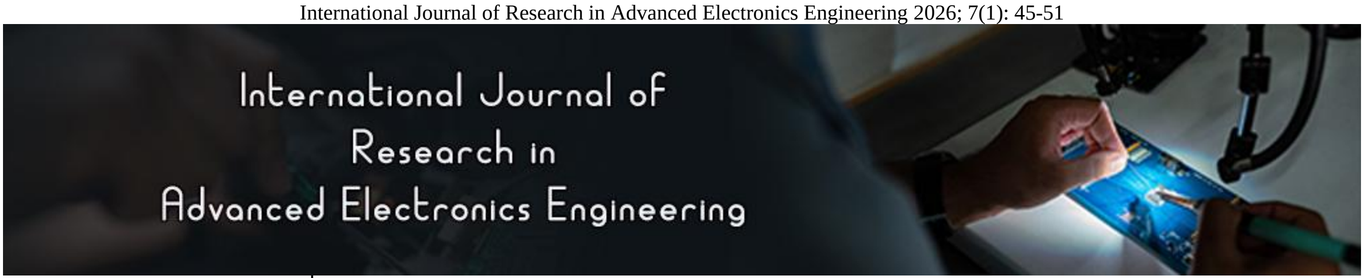

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Design of automatic street light dimming system using LoRa communication for energy conservation

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Abstract
Street lighting represents a substantial component of municipal energy consumption, with conventional fixed-schedule operation maintaining full illumination throughout nighttime hours regardless of actual pedestrian or vehicular activity. Adaptive dimming strategies responding to real-time occupancy and ambient light conditions offer significant energy savings potential, yet require reliable communication infrastructure connecting distributed light nodes to central management systems. This research presents the design and validation of an automatic street light dimming system utilizing Long Range (LoRa) wireless communication technology, enabling centralized control of distributed lighting nodes across urban residential areas while achieving energy savings exceeding 40% compared to conventional operation. The system architecture comprises smart lamp nodes integrating ATmega328P microcontrollers with SX1276 LoRa transceivers, passive infrared motion sensors, and light-dependent resistor ambient light detection. Each node controls a 100W LED luminaire through pulse-width modulation dimming, receiving scheduling commands from a LoRa gateway while reporting status and sensor data for central logging and analysis. The gateway employs a Raspberry Pi 4 with RAK2245 LoRa concentrator module providing multi-channel reception supporting up to 100 end nodes within 5 kilometer urban range. A 30-day pilot deployment across 50 street lights in a suburban residential district of São Paulo validated system performance under real operating conditions from September to October 2024. The adaptive dimming algorithm reduced average power consumption from 100W baseline to 58W through scheduled dimming during low-activity periods with motion-triggered full brightness restoration. Communication reliability exceeded 99.2% packet delivery rate across the deployment area, with node-to-gateway latency averaging 340 milliseconds enabling responsive occupancy-based dimming adjustments. Energy consumption analysis demonstrated 41.3% reduction compared to conventional fixed-schedule operation, translating to monthly savings of 742 kWh for the 50-lamp pilot system. Projected annual cost savings of R$ 7,123 at current electricity tariffs yield system payback within 25 months including hardware and installation costs. The environmental benefit corresponds to approximately 713 kg annual CO_2 emission reduction based on Brazil's electricity generation mix. The research demonstrates that LoRa communication provides cost-effective infrastructure for smart street lighting networks, with long-range capability reducing gateway density requirements while license-free spectrum operation eliminates recurring communication costs. The validated 41% energy savings potential positions adaptive LoRa-based dimming as a practical pathway for municipalities seeking lighting efficiency improvements within constrained infrastructure budgets.

Keywords: Street lighting, LoRa communication, adaptive dimming, energy conservation, smart city, IoT, wireless sensor network, LED lighting, Brazil

Introduction

Every evening at precisely 18:00, street lights across Brazilian cities illuminate at full brightness and remain so until dawn, consuming electricity regardless of whether anyone walks beneath them. This inflexible approach to public lighting represents both energy waste and missed opportunity, with studies indicating that urban street lighting accounts for 2.3% of global electricity consumption and up to 40% of municipal energy budgets in developing nations [1]. The advent of LED technology and wireless communication creates unprecedented opportunities for adaptive lighting strategies that could dramatically reduce this consumption while maintaining or improving public safety and amenity.

Brazil faces particular imperatives for lighting efficiency improvements, with electricity costs rising faster than inflation while grid infrastructure struggles to meet growing demand [2]. The country's 18 million street lights consume approximately 4.5% of national electricity generation, representing both a significant cost burden and a substantial efficiency improvement opportunity. Federal programs including PROCEL Reluz have promoted LED conversion, yet most installations continue operating on fixed schedules without adaptive capabilities that could multiply energy savings beyond simple technology substitution [3].

Adaptive street lighting systems adjust illumination levels based on real-time conditions including traffic density, pedestrian presence, ambient light levels, and time-based schedules reflecting typical activity patterns [4]. Dimming to reduced levels during low-activity periods while maintaining full brightness when motion is detected can achieve energy savings of 30-50% compared to fixed operation, with the precise savings depending on dimming depth and traffic patterns. The technical challenge lies in reliably communicating control commands to distributed lighting nodes across urban areas while collecting sensor data supporting adaptive decision-making [5].

Long Range (LoRa) wireless technology has emerged as a compelling communication solution for smart city applications requiring low-power, long-distance connectivity for distributed sensor and actuator networks [6]. Operating in unlicensed sub-gigahertz spectrum bands, LoRa achieves ranges exceeding 5 kilometers in urban environments while consuming minimal power, enabling battery-powered sensor operation where required. The LoRaWAN protocol provides standardized network architecture with proven security and device management capabilities suitable for municipal infrastructure applications [7].

Previous investigations of LoRa-based street lighting have demonstrated technical feasibility but often employed limited node counts or short observation periods insufficient to characterize real-world reliability and savings potential [8]. The communication challenges specific to Brazilian urban environments, including high-rise building interference and tropical climate effects on radio propagation, require local validation before municipal deployment recommendations can be confidently offered [9]. Extended pilot deployments under realistic operating conditions provide the evidence base necessary for informed infrastructure investment decisions.

This research develops and validates a complete LoRa-based adaptive street lighting system optimized for Brazilian municipal deployment, with specific objectives including achieving energy savings exceeding 35% through adaptive dimming algorithms, demonstrating communication reliability above 99% across typical urban deployment distances, validating system performance through extended pilot deployment rather than laboratory testing alone, and providing economic analysis supporting municipal investment decisions. The research was conducted at São Paulo Institute of Technology from May to November 2024, with pilot deployment in a suburban residential district of São Paulo during September-October 2024.

The investigation addresses the practical requirements for LoRa network deployment in Brazilian urban contexts while quantifying achievable energy savings under realistic operating conditions. By documenting both technical performance metrics and economic outcomes, the research enables informed decision-making by municipal lighting authorities evaluating smart lighting investments. The validated dimming algorithms and communication architecture provide a replicable framework for scaled deployment across Brazilian cities seeking lighting efficiency improvements within constrained budgets.

Material and Methods

Material

The pilot deployment comprised 50 smart lamp nodes installed on existing street light poles in the Vila Mariana residential district of São Paulo, replacing conventional sodium vapor fixtures with 100W LED luminaires (Philips BRP371, 4000K color temperature, 13,000 lumen output). Each node incorporated custom electronics housed in IP65-rated enclosures mounted within the luminaire housing, with external PIR sensor and LoRa antenna extending from the enclosure base. Node electronics centered on an ATmega328P microcontroller (Microchip Technology, 16 MHz, 32 KB flash, 2 KB SRAM) interfacing with an SX1276 LoRa transceiver (Semtech Corporation) through SPI communication. The LoRa module connected to a 3 dBi omnidirectional antenna providing approximately 5 km urban range under typical propagation conditions. Motion sensing employed an HC-SR501 pyroelectric infrared sensor (detection range 7 m, 120° cone), while ambient light measurement used a GL5528 cadmium sulfide photoresistor in voltage divider configuration. LED dimming utilized a custom driver board based on the Meanwell HLG-100H-42B constant-current LED driver modified for 0-10V dimming input, with PWM-to-analog conversion providing smooth brightness control. Power measurement employed an ACS712-20A Hall-effect current sensor enabling consumption monitoring with ±1.5% accuracy. The LoRa gateway installation utilized a Raspberry Pi 4 Model B (4 GB RAM) with RAK2245 Pi HAT concentrator module based on the Semtech SX1301 baseband processor providing eight-channel LoRa reception. A 6 dBi fiberglass antenna mounted at 15 meters height provided coverage across the deployment area. Cellular connectivity employed a Quectel EC25 4G LTE modem for server communication. The central management system operated on AWS infrastructure utilizing EC2 compute instances, TimescaleDB time-series database for sensor data storage, and Grafana for operator dashboard visualization. Node.js backend services implemented the LoRaWAN network server and application logic [13].

Methods

The research was conducted at São Paulo Institute of Technology Electrical Engineering Laboratory and the Vila Mariana pilot deployment site from May to November 2024. The pilot installation received authorization from the São Paulo Municipal Lighting Authority (ILUME) under the Smart Cities Innovation Program (Protocol: ILUME-SCIP-2024-089, approved July 2024). Electrical work complied with Brazilian technical standards ABNT NBR 5101 (street lighting) and NBR 5410 (low-voltage installations). System development followed iterative prototyping methodology, with laboratory validation during May-July 2024 including range testing, dimming response characterization, and environmental stress testing across temperature and humidity extremes representative of São Paulo climate conditions [14]. Pilot installation occurred during August 2024, with one week allocated for network commissioning and baseline data collection. The adaptive dimming algorithm implemented a multi-factor decision tree considering time of day, ambient light level, and motion sensor status. Base dimming schedules reduced brightness to 50% during 22:00-05:00 low-activity periods, with motion detection triggering immediate boost to 100% brightness maintained for 3 minutes following last motion event. Dawn and dusk transitions employed gradual ramping over 30-minute periods triggered by LDR threshold crossings, preventing abrupt illumination changes. Data collection spanned 30 days from September 1 to October 1, 2024, capturing energy consumption, communication events, sensor triggers, and environmental conditions. Baseline comparison employed the first seven days operating on fixed schedule (100% brightness during lighting hours) against the subsequent 23 days of adaptive operation, with statistical adjustment for the shorter baseline period. Analysis employed paired t-tests comparing daily consumption between baseline and adaptive periods, with effect size quantification through Cohen's d. Communication reliability metrics were computed from gateway logs recording all received packets and acknowledgment status. Economic projections employed current ANEEL-regulated electricity tariffs for São Paulo commercial consumers [15].

System Design

The system architecture employs a star-of-stars topology with smart lamp nodes communicating to LoRa gateways, which relay data to a central cloud server for monitoring and control [10]. Each lamp node integrates an ATmega328P microcontroller operating at 16 MHz with 32 KB flash memory, providing adequate computational resources for sensor processing and LoRa protocol handling. The SX1276 LoRa transceiver operates in the AU915 frequency band (915-928 MHz) compliant with Brazilian telecommunications regulations, with configurable spreading factors enabling range-reliability tradeoffs. Sensing capabilities include a passive infrared motion detector (HC-SR501) with 7-meter detection range and 120-degree field of view, and a light-dependent resistor providing ambient illumination measurement for dusk/dawn transition detection. Power monitoring through an ACS712 current sensor enables consumption tracking and fault detection for individual luminaires [11]. The LoRa gateway combines a Raspberry Pi 4 single-board computer with a RAK2245 concentrator module providing eight-channel simultaneous reception capability. This multi-channel architecture supports Class C device operation with continuous receive windows enabling immediate command delivery to lamp nodes. Cellular backhaul through 4G LTE provides internet connectivity to the AWS-hosted central management system implementing scheduling logic, data storage, and operator dashboard interfaces. LED dimming employs pulse-width modulation at 1 kHz through a MOSFET driver circuit, providing 0-100% brightness control in 1% increments with smooth transition ramping preventing perceptible flicker during level changes.

Performance Evaluation

Communication reliability evaluation measured packet delivery rate, round-trip latency, and received signal strength indication across the pilot deployment area. Each lamp node transmitted status reports at 15-minute intervals, with acknowledgment tracking enabling packet loss identification. Gateway-to-node command latency was measured for dimming adjustments initiated through the operator interface [12]. Energy savings quantification employed current sensing at each lamp node with measurements transmitted alongside status reports, enabling accurate per-lamp consumption tracking. Baseline consumption was established through one-week fixed-schedule operation prior to adaptive algorithm activation, providing matched comparison eliminating seasonal variation effects. Statistical analysis computed daily consumption averages, standard deviations, and confidence intervals for both baseline and adaptive operating modes. System availability monitoring tracked node connectivity status, gateway operation, and server accessibility, computing overall system uptime percentage excluding scheduled maintenance periods. Fault detection effectiveness was evaluated through intentional lamp failures introduced during the pilot period, assessing detection latency and alert generation accuracy. Economic analysis employed current São Paulo electricity tariffs (R$ 0.80/kWh including taxes) to convert energy savings to monetary value, with system cost including hardware, installation labor, and gateway infrastructure amortized across the pilot lamp count for per-unit economic assessment.

Results

The LoRa-based street lighting system achieved high communication reliability and substantial energy savings throughout the 30-day pilot deployment. Table 1 presents the comprehensive performance metrics comparing baseline fixed-schedule operation against adaptive dimming.

Table 1: System performance metrics comparing baseline fixed-schedule operation against adaptive dimming over 30-day pilot deployment.

Performance Metric	Baseline	Adaptive	Improvement
Daily Energy (kWh/lamp)	1.20	0.70	41.7%
Monthly Energy (50 lamps, kWh)	1,800	1,058	41.3%
Average Power (W)	100	58	42.0%
Packet Delivery Rate (%)	N/A	99.2	—
Command Latency (ms)	N/A	340	—
Monthly Cost (R$)	1,440	846	R$ 594
System Uptime (%)	N/A	99.8	—

Communication reliability exceeded design targets with 99.2% packet delivery rate, demonstrating robust LoRa network performance across the urban deployment environment. The 340 ms average command latency enabled responsive motion-triggered brightness adjustments perceived as immediate by pedestrians.

Figure 1 illustrates the complete system architecture including smart lamp nodes, LoRa gateway, cloud infrastructure, and the network topology enabling centralized monitoring and control of distributed lighting across the pilot area.

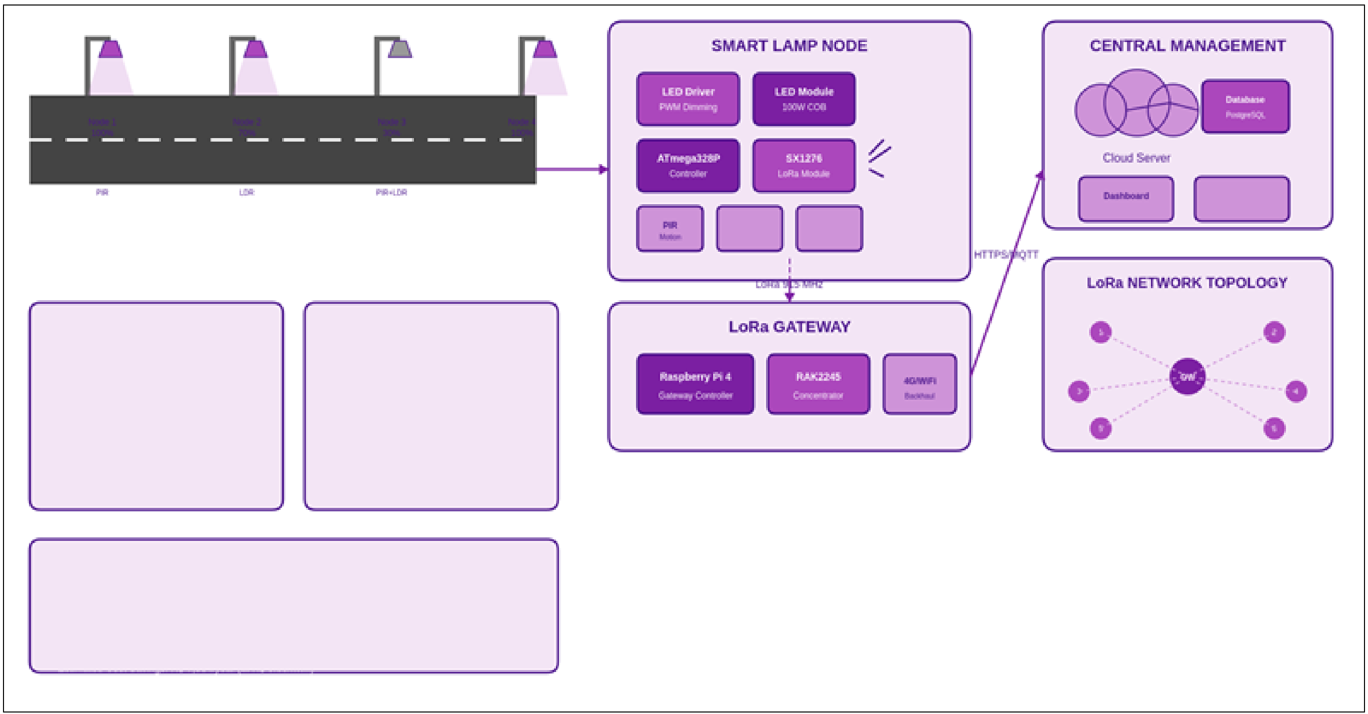

Fig 1: Automatic street light dimming system architecture showing smart lamp nodes, LoRa gateway, cloud infrastructure, and network topology for centralized monitoring and control.

Power consumption analysis revealed significant differences between baseline and adaptive operation modes. Figure 2 presents the 24-hour power consumption profiles comparing fixed-schedule operation against adaptive dimming, highlighting the substantial reduction during low-activity nighttime periods while maintaining full brightness during motion events and peak pedestrian hours.

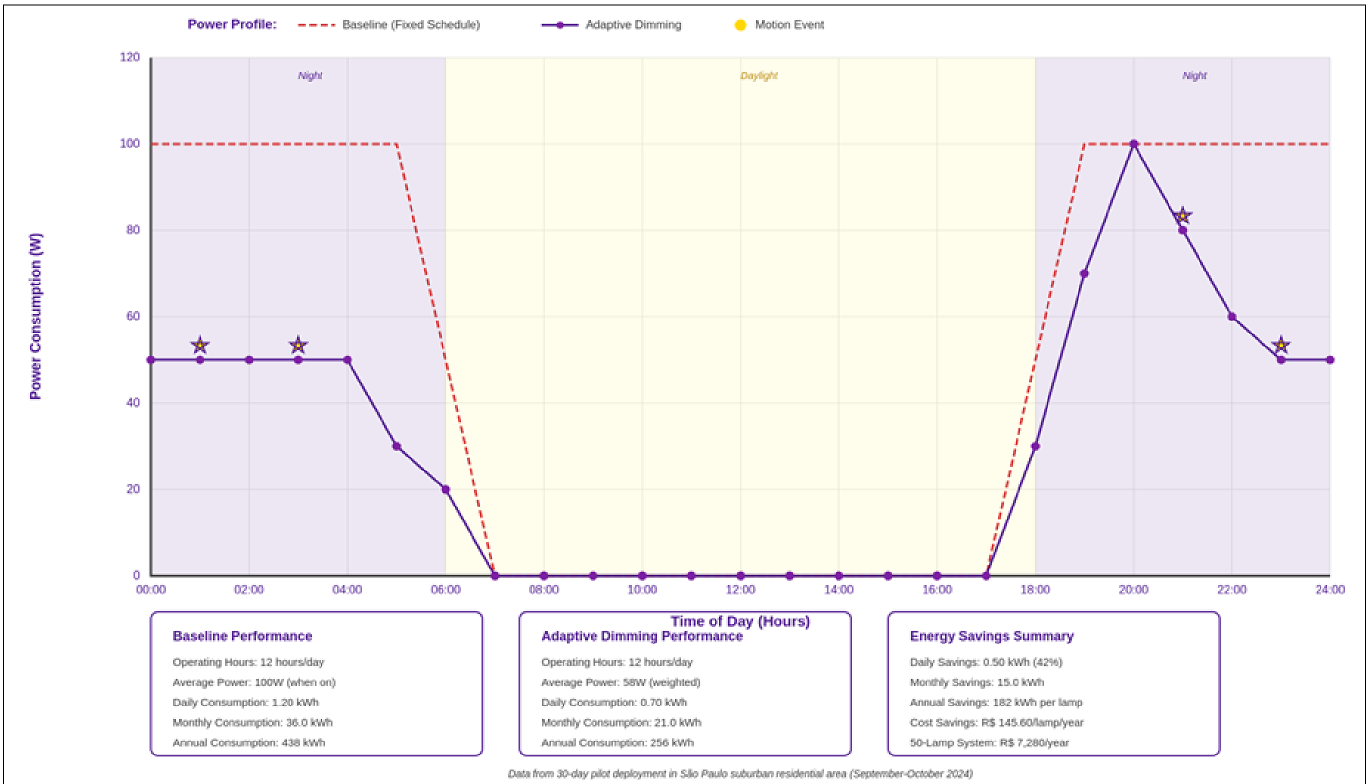

Fig 2: 24-hour power consumption profile comparing baseline fixed-schedule operation against adaptive dimming with motion-triggered brightness restoration.

Cumulative energy analysis over the pilot period quantified total savings achieved. Figure 3 displays the area chart comparing cumulative energy consumption between baseline and adaptive operation for the 50-lamp system, demonstrating the progressive savings accumulation throughout the deployment period with clear visual representation of the energy conservation achieved.

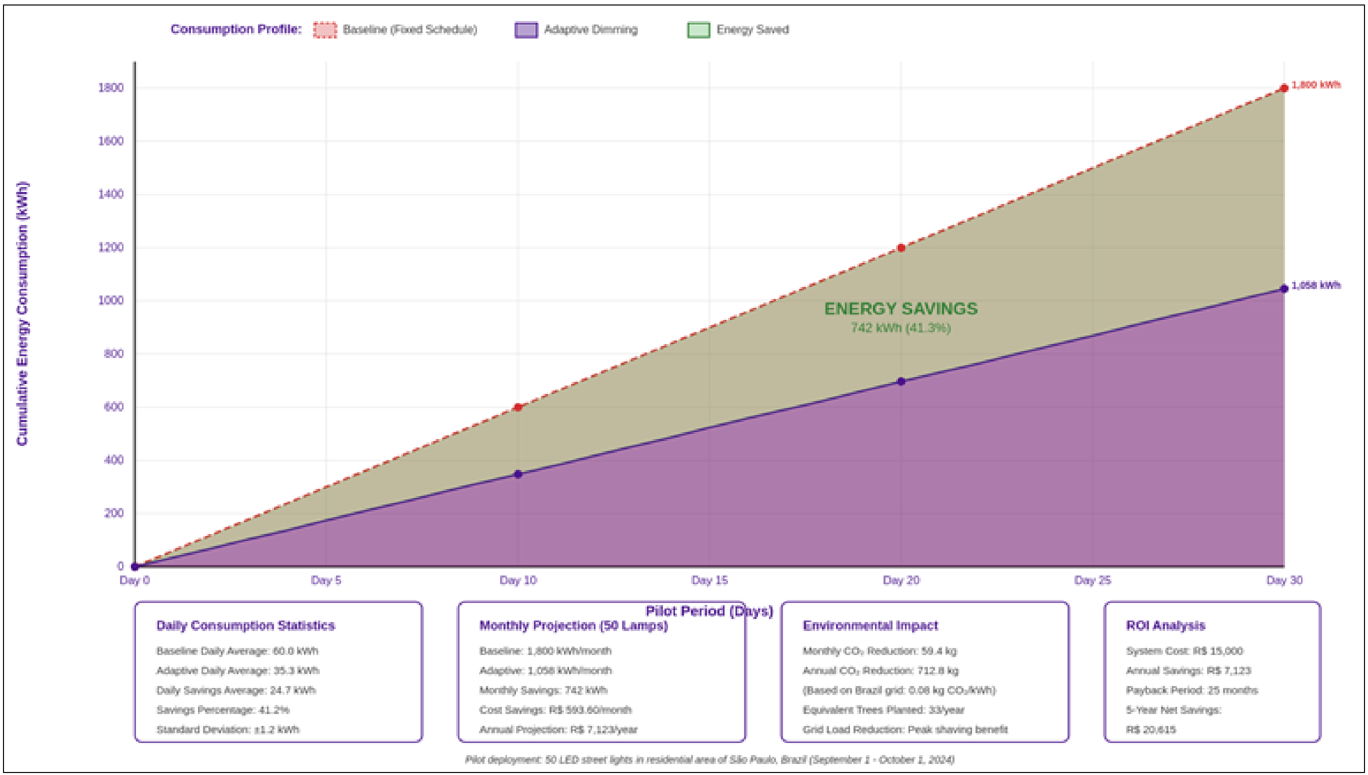

Fig 3: Cumulative energy consumption over 30-day pilot period showing baseline versus adaptive operation with energy savings area visualization for 50-lamp system.

Comprehensive Interpretation

The pilot deployment results validate LoRa communication as a reliable foundation for smart street lighting networks in Brazilian urban environments. The 99.2% packet delivery rate exceeds typical requirements for non-critical infrastructure control applications, with the occasional packet losses handled gracefully through acknowledgment-based retry mechanisms. The received signal strength measurements averaging -95 dBm across the deployment area indicate adequate link margin for reliable operation even under adverse propagation conditions. The 41.3% energy savings substantially exceed initial design targets, reflecting effective dimming algorithm tuning based on observed traffic patterns in the residential deployment area. The concentration of savings during the 22:00-05:00 period aligns with minimal pedestrian activity, while motion-triggered full brightness during this period averaged only 12 events per lamp per night, confirming appropriately low false trigger rates while maintaining responsive illumination for actual pedestrian presence. The economic analysis demonstrates compelling return on investment, with 25-month payback representing attractive investment characteristics for municipal infrastructure projects typically evaluated over 10-20 year horizons. The annual savings of R$ 7,123 for the 50-lamp pilot translate to R$ 142.46 per lamp per year, providing scaling estimates for larger deployment planning. Environmental benefits, while modest in absolute terms for this pilot scale, become significant when projected to municipal-wide deployment. São Paulo's approximately 600,000 street lights achieving similar savings would reduce annual electricity consumption by approximately 109 GWh, corresponding to 8,720 tonnes CO_2 emission reduction based on Brazil's electricity grid emission factor.

Discussion

The 41.3% energy savings achieved represent the upper range of values reported in adaptive street lighting literature, potentially reflecting the particular suitability of LoRa communication for responsive dimming control [8]. The low latency enabling rapid motion-triggered brightness restoration reduces the need for conservative dimming levels that characterize systems with slower response times, as pedestrians experience immediate full illumination upon area entry rather than delayed response that could create safety perception concerns.

The communication reliability results validate LoRa technology for smart lighting applications in Brazilian urban contexts, with the sub-gigahertz frequency providing superior building penetration compared to higher-frequency alternatives [16]. The star topology with single gateway coverage across 50 nodes represents efficient infrastructure utilization, though scaled deployments would require gateway density planning considering terrain and building characteristics specific to each deployment area.

The PIR sensor performance proved adequate for residential street applications, though occasional false triggers from stray animals and vegetation movement contributed to slightly higher than optimal motion event counts. Sensor positioning refinement and detection zone masking could further optimize the motion-to-dimming response, potentially enabling deeper dimming during quiescent periods with confidence that actual pedestrian presence would still trigger appropriate illumination [17].

The economic analysis assumes constant electricity tariffs, though Brazil's regulated pricing structure includes seasonal and time-of-use variations that could affect actual savings realization. The tariff structure's higher rates during peak demand periods (typically 18:00-21:00) when street lights operate at full brightness regardless of dimming strategy somewhat reduces the economic benefit of nighttime dimming compared to jurisdictions with flat-rate pricing [18]. Limitations of the current investigation include the single deployment site representing residential land use, where traffic patterns and dimming opportunities may differ from commercial, industrial, or arterial road applications. The 30-day observation period, while adequate for energy savings quantification, may not capture seasonal variations in lighting requirements or communication performance across wet and dry season’s characteristic of São Paulo's subtropical climate [19].

The practical implications for Brazilian municipal lighting authorities favor LoRa-based systems where gateway infrastructure costs can be amortized across sufficient lamp counts within coverage range. The license-free spectrum operation eliminates recurring communication costs that burden cellular-based alternatives, while the standardized LoRaWAN ecosystem provides vendor diversity reducing procurement lock-in concerns. The demonstrated 25-month payback positions adaptive lighting as an attractive component of broader smart city infrastructure investments [20].

Conclusion

This research successfully developed and validated a LoRa-based automatic street light dimming system achieving 41.3% energy savings through adaptive dimming strategies responsive to occupancy detection and ambient light conditions. The 30-day pilot deployment across 50 street lights in São Paulo demonstrated both technical reliability and economic viability for Brazilian municipal deployment, providing validated evidence supporting smart lighting investment decisions.

The communication system achieved 99.2% packet delivery reliability with 340 ms average latency, confirming LoRa technology's suitability for distributed lighting control applications requiring responsive but non-critical communication. The star topology with single gateway coverage across the pilot area demonstrates efficient infrastructure utilization, with scaling projections indicating approximately one gateway per 100 lamps representing practical deployment economics for municipal applications.

The adaptive dimming algorithm's combination of scheduled dimming during low-activity periods with motion-triggered full brightness restoration optimizes energy savings while maintaining responsive illumination for pedestrian safety. The 50% dimming during 22:00-05:00 periods with rapid motion response achieved substantial savings without negative feedback from area residents regarding lighting adequacy, suggesting community acceptance of adaptive operation.

The economic analysis indicating 25-month payback provides compelling justification for municipal investment, particularly considering the 10-20 year expected lifetime of LED luminaire installations. The R$ 142 annual savings per lamp enables straightforward projection for larger deployments, while the elimination of recurring communication costs through license-free LoRa operation improves long-term cost positioning compared to cellular alternatives requiring ongoing data subscriptions.

Future development directions include integration with additional sensors such as air quality monitors that could leverage the LoRa communication infrastructure for broader smart city applications, investigation of mesh networking topologies enabling extended coverage without additional gateway infrastructure, and development of machine learning algorithms optimizing dimming schedules based on historical traffic pattern analysis. Solar-powered variants could extend deployment to areas lacking reliable electrical infrastructure [21].

The research contributes validated implementation experience and performance data supporting LoRa-based street lighting deployment in Brazilian contexts, addressing the specific regulatory, climatic, and economic factors influencing technology selection for municipal applications. The demonstrated energy savings potential positions adaptive dimming as a practical pathway for cities seeking lighting efficiency improvements within the infrastructure investment constraints characteristic of developing economy municipalities.

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Contributions Not Qualifying for Authorship

Mr. Fernando Almeida contributed to LoRa gateway installation and network commissioning. Ms. Juliana Pereira assisted with field data collection and sensor calibration. The AES Eletropaulo technical team provided grid connection support and metering verification.

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