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CHARACTERIZING ENVIRONMENTAL THERMAL FLUCTUATIONS FOR USE IN TRUE RANDOM NUMBER GENERATORS

Random number generation is significant for secure communication, data security and cryptography. However, while Quantum Random Number Generators (QRNGs) rely on quantum uncertainty, environmental data can also serve as practical sources of randomness for true random number generation. Environmental data such as temperature, humidity, and wind speed exhibit continuous variability over time; these changes arise from complex weather behavior. In this paper, temperature data collected from two meteorological stations in Pakistan, Karachi and Hyderabad, are used to generate random bits. Everyday temperature values are transformed into binary sequences using a mean-based thresholding technique, followed by post-processing with the Von Neumann extractor to decrease bias and correlation. The quality of the generated random bits is evaluated using Shannon entropy, lossless compression testing with the Gzip, Bzip2, and LZMA algorithms, the NIST SP 800-22 statistical test suite and the auto-correlation analysis. The results determine that correctly processed temperature-based entropy can produce statistically usable random sequences suitable for randomness testing and security-related research.

Keywords: Random Bit Generation, temperature data, entropy extraction, Shanon entropy, auto-correlation, Von Neumann filtering, NIST SP 800-22.

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Шынайы кездейсоқ сан генераторларында пайдалану үшін қоршаған ортадағы термалық флюктуацияларды сипаттау

Кездейсоқ сандарды генерациялау қауіпсіз байланыс, деректерді қорғау және криптография үшін өте маңызды. Дегенмен, кванттық кездейсоқ сандар генераторлары (QRNG) кванттық белгісіздікке сүйенсе де, қоршаған орта деректері шынымен кездейсоқ сандарды генерациялау үшін кездейсоқтықтың практикалық көздері ретінде де қызмет ете алады. Температура, ылғалдылық және жел жылдамдығы сияқты қоршаған орта деректері уақыт өте келе үздіксіз өзгергіштікті көрсетеді; бұл ауытқулар ауа райының күрделі мінез-құлқынан туындайды. Бұл мақалада кездейсоқ биттерді генерациялау үшін Пәкістандағы, Карачидегі және Хайдарабадтағы екі метеорологиялық станцияда жиналған температура деректері пайдаланылады. Тәуліктік температура мәндері орташа мәнге негізделген шекті есептеу әдісін қолдана отырып, екілік тізбектерге түрлендіріледі, содан кейін ауытқу мен корреляцияны азайту үшін фон Нейман экстракторымен кейінгі өңдеу жүргізіледі. Генерацияланған кездейсоқ биттердің сапасы Шеннон энтропиясы, Gzip, Bzip2 және LZMA алгоритмдерін қолдана отырып, шығынсыз сығымдау сынағы, NIST SP 800-22 статистикалық сынақ жиынтығы және автокорреляциялық талдау арқылы бағаланады. Нәтижелер дұрыс өңделген температураға негізделген энтропия кездейсоқтықты тексеру және қауіпсіздік зерттеулеріне қолайлы статистикалық тұрғыдан пайдалы кездейсоқ тізбектерді жасай алатынын көрсетеді.

Түйін сөздер: кездейсоқ бит генерациясы, температура деректері, энтропияны алу, Шеннон энтропиясы, автокорреляция, фон Нейман сүзгісі, NIST SP 800-22.

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Характеризация температурных флюктуаций окружающей среды для использования в генераторах истинно случайных чисел

Генерация случайных чисел имеет важное значение для безопасной связи, защиты данных и криптографии. Однако, хотя квантовые генераторы случайных чисел (QRNG) основаны на квантовой неопределенности, данные об окружающей среде также могут служить практическими источниками случайности для генерации истинно случайных чисел. Данные об окружающей среде, такие как температура, влажность и скорость ветра, демонстрируют непрерывную изменчивость во времени; эти изменения возникают из-за сложного поведения погоды. В данной работе для генерации случайных битов используются данные о температуре, собранные на двух метеорологических станциях в Пакистане, Карачи и Хайдарабаде. Ежедневные значения температуры преобразуются в двоичные последовательности с использованием метода пороговой обработки на основе среднего значения, после чего проводится постобработка с помощью экстрактора фон Неймана для уменьшения смещения и корреляции. Качество сгенерированных случайных битов оценивается с помощью энтропии Шеннона, тестирования сжатия без потерь с использованием алгоритмов Gzip, Bzip2 и LZMA, статистического набора тестов NIST SP 800-22 и автокорреляционного анализа. Результаты показывают, что правильно обработанная энтропия, основанная на температуре, может создавать статистически пригодные случайные последовательности, подходящие для проверки случайности и исследований в области безопасности.

Ключевые слова: генерация случайных битов, данные о температуре, извлечение энтропии, энтропия Шэнона, автокорреляция, фильтрация фон Неймана, NIST SP 800-22.

Introduction

Random Number Generators (RNGs) are necessary for applications such as statistical analysis, cryptography, simulation, and secure communications. Centered on their randomness sources, RNGs are commonly divided into two categories: Pseudo-Random Number Generators (PRNGs) and True Random Number Generators (TRNGs) [1-3]. Generators that produce random numbers sequentially using deterministic algorithms are called pseudo-random number generators. [4-8]. Although these numbers appear random, they can be reproduced if the algorithm or the starting value is known, which may pose a security risk in security-critical applications [9,10]. In contrast. A TRNG is a function or a device that is based on a rather unpredictable physical phenomenon known as the entropy source. These entropy sources can originate from natural phenomena. Sources such as thermal noise, clock jitter, atmospheric noise, bioelectrical signals, environmental variations and quantum phenomena contain natural entropy that cannot be reproduced deterministically [11-15]. Among many true random number generators, QRNG systems are a special class of TRNGs in which randomness is derived from quantum-mechanical processes and offer solid analytical guarantees of indeterminacy [16-19], but still challenges such as maintaining quantum coherence, achieving precise measurement, and generating stable bits limit their practical deployment. As a result, alternative approaches, such as environmental entropy sources, have emerged as simpler, low cost and more accessible options for random number generation. These sources are neither algorithmic, like PRNGs, nor purely quantum, like Quantum Random Number Generation, but rather exploit complex natural processes. Famous examples include uses of Atmospheric turbulence, atmospheric radio noise, and natural wind flow [20-23]. By applying mathematical normalization, disordered sampling, and post-processing techniques, these real-world signals can be converted into statistically usable true random numbers suitable for secure applications [24-28]. In this research, Real-world temperature deviations are used to generate random bits, the collected data are transformed in to binary sequence followed by post processing to remove bias and correlations, which are then tested with standard randomness tests. Using temperature data from two geographically distinct meteorological stations, this study demonstrates a simple, reproducible, and low-cost approach to generating and validating random bits from real-world environmental data.

Data source

In this research, daily temperature values for Karachi and Hyderabad were extracted from earlier publications that analyzed meteorological records for different cities in Pakistan [29,30]. The daily temperature dataset is used as an entropy source for generating random bits.

Research methodology

Figure 1 illustrates the suggested methodology for temperature-based true random number generation, including data acquisition from published datasets, mean-based binary conversion, Von Neumann post-processing, and randomness evaluation using Shannon entropy and NIST SP 800-22 tests.

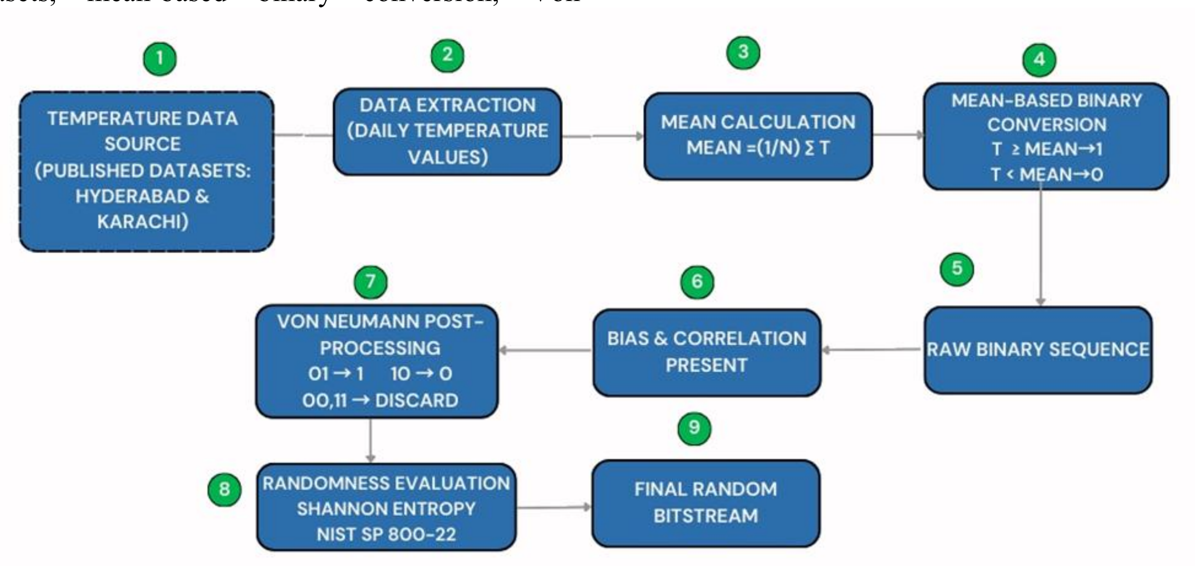

Figure 1 - Flow chart of methodology

Validation of Quantum Random Numbers

Shannon entropy testing

To initially check the randomness of the generated bit stream, a self-test based on Shannon entropy was performed. Entropy measurement provides a quantitative estimate of unpredictability in binary data and is defined as:

$$H(X) = -\sum_{i=1}^{n} p_i log_2 p_i, \qquad (1)$$

where p_i represents the probability of each possible outcome within a selected data window in Eq. (1), entropy values near 1 bit indicate highly unpredictable, statistically balanced randomness. Using reference [28], entropy was computed with a sliding-window approach over the generated sequence, as shown in Figure 2.

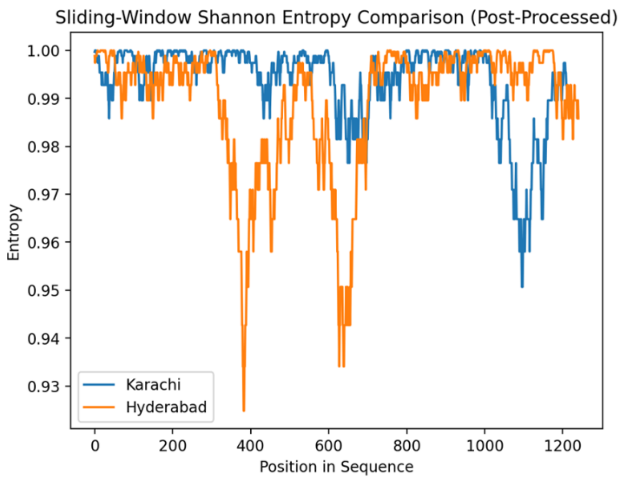

Figure 2 – Shannon Entropy Variation Across Post-Processed Binary Sequences from Karachi and Hyderabad

It is also observed from Figure 2, that Shannon entropy remains nearly 1 for both datasets, which indicates that the temperature-based entropy source, after post-processing, generates high-quality true random bits suitable for further statistical validation and practical TRNG applications

Compression test method

To calculate the randomness of the generated binary sequences, a compression test was performed. The mainidea of this test is that truly random data should not contain patterns; it should be difficult to compress. If a compression algorithm cannot significantly reduce the file size, the data can be considered highly random. In this research, binary sequences were first converted into byte format and stored as files. Three commonly used lossless compression algorithms were then applied to the files:

- Gzip
- Bzip2
- LZMA

The compression process was implemented using Python. For each dataset, the original and compressed file sizes were recorded. The compression ratio was then calculated using:

$$\text{Compression Ratio} = \text{Compression Size} / \text{Original Size} \quad (2)$$

The original and compressed file sizes were recorded and reported in Tables 1 and Table 2.

Table 1: Compression Test Results for the weather station Hyderabad, Original file size is 499 bytes

Algorithm	Compressed Size	Compression Ratio
Gzip	522	1.04609
Bzip2	659	1.32064
LZMA	560	1.12224

Table 2: Compression Test Results for the weather station Karachi, Original file size of 498 bytes

Algorithm	Compressed Size	Compression Ratio
Gzip	521	1.04618
Bzip2	673	1.35140
LZMA	560	1.12449

The compression ratio for both stations is close to 1, indicating that the binary sequences lack discernible patterns and behave similarly to random data. Therefore, the generated sequences demonstrate good randomness according to the compression-based randomness test.

NIST Test Suit

To further validate that the high entropy observed translates into statistically robust randomness, we next apply the NIST statistical suite. Figures 3 and Figure 4 show the randomness quality of the temperature data before and after applying the Von Neumann debiasing and the entropy extractor (post-processing).

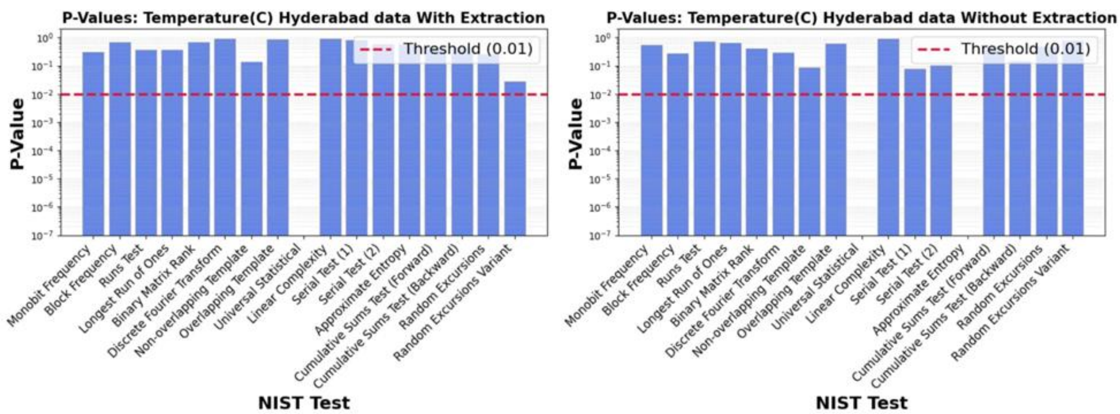

Figure 3 – P-Value Comparison of NIST Randomness Tests for Hyderabad Temperature Data

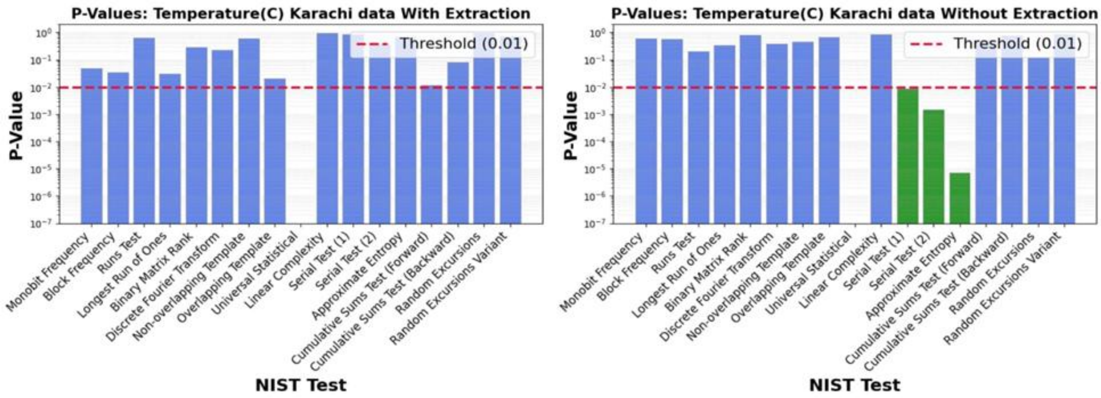

Figure 4 – P-Value Comparison of NIST Randomness Tests for Karachi Temperature Data

The raw data fails some NIST randomness tests because real-world physical measurements often exhibit small biases, and the data size for a given research is very limited. After post-processing, the sequence becomes more unpredictable and more balanced, thereby increasing the randomness of the bit sequence. Because of this enhancement, the post-processed data passes the most NIST tests in both Hyderabad and Karachi.

Autocorrelation analysis

The statistical independence of the entropy sources was evaluated by calculating the absolute autocorrelation coefficient, $|R(k)|$, for the thermal fluctuation data harvested from Karachi and Hyderabad. As illustrated in Figure 5, both datasets exhibit a rapid decorrelation, with $|R(k)|$ dropping by approximately two orders of magnitude immediately following the initial lag ($k = 1$). Throughout the observation window of 100 lags, the autocorrelation values remain predominantly suppressed within the 10^{-2} to 10^{-4} range, indicating a lack of significant periodic structures or long-term memory effects in the urban thermal noise.

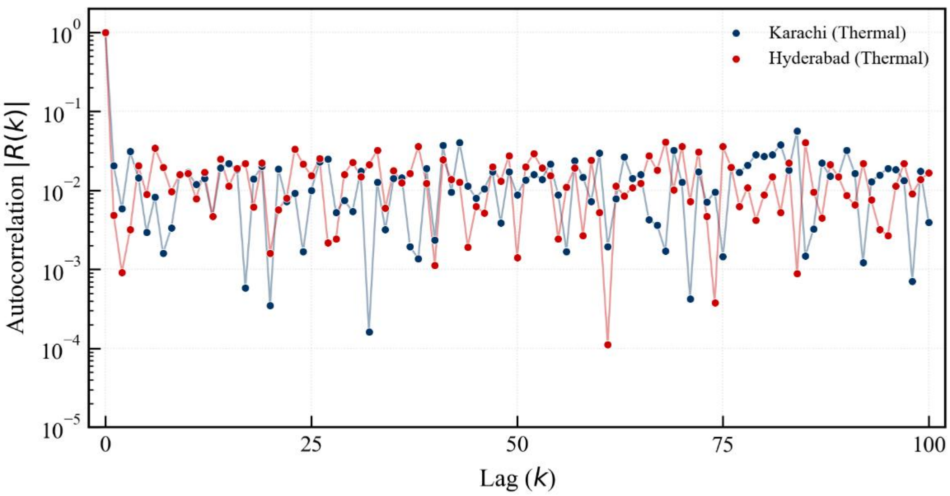

Figure 5 – Auto-correlation traces of Karachi and Hyderabad.

This near-zero residual correlation is highly advantageous for TRNGs, as it confirms a high degree of min-entropy per sample. Furthermore, the stochastic parity between the two geographically distinct cities suggests that environmental thermal noise provides a robust and spatially invariant entropy floor, requiring minimal cryptographic post-processing to achieve a statistically uniform and unpredictable bitstream.

Discussion

Although the suggested method relies on environmental temperature data rather than on a quantum source, it adheres to the fundamental principles of true random number generation. In contrast to software-based generators that depend on deterministic initial conditions, the temperature variations used in this work represent real-world physical uncertainty. To further strengthen the entropy source for practical purposes, use large volumes of data collected over multiple days and from several geographically separated weather stations. As shown by the entropy analysis and NIST results, post-processing methods are applied to remove bias and correlation without introducing artificial randomness, thereby preserving the true nature of the underlying entropy. Even if temperature-based TRNGs do not replace quantum-based QRNGs in terms of security importance, they offer a practical, low-cost form of true random number generation based on physical phenomena. This environmentally sourced TRNG could be particularly valuable for embedded Internet of Things devices operating in resource-constrained settings, where integrating quantum hardware is impractical.

Conclusion

The Aim of this research was to present a method for generating and certifying true random bits using real-world temperature data from two meteorological stations. A mean-based thresholding scheme was used to generate raw bits, followed by Von Neumann and entropy-extractor post-processing to improve randomness quality. Statistical evaluation using the sliding-window Shannon entropy technique, Compression Test Method and the NIST SP 800-22 test suite and Auto-correlation analysis confirms that the generated bit sequences exhibit strong randomness. Although not a replacement for high-speed QRNGs, the projected approach explains that environmental data can serve as a simple, low-cost source of true randomness for research and security applications.

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Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Roohi Zafar: Conceptualization, Methodology, Investigation, Data Curation, Writing – Original Draft; **Muhammad Kamran:** Conceptualization, Formal Analysis, Visualization, Writing – Review & Editing; **Tahir Malik:** Methodology, Data Curation, Writing – Review & Editing; **Kousar Shaheen:** Conceptualization, Methodology, Data Curation, Investigation.

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