful reception probability at the second CCSA round is given as $\left[1-(1-q)^{S-1}\right](1-q)^{S-1}P_{s,1}+(1-q)^{2(S-1)}P_{s,2}$. Following similar steps for all rounds, (8) occurs. It should be highlighted that, if a collision takes place, then no frame is stored at the AP, meaning that the number of combined packets at the AP in each CCSA round depends on the number of previously occurred collisions.

In this direction, to obtain (8), we need to calculate the probability of successful packet decoding at the j-th CCSA round, which can be given as

$$P_{s,j} = \Pr\left(\gamma_r^{j-1} \le \gamma_{\text{thr}} \cap \gamma_r^j \ge \gamma_{\text{thr}}\right), \quad (10)$$

which can be rewritten as

$$P_{s,j} = \Pr\left(\tilde{\Phi}d^a - |h_j|^2 \le \sum_{i=1}^{j-1}|h_i|^2 \le \tilde{\Phi}d^a\right). \quad (11)$$

By conditioning on d, $P_{s,j}$ can be calculated as

$$P_{s,j|d} = \int_0^{\tilde{\Phi}d^a}\int_{\tilde{\Phi}d^a-y}^{\tilde{\Phi}d^a} f_A(y)f_B(x)dxdy + \int_{\tilde{\Phi}d^a}^{\infty} f_A(y)dy\int_0^{\tilde{\Phi}d^a} f_B(x)dx, \quad (12)$$

where $A = |h_j|^2$, $B = \sum_{i=1}^{j-1}|h_i|^2$, and $f_v(x)$ with $v \in \{A, B\}$ denoting the PDF of gamma distribution which is given as $f_v(x) = \frac{1}{\Gamma(k_v)\theta_v{}^{k_v}}x^{k_v-1}e^{-\frac{x}{\theta_v}}$, with $k_A = m$, $k_B = m_j$, and $\theta_A = \theta_B = \theta$. Thus, after some algebraic manipulations, $P_{s,j|d}$ can be calculated as

$$P_{s,j|d} = \frac{\gamma\left(m_j, \frac{\tilde{\Phi}d^a}{\theta}\right)}{\Gamma(m_j)} - \frac{\gamma\left(m, \frac{\tilde{\Phi}d^a}{\theta}\right)}{\Gamma(m)} + \sum_{i=0}^{m_j-1}\sum_{j=0}^{i}\binom{i}{j}\frac{(-1)^j\left(\tilde{\Phi}d^a\right)^{i+m}}{i!\theta^i(j+m)}. \quad (13)$$

Finally, to obtain $P_{s,j}$ we need to consider the randomness of the RV d, which can be done through the following integration

$$P_{s,j} = \int_0^R P_{s,j|x}\, f_d(x)\, dx. \quad (14)$$

By solving (14), we obtain (9). This concludes the proof. ■

C. Average throughput of an IoT network with CCSA

Next, we calculate the average throughput which express the number of received bits per second. In more detail, the average throughput can be considered as a critical evaluation metric for IoT networks with multiple sensors, as it captures both the frequency of outages and the utilized medium access protocol's efficiency. Therefore, a throughput of the proposed network that applies CCSA is examined.

$$\bar{T} = \sum_{i=1}^{l-1} i \sum_{j=1}^{i} \left[1-(1-q)^{S-1}\right]^{i-j} (1-q)^{j(S-1)} \mathcal{P}_{s,j} + l \left[\sum_{i=1}^{l-1} \left[1-(1-q)^{S-1}\right]^{l-1-i} (1-q)^{i(S-1)} P_{o,i} + \left[1-(1-q)^{S-1}\right]^{l-1}\right], \tag{15}$$

Proposition 3: The average throughput of an IoT network that applies CCSA of l rounds with S randomly deployed sensors within a disk of radius R, can be calculated as $\bar{C} = \frac{R_t}{\bar{T}}\left(1-P_{O,l}\right)$, where $R_t = B\log_2\left(1+\gamma_{\text{thr}}\right)$ is the sensors' transmit rate, B is the network's bandwidth, and $\bar{T}$ denotes the average number of transmission rounds, which is given at the top of the page as (15).

Proof: A system's average throughput can be expressed as the transmit rate R_t multiplied with the successful data reception probability [2], [4]. However, for the examined case where multiple transmission rounds may be required for successful decoding, the average throughput needs to be divided by the average number of the transmission rounds $\bar{T}$, which are dependent on the channel conditions. Specifically, for favorable channel conditions and if no collisions occur, one transmission can be sufficient for successful decoding. On the contrary, in the case of unfavorable channel conditions, more CCSA rounds may be needed to successfully decode a packet.

Considering that the number of occurred transmission rounds is a discrete RV and that CCSA of l rounds is applied, then $\bar{T}$ can be calculated as $\bar{T} = \sum_{i=1}^{l} i \Pr\left(T=i\right)$, where $\Pr\left(T=i\right)$ is the probability that the transmission rounds are equal to i, i.e., the data transmission is terminated at the i-th round due to successful data decoding or reaching the maximum number of permitted transmission rounds. In more detail, regarding the first round, probability $\Pr(T=1)$ equals to $(1-q)^{S-1}P_{s,1}$, since to successfully decode the transmitted data at the first round, a collision should not happen while in the meantime the channel conditions must enable successful decoding. However, if $i \in [2, l-1]$ it becomes necessary to consider all possible combinations of collision events and channel conditions for each transmission. For instance, in the second round the transmitted data can be successfully decoded with probability $\left[1-(1-q)^{S-1}\right](1-q)^{S-1} P_{s,1} + (1-q)^{2(S-1)} P_{s,2}$, meaning that two distinct scenarios must be taken into account: i) The sensor encountered a collision in the first round, successfully transmitted without experiencing any collisions from the remaining $(S-1)$ sensors in the second round, and had its message decoded, and ii) The sensor managed to transmit without facing any collisions in the first two rounds, its message was not decoded in the first round, but it was successfully decoded in the second round. Regarding the final round, where the transmission ends whether the message is decoded or not, we can define the probability $\Pr(T=l)$ as the chance of message failure, either from collisions or poor channel conditions, in the previous $l-1$-th round. Hence, considering the above, $\Pr(T=l)$ is given as

$$\Pr(T=l) = \sum_{i=1}^{l-1} \left[1-(1-q)^{S-1}\right]^{l-1-i} (1-q)^{i(S-1)} \times P_{o,i} + \left[1-(1-q)^{S-1}\right]^{l-1}. \tag{16}$$

This concludes the proof. ■

TABLE I: Simulation Parameters

Parameter	Notation	Value
Reference distance	d_0	1 m
Sensor Access Probability	q	$\frac{1}{S}$
Number of sensors	S	10
Radius	R	50 m
Bandwidth	B	10 kHz
Transmit SNR	γ_t	75 dB
SNR threshold	γ_{thr}	0 dB
Spread Parameter	Ω	1
Path Loss Exponent	a	2.5
Shape Parameter	m	3
Antenna Gain	G	0 dB
Path Loss at ref. distance	C_0	-30 dB

IV. Numerical Results

In this section, the performance of an IoT network with S randomly deployed sensors that applies CCSA of l rounds is analyzed. Specifically, we validate the presented closed-form expressions and we evaluate the efficiency of the proposed RA protocol when it comes for outage performance and average throughput. The simulation parameter used for the extraction of the following figures are provided in Table I, where wit is assumed that that both the AP and IoT sensors are equipped with isotropic antennas, i.e., $G = 1$. Finally, unless it is stated otherwise sensors are assumed to be uniformly distributed within a disk of radius $R = 50$ meters.

Fig. 1 presents the outage performance of the examined CCSA protocol with respect to R for various l values. It is clearly illustrated that the utilization of CCSA leads to enhanced network outage performance. More specifically, for every R value, increased l leads to enhanced outage performance, with the performance gain between $l = 1$ and $l = 2$ being greater than the one between $l = 2$ and $l = 3$. Furthermore, as expected, it can be seen that as the disk radius R increases, then the outage probability deteriorates for all the presented cases.

In Fig. 2, the effect of the sensors' number on the network's outage performance is presented. It is noted that for every dif-

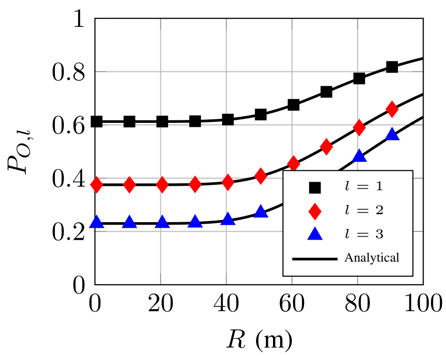

Fig. 1: $P_{O,l}$ with CCSA of l rounds versus R.

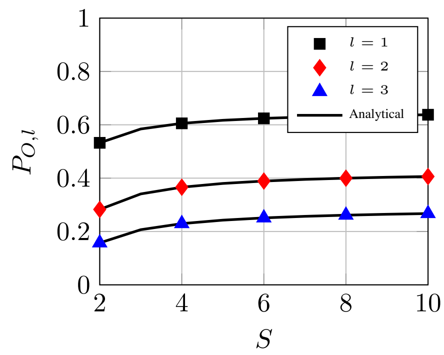

Fig. 2: $P_{O,l}$ with CCSA of l rounds versus S.

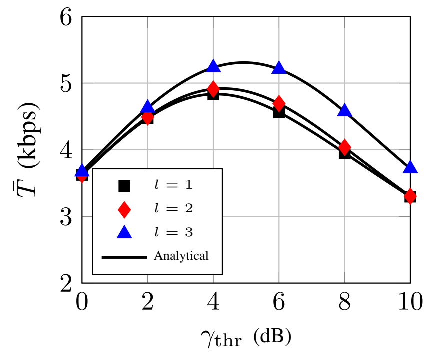

Fig. 3: $\bar{T}$ of IoT network with CCSA of l rounds versus $\gamma_{\rm thr}$.

ferent S value, sensors access probability becomes $q = 1/S$. Once again, the performance gain between $l = 1$ and $l = 2$ is greater than the one between $l = 2$ and $l = 3$. Also, it can be seen that, as S increases, $P_{O,l}$ shows an initial increase which is followed by a gradual convergence. This behavior indicates that there exists a specific S value after which, any further increase on S does not significantly affect the outage performance of the IoT network.

Finally, Fig. 3 illustrates the network's average throughput when CCSA is applied with respect to the SNR threshold value $\gamma_{\rm thr}$. Interestingly, for each l value, $\bar{T}$ shows a convex behavior, i.e., an initial increase which is succeeded by a decrease. Furthermore, it is revealed that for every examined RA protocol, the average throughput maximizes for a different $\gamma_{\rm thr}$ value, meaning that there exists an optimum transmit rate for each of the examined RA protocols. More specifically, CCSA with $l = 2$ achieves its highest average throughput value when $\gamma_{\rm thr} \approx 4.2$ dB, whereas CCSA with $l = 3$ achieves optimal average throughput when $\gamma_{\rm thr}$ is approximately equal to 5 dB. Finally, it should be highlighted, that for specific $\gamma_{\rm thr}$ regions, the transition from $l = 1$ to $l = 2$ does not lead to enhanced average throughput performance, even if the complexity of the RA protocol is increased due to the use of MRC at the receiver's side. Specifically, this occurs when $\gamma_{\rm thr} \in [0, 2.2]$ or $\gamma_{\rm thr} \in [9, 10]$. Hence, the applied RA protocol needs to be carefully selected according to the sensors' transmit rate so that the increased complexity has to offer enhanced performance.

V. Conclusions

In this work, the performance of an IoT network that applies a HARQ-CC-based RA protocol was presented. Specifically, we provided closed-form expressions for the network's outage probability and average throughput that have been validated through simulations. According to the provided numerical results, it can observed that HARQ-CC can improve the network's performance even if the multiple access of the network is based on RA protocols. Our future directions will combine the reduction of the occurred collisions through low-complexity transmission orchestration processes or through manipulating the wireless propagation via the novel concept of programmable wireless environments [11].

VI. Acknowledgments

This work has been funded by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 952690 (CYRENE).

References

[1] F. Guo, F. R. Yu, H. Zhang, X. Li, H. Ji, and V. C. M. Leung, "Enabling massive IoT toward 6G: A comprehensive survey," *IEEE Internet Things J.*, vol. 8, no. 15, pp. 11 891–11 915, Aug. 2021.

[2] A. Chelli, E. Zedini, M.-S. Alouini, M. Pätzold, and I. Balasingham, "Throughput and delay analysis of HARQ with code combining over double Rayleigh fading channels," *IEEE Trans. Veh. Technol.*, vol. 67, no. 5, pp. 4233–4247, May 2018.

[3] L. Vangelista and M. Centenaro, "Performance evaluation of HARQ schemes for the internet of things," *Computers*, vol. 7, no. 4, Sep. 2018. [Online]. Available: https://www.mdpi.com/2073-431X/7/4/48

[4] D. Tyrovolas, P.-V. Mekikis, S. A. Tegos, P. D. Diamantoulakis, C. K. Liaskos, and G. K. Karagiannidis, "On the performance of HARQ in IoT networking with UAV-mounted reconfigurable intelligent surfaces," in *Proc. IEEE 95th Veh. Technol. Conf. (VTC-Spring)*, Aug. 2022, pp. 1–5.

[5] Y. Gu, H. Chen, Y. Zhou, Y. Li, and B. Vucetic, "Timely status update in internet of things monitoring systems: An age-energy tradeoff," *IEEE Internet Things J.*, vol. 6, no. 3, pp. 5324–5335, Jun. 2019.

[6] S. A. Tegos, P. D. Diamantoulakis, A. S. Lioumpas, P. G. Sarigiannidis, and G. K. Karagiannidis, "Slotted ALOHA with NOMA for the next generation IoT," *IEEE Trans. Commun.*, vol. 68, no. 10, pp. 6289–6301, Jul. 2020.

[7] V. K. Papanikolaou, G. K. Karagiannidis, N. A. Mitsiou, and P. D. Diamantoulakis, "Closed-form analysis for NOMA with randomly deployed users in generalized fading," *IEEE Wireless Commun. Lett.*, vol. 9, no. 8, pp. 1253–1257, Aug. 2020.

[8] S. A. Tegos, G. K. Karagiannidis, P. D. Diamantoulakis, and N. D. Chatzidiamantis, "New results for Pearson type III family of distributions and application in wireless power transfer," *IEEE Internet Things J.*, vol. 9, no. 23, pp. 24 038–24 050, Dec. 2022.

[9] 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.

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

[11] C. Liaskos, A. Tsioliaridou, S. Nie, A. Pitsillides, S. Ioannidis, and I. Akyildiz, "An interpretable neural network for configuring programmable wireless environments," in *Proc. IEEE Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jul. 2019, pp. 1–5.