Analysis of Data from a 5G-Based Photovoltaic Plant Monitoring System

Sofia D. Carvalho
Telematics Department
Federal Institute of Technology of Ceará (IFCE)
Fortaleza, Ceará, Brazil
Email: carvalhosofiadiniz@outlook.com

Paulo C. M. Carvalho
Department of Electrical Engineering
Federal University of Ceará (UFC)
Fortaleza, Brazil
Email: carvalho@dee.ufc.br

Luis M. Fernández-Ramírez
Research Group in Sustainable and Renewable Electrical Technologies (SURET), Department of Electrical Engineering, University of Cadiz (UCA), Algeciras, Spain.
Email: luis.fernandez@uca.es

Paulo R. X. da Silva
Telematics Department
Federal Institute of Technology of Ceará (IFCE)
Fortaleza, Ceará, Brazil
Email: renato.xavier@ifce.edu.br

***Abstract*—This paper presents the development and testing of a data acquisition system using the AVR - Internet of Things (IoT) Cellular Mini microcontroller to monitor the temperature of photovoltaic (PV) modules on the roof of the Alternative Energy Laboratory of the Federal University of Ceara (LEA - UFC) in Fortaleza, Brazil. Temperature data are captured by PT100 and DHT11 sensors. Data acquisition is initiated through the connection of each sensor to a dedicated port of the microcontroller, with data transmitted to the cloud using the ThingSpeak platform. The initial phase of the system was tested for one month, providing insights into its operation and the integration of real-time monitoring for renewable energy systems.**

Keywords*—*IoT; data acquisition; photovoltaics; 5G.

I. INTRODUCTION

As PV systems increase their relevance, real-time data monitoring becomes crucial. For instance, accurate PV modules temperature data play a significant role in determining the efficiency and performance of PV systems [1]. In such context, our paper analyzes the implementation of a PV module temperature data acquisition system using the AVR - IoT Cellular Mini, shown in Figure 1, a microcontroller-based solution that provides real-time monitoring via wireless transmission. The PV modules are installed in a grid connected plant at the LEA - UFC in Fortaleza, Brazil (3º 44’ 15” S; 38º 34’ 22” W and 21 m). Hence, our proposed system aims to explore the use of cellular IoT technologies to enhance data transmission reliability and overall system scalability.

The mobile network architecture for IoT has been profoundly transformed with the advent of 5G, a technology that offers advanced connectivity, high reliability, and low latency—essential characteristics for the massive integration of IoT devices [2]. In the context of IoT, 5G enables the connection of a vast number of devices, ranging from environmental sensors to remote monitoring systems, with unprecedented efficiency and coverage [3]. The combination of 5G with long-range, low-power cellular communication technologies, such as Long Term Evolution (LTE) for machine communication (LTE-M) and Narrowband IoT (NB-IoT), promotes efficient coexistence of devices in urban and rural areas [4]. These licensed technologies bring benefits in terms of service quality and greater coverage, essential for large-scale and critical IoT applications. LTE-M, part of 3GPP Release 13, operates on licensed frequency bands, integrating seamlessly into 5G network infrastructure [3]. With its ability to provide higher bandwidth and lower latency, LTE-M is particularly useful in scenarios where data transmission demands superior quality of service, such as in PV plant management [4]. The integration of LTE-M into 5G networks becomes essential to ensure efficient coverage in locations where 5G alone cannot reach, such as rural areas. Additionally, LTE-M can coexist with NB-IoT within the 5G architecture, enabling efficiency and the expansion of IoT device use, providing solutions suitable for both large cities and regions with lower population density [3].

The AVR-IoT Cellular Mini microcontroller is a compact and versatile solution for integrating IoT devices into LTE-M networks. This microcontroller enables secure hardware authentication in the cloud using the ATECC608B device, which provides Elliptic Curve Cryptography (ECC), ensuring the integrity and confidentiality of transmitted data [5]. With full support for the Arduino platform, the AVR128DB48 facilitates the development and implementation of customized IoT solutions. The GM02S communication

Figure 1. Microchip AVR-IoT Cellular Mini.

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module, which operates with ultra-low power consumption, is responsible for connecting to the LTE-M network, being essential for efficient and secure data transmission. Thus, the integration of the AVR-IoT Cellular Mini with the LTE-M network allows for the creation of robust monitoring systems, such as remote PV plant control, ensuring connectivity and security in the transmission of collected data. The paper is organized as follows: Section I is the introduction, Section II brings out the state of the art, Section III shows the system design and setup, Section IV provides the results and Section V brings the conclusions.

II. STATE OF THE ART

The potential of IoT technology and 5G is analyzed in [6], highlighting their main features and the synergy between them. The central proposal is a monitoring system for decentralized PV plants, utilizing an AVR-IoT microcontroller, which stands out for its efficient 5G connectivity and low power consumption. Green IoT emerges as a sustainable approach for efficient communication, data management, and device utilization. Integrating technologies, such as Wireless Sensor Networks (WSN), Cloud Computing (CC), Machine-to-Machine (M2M) Communication, Data Centres (DC) and advanced metering infrastructure, Green IoT reduces energy consumption and promotes environmentally friendly practices across design, manufacturing and usage [7]. This review explores advancements of Green IoT for smart grids, paving the way towards sustainability, covering energy-efficient communication protocols, intelligent energy management, renewable energy integration, demand response, predictive analytics and real-time monitoring. With the advent of cloud computing, the challenges and opportunities resulting from grid expansion can be addressed more efficiently.

The role of energy management systems in both research and industrial practices is discussed in [8], recognizing the importance of both as stakeholders in this domain. The investigation comments on various IoT-related issues concerning PV production, offering insights for future research. 5G use in IoT monitoring systems, such as those utilizing the AVR IoT 5G microchip board, aligns closely with several key aspects of modern 5G applications. First, 5G's role as a General-Purpose Technology (GPT) is highly relevant, enabling the widespread integration of IoT devices into various applications, including monitoring systems.

A critical factor in the efficient use of 5G in IoT systems is network slicing [6]. This concept allows for the logical separation of different bandwidth capacities within the 5G network, ensuring that the Quality of Service (QoS) is maintained across different applications. Network slicing ensures that the devices receive the necessary bandwidth and performance without interference from other network uses. Moreover, the complementarity between physical and virtual components of IoT systems is crucial. The IoT monitoring system integrates the AVR board hardware with the virtual infrastructure provided by 5G networks, such as cloud storage and data processing. This ensures reliable operation between the physical sensors and the software managing the data. Cybersecurity is another vital aspect, ensuring that communication between IoT devices and 5G remains secure. The focus on end-to-end slice security within 5G networks is highly relevant for the project, as it provides protection against cyber threats, ensuring data integrity and privacy in the monitoring system.

Smart cities aim to optimize operations such as waste and traffic management, water supply, crime tracking, and pollution monitoring by leveraging interconnected IoT devices [10]. The challenge lies in the real-time exchange of vast amounts of data required for smart city applications. Device-to-Device (D2D) communications, which offer higher bandwidth and lower latency, are often used to meet this need, as they do not require infrastructure, making them cost- and time-effective. However, the lack of third-party verification in D2D communications introduces security risks. To address this, the paper proposes a secure and lightweight mutual authentication and key agreement protocol for WiFi Direct, utilizing a commit/open pair and the Diffie-Hellman key exchange algorithm. Simulations show that the protocol effectively authenticates D2D devices in the WiFi Direct environment, resisting common attacks such as Denial of Service (DoS) and Man-in-the-Middle (MITM).

The impact of 5G technology in improving connections and increasing efficiency across various fields is discussed in [11]. Operating at higher frequencies, 5G technology offers greater data capacity, lower latency, and higher reliability, enabling the emergence of new services like remote medical procedures and M2M communication. Additionally, the article explores the role of nanomaterials, such as graphene and carbon nanotubes, in the development of nanoantennas, which are essential for enhancing 5G communications.

The implementation of communication networks plays a crucial role in expanding global knowledge [12]. Crowds are utilized to support a large number of internet networks, such as Wi-Fi, or accommodate heterogeneous devices like tablets and smartphones, under various conditions, including downloading or using apps like Spotify. 5G technology, with its ability to connect more users in a specific geographical area, can reduce miscellaneous costs and provide faster solutions. Existing technologies are limited in their capabilities, and society requires greater accuracy and safety in the digital age, which necessitates an upgrade to 5G technology. The Massive IoT (MIoT) concept cannot be achieved with current technologies, as they lack the capacity to handle the massive amounts of information carried by devices and fail to provide the precision required for mission-critical services like industrial automation. The faster and more robust capabilities of data transfer, brought about by upgrades to mobile electronic systems, are accompanied by a wide range of complementary changes. These changes are supported by harmonized spectrum bands, updated international technical standards, new requirements for network operation, innovative cellular devices, and expanded services with a broader array of potential commercial applications.

A systematic outline of the development of 5G-related research until 2020 is presented in [13], based on over

10,000 science and technology publications. The study addresses the emergence, growth, and impact of this area, providing insights into disciplinary distribution, international performance, and historical trends.

5G technology evolution is discussed in [14], highlighting its rapid development, the increase in the number of operators and devices, and the ongoing discussions about innovation, competition, and policy implications. The analysis reveals that 5G technologies complexity has increased over time, resulting in a growing concentration of patents in a few countries, primarily the USA, China, and South Korea. Although Europe has improved its collective position, it still faces significant challenges compared to Asia. The study also notes that the geographical diversity in scientific publications on 5G has increased over time, with a growing participation of universities compared to non-academic organizations. The quality of publications varies depending on the criteria used for evaluation, with China leading in total citation counts, while the USA stands out in terms of average quality. Finally, the article suggests that coordinated action at the European Union level may be crucial for the block to take a leadership role in 5G innovation, emphasizing the need for careful public policies and flexible regulations to maximize the benefits of the technology. The exponential growth of data traffic within modern communication systems has led to a critical shortage in system information rate and increased carbon emissions [7]. Massive multiple-input multiple-output (MIMO) techniques present a promising solution to boost both energy and spectrum efficiency, positioning them as a vital component for next-generation wireless networks.

III. SYSTEM DESIGN AND SETUP

The proposed system, shown in Figure 2, is composed of PT100 temperature sensors connected directly to PV modules on the LEA roof. Each sensor is wired to a specific port in the AVR-IoT Cellular Mini microcontroller, which serves as the core data processing unit. Once connected, the microcontroller begins the acquisition of temperature data; sequentially, it sends the data via cellular communication to the cloud-based ThingSpeak platform [15]. To connect the AVR IoT board via 5G, it is necessary to switch the carrier on the pre-installed chip from Truphone to the local carrier that supports 5G. Although the chip on the board supports LTE- M, this configuration enables connectivity with 5G networks. where real-time data visualization and further analysis can be conducted.

ThingSpeak acts as the interface between the microcontroller and the monitoring system, ensuring reliable communication between the hardware and the analytical tools. Data is then stored in a MySQL database, which integrates with ThingSpeak to facilitate data organization and access for extended analysis. During the one-month trial period, the system continuously recorded temperature data from the PV modules, providing an initial dataset to evaluate the system's effectiveness. With the integration of 5G, LEA benefits from faster and more reliable communication, enhancing the efficiency of the entire system. Additionally, one of the most significant advantages of using 5G in the monitoring system is the fast downlink allowing for real-time transmission of large volumes of data. This is critical for PV plants monitoring, enabling immediate detection and response to potential issues, such as overheating or system inefficiencies, in near real-time; this means that the temperature data collected can be analyzed almost instantly.

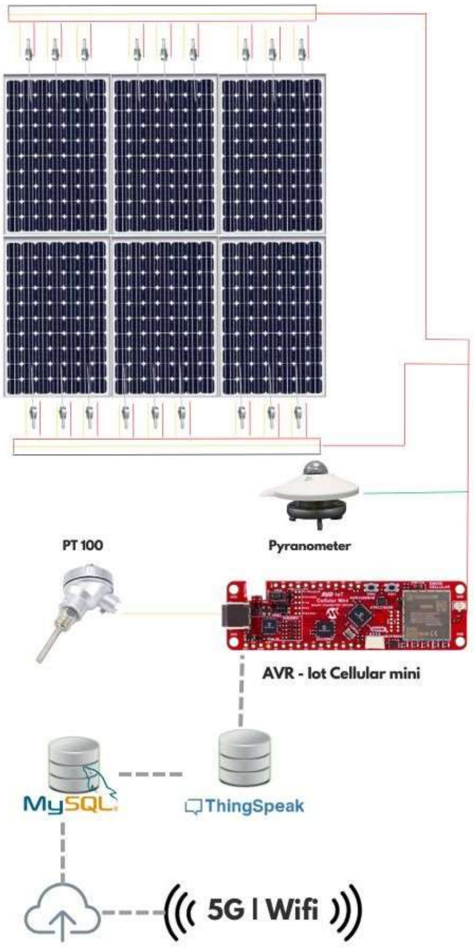

Figure 2. Proposed data acquisition system.

IV. RESULTS

Scalability and device density 5G [8] is designed to handle a much higher density of connected devices compared to previous generations, supporting up to one million devices per square kilometer. Such characteristics are ideal for IoT-based systems like the one in [16], which has a low-cost wireless monitoring system, employing NodeMCU boards, Raspberry Pi, and IoT technologies to monitor and analyze PV modules data. 5G high device density capability allows future expansions of the monitoring system, whether by adding more sensors, integrating additional types of data or scaling the system to larger installations.

Energy efficiency 5G technology is optimized for energy-efficient communication, which is critical for IoT applications like the LEA monitoring system. By reducing device power consumption during data transmission, 5G helps to extend the operational life of the sensors and microcontroller, especially in PV powered systems. This contributes to overall energy savings and ensures that the monitoring system can function effectively without draining excessive power.

Irradiance measurements, recorded every minute, shown in Figure 3, are fundamental for PV systems, allowing an accurate analysis of the amount of solar energy received by the modules. Our study uses an LP02 pyranometer with a sensitivity of 18.56 µV/W/m² to obtain irradiance data throughout a typical dry day, from 00:00 to 23:00 pm. The irradiance peak was recorded at noon, reaching 971.29 W/m²; the measured irradiance reveals a characteristic diurnal pattern, with a gradual increase in the early morning hours, a sharp peak around noon, and a gradual decline until late afternoon. Identifying this pattern is important for predicting PV generation, understanding the contribution of irradiance to PV performance [17]. The analysis of PV actual efficiency is crucial for verifying whether the system is operating as expected or if there are inefficiencies, such as performance loss due to shading, dirt on the panels, or component failures. Such monitoring of irradiance and system efficiency over time allows for the detection of anomalies and prevention of potential failures, contributing to the maintenance and reliability of the PV system.

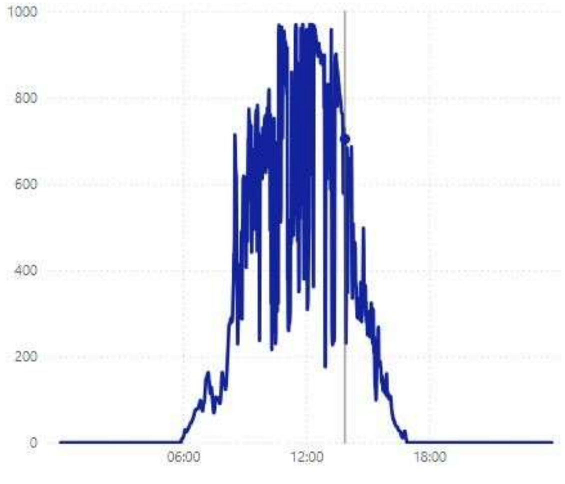

Figure 3. Measured irradiance data (W/m).

Ambient temperature data, shown in Figure 4, is a relevant parameter for evaluating PV performance, as temperature has a negative impact on PV efficiency. The temperatures vary between 22.5°C and 35.03°C, with a concentration between 24°C and 34°C. The data obtained demonstrate stability, with an average temperature of approximately 24.28°C. A PT100 sensor is used to record ambient temperature at regular intervals from 00:00 to 23:00 pm. A characteristic diurnal variation is verified: a gradual temperature increase in the early morning, reaching a peak around noon, coinciding with the time of maximum irradiance, and a gradual decrease through the afternoon. By correlating ambient temperature data with irradiance, it is possible to better understand PV systems behavior under real operating conditions, helping to identify potential cooling needs or system optimization to mitigate the effects of high temperatures, especially in hot climate regions.

Figure 4. PT100 based measured ambient temperature (ºC).

DHT11 based ambient temperature measurements, shown in Figure 5, were done in the same period of the data from the PT100 sensor; the data were recorded and organized for statistical analysis, enabling the identification of patterns and trends. The temperatures vary between 22.94°C and 35.93°C, with a concentration between 23°C and 35°C. The data obtained demonstrate stability, with an average temperature of approximately 24.5°C.

Figure 5. DHT11 based measured ambient temperature (°C).

The 250 Wp module temperature is shown in Figure 6, considering the same day analyzed before. Under intense irradiation, the module surface temperature can increase considerably, often being 20°C to 40°C higher than the ambient temperature. For example, at 8:00 am the module temperature is 31.18°C and the ambient temperature is

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Figure 6. Measured module temperature (°C).

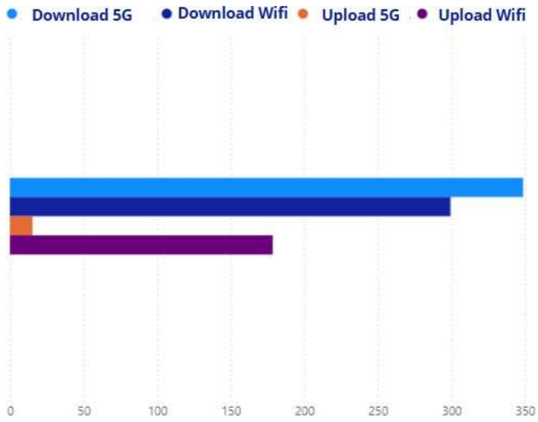

Figure 7. 5G and WiFi download and upload speeds (Mbps).

26.7°C; by 12:00 am, the module temperature rises to 58.43°C, while the ambient temperature reaches 32.47°C. Module temperature data can be used to calculate PV efficiency, as well as to predict electricity production.

The latency, which measures the time necessary for a data packet to travel to its destination and back, is lower for the Wi-Fi connection: WiFi shows a latency of 7 ms, a download speed of 299.4 Mbps, and an upload speed of 178.6 Mbps; 5G shows a latency of 18 ms, a download speed of 346.8 Mbps, and an upload speed of 15.3 Mbps. 5G and WiFi comparative performance is shown in Figure 7.

Comparing PT100 and DHT11 temperature data (see Figure 8), PT100 provides higher accuracy and stability, better reflecting temperature variations throughout the day.

Figure 8. Comparison of DHT11 and PT100 temperature data.

In contrast, DHT11, with lower sensitivity and precision, shows more irregular variations and is less responsive to sudden temperature changes, making the sensor more suitable for general monitoring applications where high accuracy is not critical.

V. CONCLUSIONS

All those mazes are price wise the table pie you reason whyFor the developed data acquisition system, which requires handling and downloading of large amounts of data, 5G proves to be more efficient despite the slightly higher latency. Although Wi-Fi has lower upload and download speeds, its responsiveness is superior, which can be crucial for activities requiring quick response times. On the other hand, 5G connection excels in download speed. With 316.4 Mbps, 5G is ideal for data-intensive activities like high-definition streaming and large file downloads. However, while an upload speed of 31.3 Mbps is acceptable, it falls behind the Wi-Fi performance. The choice between 5G and Wi-Fi may depend on the user's specific needs. For tasks that require high download speeds and can tolerate a little more latency, 5G proves to be advantageous. However, for activities that require low latency and a more stable connection, especially indoors, Wi-Fi may be the better option.

Comparing WiFi and 5G connectivity, our study shows that WiFi provides a lower latency, and a significantly higher upload rate compared to 5G. Such behavior suggests that, while 5G offers advantages in mobility and coverage, WiFi is more suitable for applications that require high data transmission rates and rapid response times, which are essential for continuous, real-time temperature monitoring of PV systems.

LTE-M technology, used in the research, designed specifically for connecting IoT devices, prioritizes low bandwidth and variable latency, characteristics inherent to its proposal for efficient and cost-effective connection for devices with low data throughput demands and high energy savings needs.

Although 5G is known for offering low latency and high bandwidth, LTE-M acts as an enabler for one of the pillars of 5G, massive Machine Type Communication (mMTC). This pillar is aimed at massive communication between IoT devices, which, unlike end-user applications, does not necessarily require high bandwidth or minimum latency. LTE-M has been adapted for the 5G ecosystem, integrating with mMTC and expanding support for the growing demands of the IoT in a massive communication structure. Therefore, it is natural for us to test the data flow in the order of Mbps and the latency can go up to 50 ms according to the standard specifications.

The choice of PT100 and DHT11 considers cost-effectiveness and accessibility for an initial test; however, DHT11 lower accuracy and narrower range can be a limitation. Hence, for future studies, more precise alternatives, such as DS18B20 or other advanced sensors, can be explored to improve data reliability. The first results also motivate a longer testing period, under different meteorological conditions, aiming to assess the long-term reliability and accuracy of the proposed monitoring system. Other areas that need deeper analysis are a) comparison with other monitoring systems for PV applications, including aspects such as accuracy, cost, and ease of implementation, b) integration of additional metrics, such as voltage and current, to offer a broader perspective and c) adaptability of the monitoring system to larger PV plants, including challenges such as communication protocols, power consumption, and data handling.

It is important to mention, no published studies or systems have been identified that employ a similar methodology, making this research innovative in the field, offering a foundation for further exploration and development of the integration of advanced communication technologies with IoT. Future works can expand the area with additional tests, increasing the number of sensors and easing the comparison of experiences.

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