Comparative Analysis of Constructed and Simulation Optimized Yagi Antennas for LoRa 868 MHz Communication

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Abstract: This paper investigates the impact of antenna design on the performance of LoRa communication systems through experimental and simulation-based analysis of three antenna models: a commercial omnidirectional antenna, a manually constructed Yagi antenna, and a simulation-optimized Yagi antenna, all designed for 868 MHz operation. The study focuses on evaluating critical communication parameters, including received signal strength (RSSI), signal-to-noise ratio (SNR), voltage standing wave ratio (VSWR), and packet loss under real-world conditions over a 2 km line-of-sight rural test range. The results demonstrate that directional Yagi antennas, especially those optimized via electromagnetic simulation tools, significantly outperform omnidirectional models in terms of signal reliability and link efficiency. The findings confirm that the integration of open-source design tools and accessible fabrication technologies enables the development of high-performance antennas suitable for deployment in decentralized, long-range IoT infrastructures.

Keywords: 868 MHz, IoT, LoRa, RSSI, SNR, VSWR, Yagi

Introduction

Low-power wireless communication technologies that enable reliable data exchange over long distances represent the technological foundation of modern Internet of Things (IoT) systems. Among them, LoRa [1] stands out in particular, utilizing chirp spread spectrum (CSS) modulation, which is known for its robustness in conditions of low signal strength and high interference. This characteristic enables stable communication in scenarios where traditional wireless networks exhibit significant performance limitations.

Thanks to the combination of long-range capability and low power consumption, LoRa technology is increasingly used in applications such as smart city systems, remote agricultural monitoring, industrial process control, critical infrastructure management, and environmental sensing. In all these cases, antenna performance is a key factor that directly affects transmission efficiency, link reliability, and the overall energy optimization of the system.

In scenarios where long-range communication is essential and systems are constrained by power and resources, high-gain directional antennas become an indispensable part of the architecture. Among the available solutions, Yagi antennas [2] stand out as particularly effective due to their ability to form a narrow radiation beam in a well-defined direction. Their geometry consisting of a reflector, an active dipole, and multiple directors enables energy focusing and reduced losses, resulting in higher signal-to-noise ratio (SNR)[3] and lower impact from reflected or scattered energy.

Practical applications and numerous experimental studies confirm that Yagi antennas are optimal for stationary LoRa nodes, where the orientation of the link is known and constant. Their key advantages include high gain, a directional radiation pattern, mechanical simplicity, and low manufacturing cost, making them suitable for both industrial use and research prototypes.

Although electromagnetic simulation tools such as 4NEC2 and MMANA-GAL, enable the design of antennas with a high degree of precision using methods like the Method of Moments (MoM) and Finite Element Method (FEM), their results often differ from real-world performance due to simplified assumptions. Factors such as mechanical tolerances, properties of the supporting materials, the quality of electrical connections, and the influence of the local environment significantly affect antenna behavior under real conditions.

For this reason, a combined experimental-optimization approach is increasingly applied in the modern development of antennas for LoRa systems. This approach involves an initial design based on theoretical models, prototype fabrication, followed by iterative optimization based on empirical measurements of parameters such as reflected power, standing wave ratio (SWR), input impedance, radiation pattern, and polarization.

This study addresses the following key research questions:

1. What are the performance differences between an empirically constructed and a simulation-optimized Yagi antenna for LoRa communication?
2. To what extent do antennas of different constructions contribute to improvements in signal strength, link stability, and packet loss reduction?
3. Is it possible to achieve performance levels that meet professional LoRa infrastructure standards using limited resources?

The aim of this work is to provide a practical insight into how the geometry and fabrication method of a Yagi antenna directly influence the reliability and range of LoRa networks, through a combination of field measurements and engineering analysis. This study relies not only on theoretical modeling and simulation but also on real-world testing, with the goal of offering a meaningful guideline for the future design of antennas in long-range IoT systems.

Methods and materials

As part of this research, two models of Yagi antennas were developed for an operating frequency of 868 MHz [4], with the goal of conducting a comparative analysis of their performance in long-range LoRa communication systems. A commercial omnidirectional antenna was also included as a reference point in the testing process to clearly highlight the differences between directional and non-directional solutions.

The first model was constructed using an empirical approach, without the use of simulation tools.

The construction was based on practical knowledge, references from the literature, and multiple tests conducted under real-world conditions. The mechanical structure of the antenna was realized using 3D printing, while the elements were made of 2 mm diameter copper wire, enabling simple and precise fabrication.

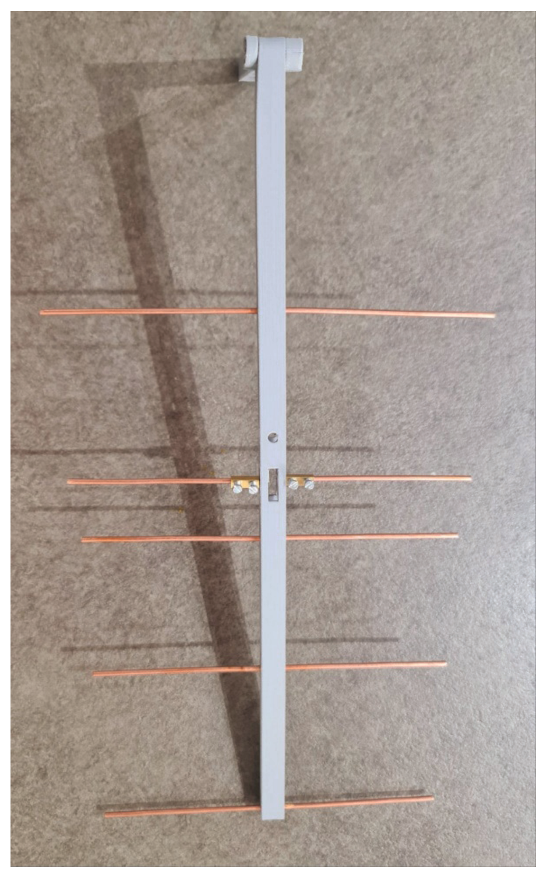

Figure 1. *Optimized 5-element Yagi antenna*

The antenna consists of five elements: one reflector, an active dipole, and three directors, as shown in Figure 1.

The reflector, with a length of 168 mm, is positioned at the beginning of the boom and directs electromagnetic energy forward, reducing backward radiation losses.

The dipole, measuring 159 mm in length, is positioned 69.1 mm from the reflector and has a gap between its arms (gap ≤ 4.6 mm), which allows for easy connection with a coaxial cable.

The directors measure 151 mm (D1), 149 mm (D2), and 147 mm (D3) in length, and are placed 95 mm, 157 mm, and 231 mm respectively from the reflector, thereby enhancing the focus of the radiation and increasing the antenna's directivity.

All elements are mounted on a 10 mm diameter boom made of ASA plastic due to its mechanical strength, UV resistance, and favorable dielectric properties that do not compromise RF performance. The total length of the antenna is 235 mm, and the expected gain is estimated at approximately 10 dBi, which was confirmed through preliminary measurements under real-world conditions.

The second model was designed based on theoretical calculations and optimized through simulations using software tools such as 4NEC2 [5] and MMANA-GAL [6], applying the Method of Moments for electromagnetic analysis. Through iterative simulations, the spacing between elements, their lengths, and the input impedance were precisely adjusted to achieve optimal matching and maximum antenna gain.

All three antenna models, the empirical Yagi, the simulation-optimized Yagi, and the commercial omnidirectional antenna were tested under identical conditions in an open field, along a path with clearly defined line-of-sight and a distance of exactly 2 kilometers. The locations were carefully selected to eliminate physical obstructions and minimize external electromagnetic interference, simulating real-world applications in rural environments such as precision agriculture, environmental monitoring, and remote IoT nodes.

During the testing, the following key parameters were measured:

1. Received Signal Strength Indicator (RSSI)
2. Signal-to-Noise Ratio (SNR)
3. Reflected power expressed through VSWR
4. Link stability and packet loss

In order to ensure the highest possible accuracy during the measurement process, a combination of specialized equipment was employed. The tinySA Ultra spectrum analyzer was utilized to assess the frequency characteristics and real-time behavior of the transmitted and received signals, enabling detailed insight into the spectral distribution and potential interference. In addition, the TZT SV4401A [7] vector network analyzer (VNA) was used for comprehensive analysis of antenna parameters, such as reflection coefficient, impedance matching, and standing wave ratio (VSWR), providing essential data for evaluating the performance and tuning of the antenna systems.

To further enhance measurement reliability and sensitivity, especially when capturing weak signals over long distances, low-noise amplifiers (LNAs) were integrated into the setup.

Specifically, the ZS-406 and ZK-06-BM LNAs were employed to amplify the received signals with minimal added noise, preserving signal integrity and enabling the detection of subtle variations in communication quality. The use of these devices ensured that even the smallest discrepancies in antenna performance could be accurately identified and analyzed.

Figure 2 presents the flowchart of the Yagi antenna construction process for the 868 MHz frequency, outlining all essential steps: from selecting the operating frequency and calculating the dimensions of the elements, through preparing and assembling the physical components, to verifying electrical connections, measuring performance, and completing the final assembly. The diagram also incorporates conditional logic, if the antenna is not properly tuned, the user is guided back to the step of adjusting the lengths and positions of the elements, followed by a new round of measurements. This clearly illustrates an iterative approach that ensures optimal antenna response and reliable performance under real-world conditions.[8]

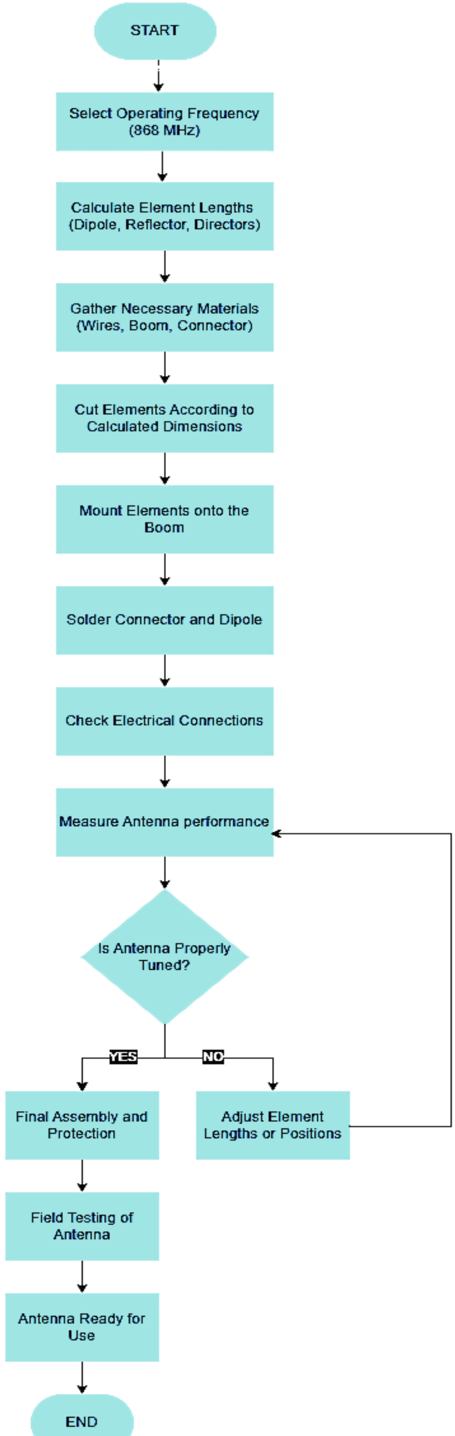

Figure 2. *Flowchart of Yagi antenna construction process*

Results

The evaluation of antenna performance was conducted on March 28, 2025, under real-world conditions in the territory of the Republic of Srpska, along the Prijedor–Banja Luka route. The test site featured clearly defined line-of-sight visibility and an exact distance of 2 kilometers, located in a rural area with minimal electromagnetic interference.

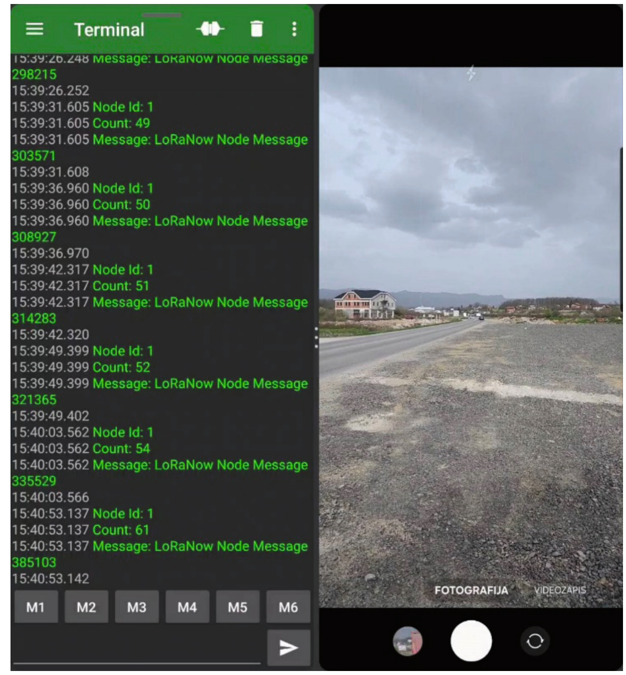

Figure 3. *LoRa communication test with visible line-of-sight at a 2 km distance, recorded on March 28, 2025.*

A visual representation of the test location and terminal interface showing successfully received packets is provided in Figure 3, clearly illustrating an open terrain with an unobstructed line-of-sight, as well as stable communication between the transmitting node and the receiving unit during the field test.

The test configuration included three antennas with different characteristics and gains, representing the antenna's ability to direct transmitted or received electromagnetic energy in a specific direction. Antenna gain, expressed in decibels relative to an ideal isotropic radiator (dBi), is one of the key parameters that directly affects communication efficiency, especially over long distances.[9]

High-gain antennas concentrate energy into a narrower radiation beam, which enables significantly greater range and higher signal strength in the targeted direction. This is particularly useful in point-to-point links, where precise antenna orientation is essential. On the other hand, low-gain antennas exhibit a wider radiation pattern, covering a larger area but with lower signal intensity, making them suitable for multi-node network applications where broad coverage is required.

During testing, antennas were carefully selected to cover different application scenarios from highly directional links focused on maximum range and minimal losses, to broadband configurations suitable for local signal distribution within a wider area.

Directional antennas, such as Yagi models, were used in point-to-point scenarios where precise alignment with the receiving node was possible, while omnidirectional antennas were used to test transmission reliability in multi-node networks, where uniform radiation in the horizontal plane was needed.

This diversity of configurations enabled a comprehensive evaluation of system performance in real-world conditions. During measurements, key parameters were analyzed, such as transmission reliability (number of successfully received packets without errors) and received signal strength expressed in dBm (RSSI) as well as link stability during continuous communication. Special attention was given to identifying signal quality fluctuations depending on antenna orientation, terrain configuration, and the specific type of antenna used. This provided a clear insight into the practical efficiency of each antenna under real-world environmental conditions.[10]

The commercial omnidirectional antenna, as a non-directional design with a nominal gain of approximately 2.15 dBi, is best suited for applications that require uniform circular coverage in the horizontal plane, such as networks with multiple nodes or systems where precise antenna orientation is not feasible. However, due to its dispersed radiation pattern, this antenna has a limited range and lower signal intensity in any particular direction, which significantly reduces its effectiveness in applications where focused transmission over long distances is required.

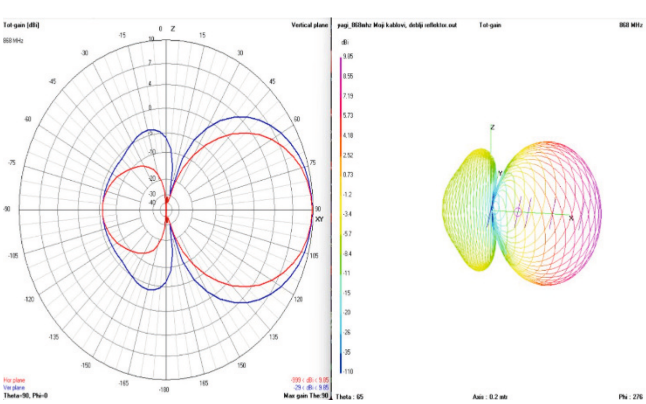

Figure 4. *Radiation pattern of the empirically constructed Yagi antenna at 868 MHz*

In contrast, the empirically constructed Yagi antenna, built without the use of simulation software, was designed based on practical knowledge and prior experience with directional antennas. This antenna provides a notable directional gain of approximately 9.85 dBi, enabling more efficient energy transfer in the desired direction. The radiation pattern of this empirical Yagi antenna is shown in Figure 4, clearly illustrating a pronounced main lobe oriented in the target direction of signal propagation, along with significantly reduced side lobes, which confirms its directive nature and suitability for point-to-point communication.

In addition to the main lobe, the radiation pattern also shows significantly reduced side lobes, indicating high selectivity and focused radiation characteristics. This radiation structure confirms the directive nature of the antenna and its ability to concentrate electromagnetic energy in a single direction, thereby minimizing losses caused by radiation in unwanted directions.

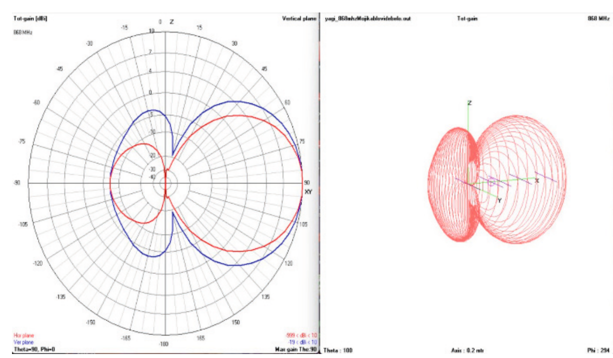

Figure 5. *Radiation pattern of the optimized Yagi antenna for 868 MHz*

As shown in Figure 5, the optimized Yagi antenna model was developed using electromagnetic simulation in the software tools 4NEC2 and MMANA-GAL. The model was carefully designed with precisely defined element lengths and optimized spacing, resulting in a high degree of radiation directivity. Simulation results confirm a gain of 10 dBi, which represents a significant improvement over the empirically constructed model and enables more efficient transmission of electromagnetic energy in the dominant direction.

The radiation pattern clearly shows a focused main lobe and minimal side lobes, indicating high design quality and suitability for long-distance communication with minimal losses.

The analysis of the received signal strength indicator (RSSI) revealed significant differences between the examined configurations. The omnidirectional antenna generated a signal in the range of –95 dBm to –90 dBm, with significant instability and variability in reception. The empirically constructed Yagi antenna demonstrated improved performance, with a stabilized signal level between –85 dBm and –82 dBm. The most favorable values were achieved with the optimized Yagi model, with a detected signal in the range of –80 dBm to –76 dBm and minimal fluctuation.

Measurement of the signal-to-noise ratio (SNR) further confirmed the advantage of directional antennas over omnidirectional ones. In the omnidirectional model, SNR fluctuated between –1 dB and +2 dB, while the empirical antenna reached up to +4 dB. The optimized model achieved stable values in the range of +6 dB to +8 dB, which directly contributes to improved communication link quality and data transmission reliability.

The impedance matching parameter, expressed as the voltage standing wave ratio (VSWR), showed a high reflected component for the omnidirectional model, with values around 2.0, indicating poor adaptation to the transmission system and higher losses. The empirical model achieved significantly lower values, between 1.5 and 1.7, while the optimized antenna recorded near-ideal matching with values ranging from 1.1 to 1.3, confirming the quality of the design and precise tuning.

Link reliability was further quantified by measuring the packet loss parameter. The highest packet loss rate up to 7 percent was recorded when using the omnidirectional antenna. The empirical design significantly reduced losses to below 3 percent, while the optimized model enabled almost uninterrupted communication with losses of less than 1 percent.

The combined analysis of all measured parameters clearly highlights the superiority of the software-optimized Yagi antennas, which consistently deliver better performance across all evaluated categories compared to other models.

The optimized design provides higher gain, more stable reception, a more favorable signal-to-noise ratio (SNR), lower voltage standing wave ratio (VSWR), and virtually negligible packet loss. While the empirically constructed antenna offers a functional solution under limited technical resources, its performance remains below that of precisely modeled antennas. On the other hand, omnidirectional antennas though easy to implement and useful in applications requiring coverage in all directions demonstrate clear limitations in link stability and range, especially in environments where high communication reliability is essential.

Discussion

The experimental results clearly demonstrate the technical superiority of directional Yagi antennas over commercial omnidirectional models in LoRa communication systems with direct line-of-sight conditions. Across all key communication parameters, Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), Voltage Standing Wave Ratio (VSWR), and packet loss rate, the Yagi antennas provided more stable and efficient long-range transmission [11].

The software-optimized Yagi antenna, designed using electromagnetic simulation tools, achieved the most favorable results across all measured metrics. Fine-tuned geometric parameters, including the lengths and spacing of the reflector, driven element, and directors, along with precise impedance matching, led to highly focused radiation, minimal reflected power, and effective energy transfer toward the receiver.

Notably, the empirically constructed Yagi antenna, developed without simulation tools, still demonstrated remarkably good performance compared to the reference omnidirectional model [12]. However, the performance gap between it and the software-optimized version clearly highlights the importance of accurate electromagnetic modeling in antenna design.

Figure 6. illustrates the performance differences among the tested antennas, highlighting the technical superiority of the Yagi designs [13]. especially the one optimized through simulation.The optimized model consistently delivers the lowest signal losses and highest signal quality, while the empirical design proves that acceptable performance is achievable even without advanced tools, provided the physical dimensions are properly calculated and implemented.

In contrast, the omnidirectional antenna, while easy to deploy, exhibits limited capabilities due to its

Parameter	Commercial Omnidirectional	Empirical Yagi	Optimized Yagi
RSSI (dBm)	-95 to -90	-85 to -82	-80 to -76
SNR (dB)	-1 to +2	up to +4	+6 to +8
VSWR	approx. 2.0	1.5 – 1.7	1.1 – 1.3
Packet Loss (%)	up to 7%	< 3%	< 1%
Approx. Gain (dBi)	~2.15	~9.85	~10
Directivity	Low (omnidirectional)	High (directional)	Very high (optimized)

Figure 6. *Comparative performance of tested antennas across key communication parameters*

uniform radiation pattern and low gain. This makes it less suitable for scenarios that demand long-range, high-reliability IoT communication.

The empirically constructed Yagi antenna, although developed without precise simulations, demonstrated remarkably good performance compared to the omnidirectional reference. This confirms that even practically implemented, low-budget configurations when properly dimensioned and well-crafted can represent a viable solution for rural and stationary IoT nodes [14].

The observed performance gap between the empirically constructed and the software-optimized Yagi antenna models clearly highlights the importance of accurate electromagnetic modeling in antenna design.

Numerical optimization of key geometric parameters including element spacing, the lengths of the reflector, dipole, and directors, as well as precise impedance matching significantly contributes to improved energy directionality and reduced reflected power. This results in more efficient transmission and better alignment with the characteristics of the transceiver system [15].

In contrast, the omnidirectional antenna exhibits limited performance in terms of signal stability and directional energy efficiency, primarily due to its uniform radiation pattern and relatively low gain. While it is easy to deploy and suitable for specific network topologies, its effectiveness significantly diminishes in scenarios that demand long-range coverage and high communication reliability.

Conclusion

This research presents a methodological approach that combines numerical electromagnetic simulation with experimental validation for the development of a Yagi antenna optimized to operate in the 868 MHz band, which is essential for modern IoT systems and low-power wireless communication networks.

Through parallel analysis of an empirically constructed and a simulation-optimized antenna, it has been confirmed that the use of open-source software tools (4NEC2, MMANA-GAL) in conjunction with accessible manufacturing technologies can achieve significant directivity and gain, meeting the technical requirements of long-range communication in LPWAN networks.

The experimental results clearly demonstrate a performance improvement of the optimized model compared to the non-optimized version, thereby confirming the validity of the simulation methodology and its applicability in low-budget development environments. The contribution of this study lies in providing a concrete procedure for antenna design and evaluation, which can serve as a foundation for further application development in areas such as precision remote monitoring, agricultural automation, infrastructure management, and smart sensor systems.

Beyond its technical contribution, this work highlights the potential for decentralized development of advanced communication components in resource-constrained settings, thereby fostering scientific and technological inclusiveness. This approach is particularly valuable for research institutions, educational organizations, and development centers aiming to create functional and scalable solutions in the field of wireless communications.

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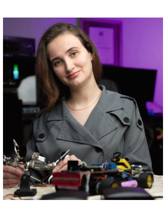

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