

On the Error Floor Evaluation of NOMA-Irregular Repetition Slotted ALOHA

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Abstract—In this work, we provide a simple yet tight analytical approximation of the packet loss rate in the error floor region for a non-orthogonal multiple access (NOMA)-based irregular repetition slotted ALOHA (IRSA) scheme. Considering an Internet of Things (IoT) scenario, users randomly select both the number of replicas based on a designed degree distribution and the transmission power from predetermined levels, while successive interference cancellation is performed at the receiver. Our derived packet loss rate expression in the finite length regime is promptly evaluated. Its accuracy is validated through Monte-Carlo simulations, demonstrating a strong match even for systems operating at channel loads exceeding 1 [packets/slot].

Index Terms—Non-orthogonal multiple access, irregular repetition slotted ALOHA, error floor evaluation, finite length

I. INTRODUCTION

The convergence of the Internet of Things (IoT), massive-type machine communications (mMTC), and 6G technology promises to revolutionize connectivity, enabling a vast array of low-cost devices to seamlessly exchange data [1]. A crucial aspect of IoT and mMTC is implementing efficient medium access methods capable of handling sporadic transmissions from a massive number of IoT devices. *Modern random access* protocols play a pivotal role in this context [2], offering flexible and scalable solutions to manage connectivity amongst the dynamic and often unpredictable nature of IoT deployments. These protocols enable devices to access the network without prior coordination, optimizing resource utilization while ensuring reliable and timely data transmission.

A notable contribution in modern random access schemes was provided in [3], with the development of irregular repetition slotted ALOHA (IRSA). This protocol combines packet diversity with successive interference cancellation (SIC), enabling the resolution of collisions. In IRSA, users transmit a variable number of replicas over a frame according to a predesigned distribution. The IRSA protocol was further investigated by incorporating power diversity per user in [4], [5] and per replica in [6], [7]. The advantage of power diversity lies in exploiting the capture effect, which enables the SIC algorithm to solve collisions even when multiple users transmit in the same slot.

In parallel to this, NOMA-based schemes, originally proposed for downlink transmissions, were also introduced for random access in the pioneering work [8]. NOMA schemes rely on accurately defining a set of power levels from which

users can choose. This approach ensures that collisions involving packets with different power levels can be resolved effectively. Thus, the SIC algorithm benefits from both the diversity of transmitting multiple packets and the diversity of power levels. In this context, NOMA-based random access schemes have been the subject of recent research.

Bounds on the throughput of the NOMA-ALOHA scheme were presented in [9], and the optimal load was analyzed in massive IoT scenarios with sparse user activity. In [10], the authors investigate the asymptotic performance of a slotted ALOHA scheme with NOMA to predict throughput performance. The analysis assumes that users can place their replicas within an infinitely long frame. This assumption allows for the effective use of density evolution to understand the system's behavior. Similarly, asymptotic analysis using density evolution was also conducted for a special case of IRSA, namely contention resolution diversity slotted ALOHA (CRDSA), in [11]. In [12], the replica degree distribution and power distribution are jointly optimized in the asymptotic regime using density evolution for NOMA-coded slotted ALOHA. This modern random access protocol integrates packet-level erasure correcting codes with SIC techniques. Similarly, [13] presents an asymptotic analysis for NOMA-IRSA, focusing on the optimization of degree distribution and power levels.

In the existing literature, most studies consider the performance of NOMA random access schemes under the assumption of infinitely long frames [9]–[13]. However, to the best of our knowledge, an analysis of their performance in the non-asymptotic regime is missing. To address this gap, this work evaluates the performance of NOMA-IRSA schemes in the more practically relevant finite frame lengths. Specifically, we derive a tight analytical approximation of the packet loss rate for low and moderate channel loads, i.e., in the error floor region.

Unlike the accurate yet involved approximation proposed in [14] and [15], we present here a computationally efficient one-shot expression derived from the balls in bins (BiB) problem. In [15] authors present an approximation for the IRSA scheme under the assumption of very short frames, limited to a maximum of 50 slots. In contrast, this work evaluates the NOMA-IRSA scheme, demonstrating its validity even for significantly longer frames. Furthermore, we propose a simplified method for evaluating the error floor, offering reduced complexity compared to the approaches in [14], [16], [17]. This work also provides an extension of the study presented in [18], which estimates the packet loss rate in a multipacket detection scenario under conditions of low channel loads and for a specific degree distribution. In the results

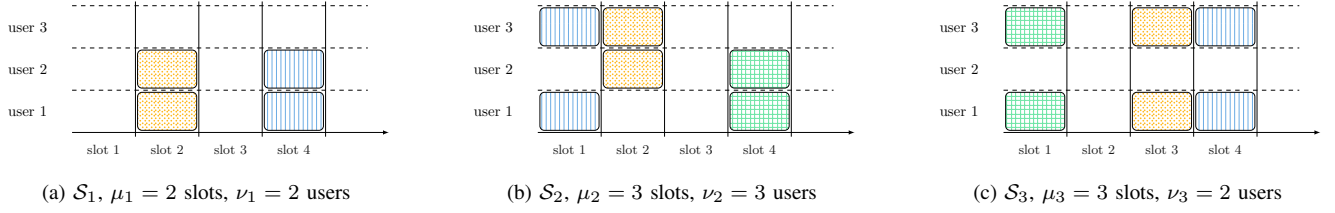


Fig. 1. Stopping sets in NOMA-based IRSA with the corresponding number of users and slots. The filling color-patterns represent different power levels.

section, we show that the solutions proposed in this work provide more accurate results for the NOMA-IRSA scheme compared to the evaluation given in [18].

Finally, we validate the proposed expression through Monte-Carlo simulations, showing a strong match even for systems operating at moderate channel loads.

The rest of the paper is organized as follows. Section II presents the system model, while in Section III the packet loss rate approximation is derived. Numerical results are given in Section IV, and Section V concludes.

II. SYSTEM MODEL

We consider a system where m uncoordinated IoT active nodes (users) transmit packets over a shared uplink wireless channel to a common receiver. A medium access control (MAC) frame is composed by n consecutive slots where the duration of a slot equals a packet duration. Users are frame and slot synchronized. The system channel load G is

$$G = \frac{m}{n} \quad [\text{packets/slot}].$$

A NOMA-IRSA scheme is considered. Following the IRSA protocol, each user sends r replicas of the generated data packet and uniformly places them across the n available slots in a frame. The number of replicas r to transmit is determined by a predefined degree distribution. The polynomial formulation of IRSA degree distribution can be written as [3]

$$\Lambda(x) = \sum_{r=2}^{r_{\max}} \lambda_r x^r, \quad \text{with} \quad \sum_{r=2}^{r_{\max}} \lambda_r = 1, \quad (1)$$

where λ_r represents the probability that a user transmit r replicas. Each replica has a pointer indicating where its copies are placed over the frame. This information is used by the receiver during the decoding process.

After determining the number of replicas to transmit, the user selects the transmission power level for each replica uniformly from the L available options, as suggested in [8]. We denote the power levels by

$$p_1 > \dots > p_L > 0, \quad \text{with} \quad p_k = \gamma(I_k + 1),$$

where γ is the target signal-to-interference and noise ratio (SINR) and $I_k = \sum_{j=k+1}^L p_j$ with $I_L = 0$. With easy manipulations, the k -th power level can be written as

$$p_k = \gamma(\gamma + 1)^{L-k}. \quad (2)$$

The transmission rate R is defined through $R = \log_2(1 + \gamma)$.

At the receiver side, SIC is performed. Assuming the use of capacity achieving codes [3], the receiver can decode a

replica whenever its SINR, denoted by Γ , meets or exceeds a predefined threshold, i.e., $\Gamma \geq \gamma$. Note that interference-free replicas can always be decoded. Additionally, a slot with replicas all transmitted at different power levels can be resolved through intra-SIC iterations (i.e., following the traditional NOMA principles). Once a replica is decoded, the receiver can determine the position of its copies and remove them from the frame using inter-SIC [3]. The decoder may iterate multiple times over each slot and the entire frame until all replicas are decoded or no more replicas with $\Gamma > \gamma$ are present.

III. PACKET LOSS RATE APPROXIMATION

In this section, we consider results from the balls into bin (BiB) problem to derive a tight one-shot formula approximation of the packet loss rate, denoted by PLR.

A. Balls into bin problem

The general BiB problem, see e.g. [19], consists in independently throwing $\bar{m}$ balls into $\bar{b}$ bins. This setup can be mapped to the NOMA-IRSA scenario, where each ball represents a user transmitting its replicas, and $\bar{b}$ bins represent all possible combination of slots in which a user can place its replicas.

Following this parallel, multiple balls landing in the same bin correspond to multiple users transmitting their replicas in the same slots. The BiB problem allows us to evaluate distribution of the number of bins containing t balls. Let Y_t be the random variable (rv) denoting the number of bins containing exactly t balls. Then, from [19], we have that

$$\Pr\{Y_t = y_t\} = \frac{\bar{m}!}{\bar{b}^{\bar{b}}} \sum_{k=0}^{\bar{b}-y_t} (-1)^k \binom{y_t + k}{y_t} \frac{(\bar{m} - k)^{\bar{m}-y_t}}{(t!)^k (\bar{m} - kt)!}. \quad (3)$$

As shown in [19], for $\bar{m} \rightarrow \infty$ the rv Y_t can be approximated to a Poisson random variable with parameter β_t , i.e.

$$Y_t \sim \mathcal{P}(\beta_t) \quad \text{and} \quad \beta_t = \frac{\bar{b}}{t!} \left(\frac{\bar{m}}{\bar{b}} \right)^t.$$

B. Packet loss rate as BiB

The packet loss rate PLR is defined as the probability that a user is not successfully decoded at the end of the SIC process. In IRSA, the PLR at low channel load can be approximated by addressing the so call *stopping sets* [14]. A stopping set is a configuration where the decoder gets stuck because multiple users transmit their replicas in the same slots, preventing any

$$\text{PLR} \approx \frac{1}{L^2} \frac{2(\lambda_2)^2 m}{n(n-1)} + \frac{1}{L^3} \frac{2(n-2)(\lambda_2 m)^2}{n^2(n-1)^2} + \frac{1}{L^3} \frac{6(\lambda_3)^2 m}{n(n-1)(n-2)}. \quad (5)$$

TABLE I

Parameters of considered stopping sets for m users and n slots

i	μ_i	ν_i	$\bar{m}$	$\bar{b} = b(\mu_i, \nu_i)$
1	2	2	$\lambda_2 m$	$\binom{n}{2}$
2	3	3	$\lambda_2 m$	$\binom{n}{2} / \sqrt{2(n-2)}$
3	3	2	$\lambda_3 m$	$\binom{n}{3}$

of them from being decoded. A stopping set is characterized by ν , the number of users, and μ , the number of slots involved, respectively. When power diversity is considered as in the NOMA-IRSA scheme, the receiver applying SIC fails to decode the users if every slot belonging to a stopping set contains packets transmitted at the same power.

We denote by $\sigma(\mu)$ the event in which each of the μ slots of an stopping set contain colliding replicas transmitted at the same power. Considering in total L different level of power, we have

$$\Pr\{\sigma(\mu)\} = \frac{1}{L^\mu}.$$

We evaluate an error floor expression by accounting for the three most probable stopping sets that can occur for NOMA-IRSA, denoted with $\mathcal{S} = \{\mathcal{S}_1, \mathcal{S}_2, \mathcal{S}_3\}$. An example of each stopping set is illustrated in Fig 1. The stopping set $\mathcal{S}_1$ consists of two users transmitting two replicas each in the same time slots at the same power. The stopping set $\mathcal{S}_2$ consists of three slots and three users, each transmitting two replicas different time slots, resulting in collisions where each user interferes with the other two. Also in this case, each slot has colliding replicas at the same power. The stopping set $\mathcal{S}_3$ consists of two users transmitting three replicas each in the same three slots at the same power. Note that $\mathcal{S}_1$ and $\mathcal{S}_2$ can occur only if the IRSA distribution (1) includes a non null probability for a user transmitting two replicas, i.e., if $\lambda_2 > 0$. Similarly, $\mathcal{S}_3$ can only occur if $\lambda_3 > 0$. Note that these are the most representative stopping sets for the NOMA-IRSA scheme under evaluation. As demonstrated in the results, they are sufficient to provide an accurate evaluation of performance.

The probability mass function of the stopping set $\mathcal{S}_i$ can be determined using (3) by mapping it to the BiB problem. Given m users and n slots, the probability that the stopping set $\mathcal{S}_i$ occurs u times within a frame is expressed as $\Pr\{Y_{\nu_i} = u\}$. The value of $\nu_i, \mu_i, \bar{m}$ and $\bar{b} = b(\mu_i, \nu_i)$ are provided in Table I. In the appendix section, we discuss and explain the derivation $b(\mu_2, \nu_2) = b(3, 3)$ which does not have a straightforward correspondence to the classic balls-in-bins problem.

The packet loss rate is approximated by evaluating, for each stopping set, the ratio of users colliding (positive cases) to the

total number of transmissions (total cases) as follows

$$\begin{aligned} \text{PLR} &\approx \sum_{\mathcal{S}_i \in \mathcal{S}} \Pr\{\sigma(\mu_i)\} \frac{\sum_{u=1}^{\infty} \nu_i u \Pr\{Y_{\nu_i} = u\}}{m} \\ &= \sum_{\mathcal{S}_i \in \mathcal{S}} \frac{1}{L^{\mu_i}} \frac{\nu_i}{m} \sum_{u=1}^{\infty} u \Pr\{Y_{\mu_i} = u\}. \end{aligned}$$

Recalling that Y_t can be considered Poisson distributed, then

$$\text{PLR} \approx \sum_{\mathcal{S}_i \in \mathcal{S}} \frac{1}{L^{\mu_i}} \frac{\nu_i}{m} \sum_{u=1}^{\infty} u \frac{(\beta_{\nu_i})^u}{u!} e^{-\beta_{\nu_i}}.$$

Observing that

$$\sum_{u=1}^{\infty} u \frac{(\beta_{\nu_i})^u}{u!} e^{-\beta_{\nu_i}} = \beta_{\nu_i},$$

we have

$$\begin{aligned} \text{PLR} &\approx \sum_{\mathcal{S}_i \in \mathcal{S}} \frac{1}{L^{\mu_i}} \frac{\nu_i}{m} \frac{\bar{b}}{\nu_i!} \left(\frac{\bar{m}}{\bar{b}}\right)^{\nu_i} \\ &\approx \sum_{\mathcal{S}_i \in \mathcal{S}} \frac{1}{L^{\mu_i}} \frac{1}{(\nu_i - 1)!} \left(\frac{\bar{m}}{\bar{b}}\right)^{\nu_i - 1}. \end{aligned} \quad (4)$$

Finally, by substituting the values from Table I into each stopping set in (4) and performing straightforward manipulations, we derive the approximated equation for the packet loss rate given in (5).

Equation (5) addresses the challenge of dealing with more complex formulations often required for evaluating the packet loss rate PLR in the error floor region, as seen in works such as [14]–[17]. By contrast, the proposed expression provides a simple and efficient method for PLR computation.

While one might initially consider the proposed expression a bound for the PLR, given that it accounts for a finite number of stuck occasions for the receiver, this claim cannot be made rigorously. This limitation arises because (5) is derived by approximating certain terms, preventing it from being formally classified as a bound.

IV. NUMERICAL RESULTS

This section examines the validity of the proposed PLR approximation. We consider different setups and compare the simulation results with the analytical form presented in (5).

In our first scenario we consider a frame length of $n = 200$ slots, target SINR $\gamma = 3\text{dB}$, and $L = 3$ different levels of power. According (2), we have $p_1 = 17.9007, p_2 = 5.9763$, and $p_3 = 1.9953$. For $n = 200, \mu_2 = 3$ and $\nu_2 = 3$, the number of bins is given by $b(3, 3) = 1000$. The packet loss rate PLR for NOMA-IRSA, plotted as a function of the channel load, is shown in Fig. 2. The following degree distributions,

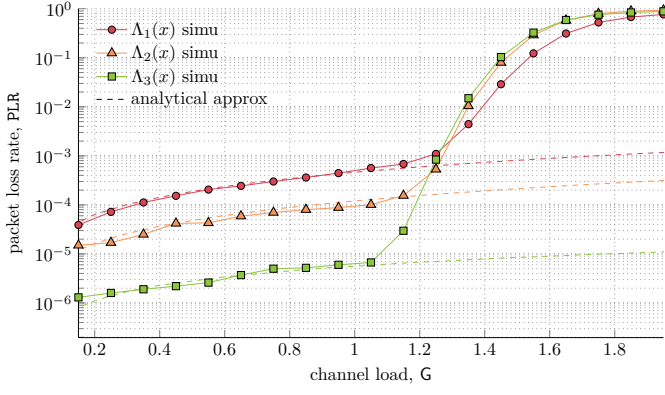


Fig. 2. Packet loss rate as a function of channel load for NOMA-IRSA for $n = 200$ slots, $L = 3$ power levels, and $\Lambda_1(x)$, $\Lambda_2(x)$, and $\Lambda_3(x)$. Curves with markers represent simulation results, while dashed lines correspond to the analytical approximation given in (5).

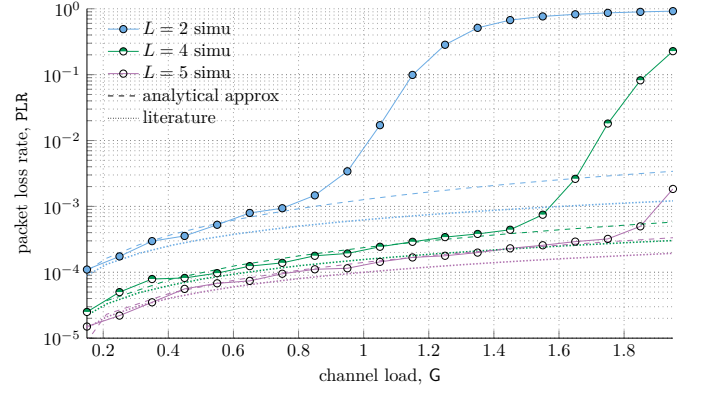


Fig. 3. Packet loss rate as a function of channel load for NOMA-IRSA with $n = 200$ slots, $\Lambda_1(x)$, and different powers levels. Curves with represent simulation results, dashed lines indicate the approximation given by (5), and dotted lines shows results from literature in [18].

commonly employed in literature and known to offer good performance [3], are considered

$$\begin{aligned}\Lambda_1(x) &= 0.50x^2 + 0.50x^3, \\ \Lambda_2(x) &= 0.25x^2 + 0.60x^3 + 0.15x^8, \text{ and} \\ \Lambda_3(x) &= x^3.\end{aligned}$$

The marker curves correspond to Monte-Carlo simulation while the dashed lines represents the packet loss rate approximation given in (5). Notably, the derived PLR accurately predicts the simulated PLR across all considered IRSA degree distributions in the error floor region. Note that the error floor region for NOMA-based IRSA schemes includes not only low channel loads but also moderate channel loads. Focusing on a PLR of practical relevance, e.g. 10^{-3} , we observe that channel load up to 1.20 [packets/slot] can be supported.

These initial results demonstrate that the proposed expression is effective for evaluating a NOMA-based IRSA. The provided expression offers a fast and simply method for assessing the performance of the system, remaining accurate even at very low values of packet loss rate.

Note that the derived approximation is valid in the error floor region but, as expected, diverges under high channel loads, i.e., in the waterfall region. This divergence arises because the behavior of the SIC algorithm at high loads is influenced by factors beyond the stopping sets; specifically, the SIC process can stall due to excessive traffic. An analytical evaluation in the waterfall region for NOMA-IRSA can be implemented assuming infinitely long frames, a scenario that has been extensively documented in the literature, for example, in [9]–[13].

In our second scenario, represented in Fig. 3, we plot the packet loss rate as a function of the channel load for degree distribution $\Lambda_1(x) = 0.50x^2 + 0.50x^3$. This is done for different levels of power L considered, with frame length $n = 200$ slots and target SINR of $\gamma = 3\text{dB}$. The aim of these results is to compare our evaluation with the findings proposed in [18]. As expected, the packet loss rate improves as the number of power levels increases. This is because the receiver can resolve more collisions, thanks to a higher probability of encountering

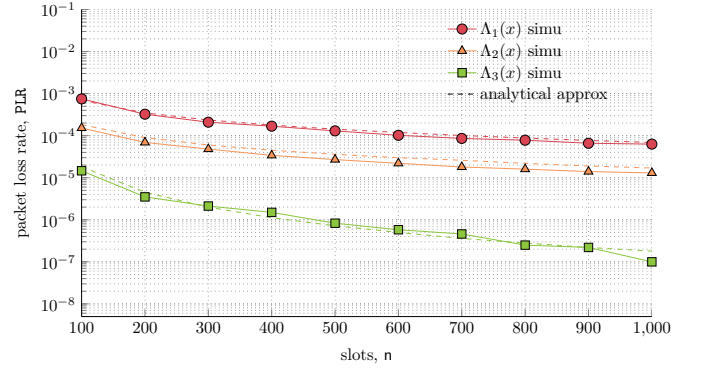


Fig. 4. Packet loss rate against frame length for NOMA-IRSA at $G = 0.80$ [packets/slots], $L = 3$ power levels, for $\Lambda_1(x)$, $\Lambda_2(x)$, and $\Lambda_3(x)$. Curves with markers represent simulation results, while dashed lines correspond to the analytical approximation given in (5).

colliding replicas with different power levels. Note that there is a trade-off between increasing the number of power levels, which leads to higher energy consumption, and the system's performance. This balance requires a dedicated investigation. The dashed lines represent the proposed approximation, which remains accurate in the error floor region for any number of power levels considered. Dotted lines are results where only considers the stopping set $\mathcal{S}_1$ as proposed in [18]. It can be observed that the approximation in [18] holds well only for low channel loads and becomes less accurate as the channel load increases to moderate levels. This is because, for many degree distributions, as the number of transmitting users increases, the probability of $\mathcal{S}_2$ and $\mathcal{S}_3$ occurring becomes non-negligible. This plot demonstrates that, for any value of L , the proposed analytical evaluation consistently outperforms the performance of the existing approximation.

Finally, we further evaluate the proposed approximation for different MAC frame lengths. In our last scenario we consider $\Lambda_1(x)$, $\Lambda_2(x)$, and $\Lambda_3(x)$ for $L = 3$ power levels, target SINR $\gamma = 3$, and fixed channel load $G = 0.80$ packets/slot. As shown in Fig. 4, the approximation remains accurate for every value of n slots considered in the frame and across all IRSA distributions. Increasing the number of available slots

decreases the packet loss rate (PLR), as the probability of users experiencing lock situations becomes lower.

V. CONCLUSIONS

In this work, the packet loss rate for NOMA-IRSA scheme is evaluated, targeting IoT and mMTC applications with finite frame length. A tight approximation of the PLR performance is presented and validated through Monte-Carlo simulations. The results demonstrate a perfect match for different degree distributions, across different power levels and frame lengths. The proposed analysis provide valuable insights for IoT network design by offering a simple and fast computational evaluation of the system's performance.

Additionally, while previous studies focus on the waterfall region of the NOMA-IRSA scheme, this work complements them by providing the evaluation of the error floor.

APPENDIX

The evaluation of number of bins $\bar{b} = b(\mu_i, \nu_i)$ for stopping sets $\mathcal{S}_1$ and $\mathcal{S}_2$ is straightforward, as these cases are align with the BiB problem. Recalling that, balls represent users, while bins represent the possible combinations of slots where users can place their replicas. When two balls land in the same bin, it corresponds to users transmitting their replicas in the same slots. In contrast, the interpretation of $\bar{b} = b(\mu_i, \nu_i)$ for the stopping set $\mathcal{S}_3$ is not applicable because the number of slots involved in the stopping set ($\mu_i = 3$) differs from the number of slots where a user place their replicas (two).

To find a analog formulation to BiB for this case we empirically derive a solution by first determining the packet loss rate given by users involved only in the scenario given by stopping set $\mathcal{S}_3$ through simulations, i.e. $\text{PLR}(\mathcal{S}_3, n)$. Simulations are performed for different values of slots n for a fixed channel load, e.g. $G = 0.4$ [packets/slot], and one power level $L = 1$.

Two key observations are fundamental to have an evaluation of $\bar{b}$. First, from equation (4), we can express $\bar{b}^2$ as

$$\bar{b}^2 = \frac{\bar{m}^2}{2\text{PLR}(\mathcal{S}_3, n)}.$$

Second, simulation results revealed that the trend of $\bar{b}^2$ as a function of n closely aligns with the behavior of $\binom{n}{2}$. Given this trend, we hypothesize that

$$\bar{b}^2 = \binom{n}{2} \frac{1}{g(n)^2},$$

where $g(x)$ is a linear function of the form $g(x) = a_0 + a_1x$. To proceed, we use a fitting function (e.g. in Matlab) to determine the coefficients a_0 and a_1 , allowing us to approximate the relationship between $\bar{b}$ and n . As a result, we obtain the values $a_0 = -4$ and $a_1 = 2$, allowing us to write

$$b(\mu_2, \nu_2) = \bar{b} = \binom{n}{2} \frac{1}{\sqrt{2(n-2)}}.$$

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