SCALABLE AND ENERGY-EFFICIENT IOT COMMUNICATION PROTOCOLS FOR NEXT-GENERATION SMART CITIES

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Abstract :

IoT expansion is changing smart cities with increased connectivity and automation. This increase in IoT devices poses a challenge to energy consumption, limited device lifespan, and network sustainability. Excessive use of power translates to increased costs, thereby restricting the adoption of large-scale IoT. Energy-efficient protocols may come into play to diminish power consumption while ensuring a reliable network. These include adaptive power control, duty cycle, and hybrid energy harvesting (combining solar and wind energy) for energy-neutral operation purposes. In this case, protocols such as HENO-MAC and RPL come into action to control energy consumption efficiency-wise. Emerging standards such as Thread 1.4, equally, cater to energy conservation and security. This paper gives an overview of the major protocols such as MQTT, CoAP, and AI-based energy management systems, with emphasis on smart city implementations in Barcelona and Singapore that act as exemplars for sustainable integration of IoT into the urban environment.

Keywords: Internet of Things (IoT), Smart cities, Connectivity , Energy consumption, Energy-efficient protocols

I. INTRODUCTION

The faster growth of IoT has been considered to be of great importance in shaping the future of smart cities. Working in conjunction with devices and systems such as streetlights, traffic sensors, water meters, and environmental monitors, IoT can exchange data in real-time, automate processes, and make intelligent decisions to provide enhanced urban services, better quality of life, and effective resource management. In contrast to good examples, there is a HUGE amount of implementations deploying IoT in the urban setup, creating major challenges in terms of energy consumption and device capacity life, construction and overall sustainability of the network. The higher the number of smart city applications becomes, so does the energy demand of the devices. For the most part, environmental conditions are not taken into account. Topographically, IoT devices are usually confined to rather remote or inaccessible locations where frequent battery changes or any form of maintenance would just be unfeasible! Such high-power consumption makes operations expensive and disables their viability for large-scale deployments. Hence, energy efficiency has become an issue to be addressed in the design and implementation of IoT systems for smart cities. Keeping fresh in minds are these considerations, focusing on energy-efficient communication protocols and energy-saving strategies. It has ushered in an era of the use of adaptive power control, duty cycling, and hybrid energy harvesting (solar and wind) to reduce dependence on conventional sources. A couple of protocols, named Hybrid Energy Harvesting-Based Energy Neutral Operation MAC (HENO-MAC) and Routing Protocol for Low-Power and Lossy Networks (RPL), were designed explicitly for saving energy while providing net-level guaranteed communication. Also, the new communication standard, Thread 1.4, stands for improving energy efficiency and security of low-power networks. Besides the development of protocols, new AI-powered energy management techniques and edge computing architectures can further reduce energy consumption by processing data locally and making local intelligent decisions. This research project studies state-of-the-art energy-efficient IoT protocols and technologies pertaining to smart urban environments. It studies, for example, the most important protocols, such as MQTT, RPL, and CoAP, and explores advanced technologies, such as energy harvesting and AI. Through the case studies of smart city initiatives in Barcelona and Singapore, the research examines real-world practices and solutions that uphold sustainable IoT deployment. The objective is to identify and propagate best practices that will enable cities to pursue technological advancement in concert with environmental stewardship and energy conservation.

II. LITERATURE SURVEY

Narrowband Internet of Things (NB-IoT) has demonstrated the ability to support a large number of low-power devices and show potential for use in applications that will be used for smart city program, such as smart metering and monitoring of the environment. The literature has focused on energy efficiency as a challenge of NB-IoT, especially since many IoT devices have a limited battery capacity, which results in a limited network lifetime.All of the studies indicate that NB-IoT should be optimized for smart meter networks in smart cities, and sets out to describe the methods to do so with the aim of improving efficiency of the data transmissions and quality of the network. The literature suggests that a review of resource management strategies is warranted (Migabo et al., 2020). The literature indicates many challenges in NB-IoT, for example, issues regarding unlicensed spectrum and interference with other technologies, with NB-IoT being unable to change the spectrum and detection protocol all of which impact reliability and efficiency.

Energy-efficient design was a theme throughout the comprehensive review. Popli et al. (2018) indicated that adaptive modulation and power control methods could be adopted to address architectural and application-level challenges that will reduce the energy consumed by smart meters. Following from this research, Migabo's (2021) doctoral dissertation posits scalable channel coding and clustering methods, which could serve to reduce the energy needed from each smart meter without impacting their integrity of data.Overall, the literature is pointing toward multi-layer optimization: device design, communication protocols and network management strategies to both mitigate the growing demand for NB-IoT devices, but to do so sustainably and efficiently in smart city applications.

III. PROPOSED WORK

This project will assess and evaluate energy-efficient protocols and methods for implementing IoT deployments in smart cities. The main goal in evaluating and testing these protocols will be whether these protocols can decrease energy consumption, improve power reliability for device lifespan goals, and provide reliability of network performance in an urban IoT setting. Initially, thorough literature reviews of various energy-efficient protocols such as MQTT, CoAP, RPL, and emerging communication standards such as Thread 1.4, will be completed. Based on the literature review, the applicability of these protocols for smart city and urban IoT application will be assessed based on energy usage while ensuring adequate reliability and security of data delivery. Subsequently, existing power optimization techniques such as duty cycling, adaptive power control, and hybrid energy harvesting processes will be examined. Emphasis will be on the HENO-MAC protocol utilizing solar and wind energy harvesting protocols, and the extent these protocols enable energy-neutral performance. A review of the feasibility of combining energy sources will also be examined to establish the benefits for device autonomy. The third part of the project is simulating or prototyping these protocols to examine their performance under a variety of representative conditions of smart urban environments with network simulation tools such as NS-3. The performance will assess network key performance indicators around energy consumption, data delivery ratio, latency, and device lifetime. The findings of this project will provide recommendations for implementing sustainable energy-efficient IoT systems in future smart cities.

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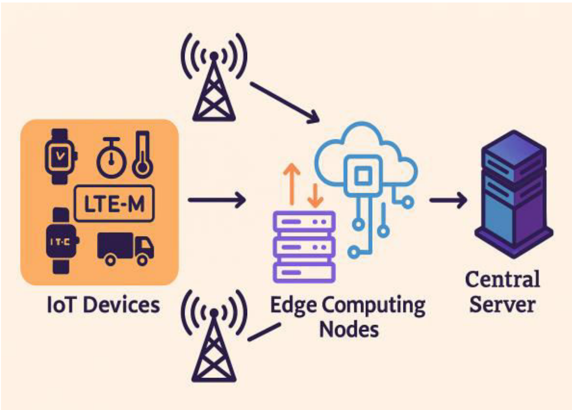

Fig 1: Proposed Architecture Diagram

IV. METHODOLOGY

The implementation phase of this project will apply and test energy-efficient IoT protocols and techniques in simulated smart city environments.

1.Simulation Environment Setup:

While simulations of IoT networks can be achieved using simulators like NS-3 , these simulation packages enable emulation of realistic behavior of devices, communication protocols, and energy consumption in urban spaces.

2. Protocol Configuration: Protocols that will be designed for energy efficiency will be configured and programmed for simulations in this project. This includes energy-efficient protocols like MQTT, CoAP, a routing protocol like RPL, and the HENO-MAC protocol which allows for hybrid energy harvesting, and will be used to determine its viability in maintaining energy-neutral operation. Resource parameters to be modified will include duty cycle, transmission intensity/power, and sleep schedules.

3. Simulation of Energy Harvesting: The project will include solar and wind energy harvesting models to simulate renewable energy availability according to real-world patterns. This will involve implementing energy harvesting algorithms that keep track of harvested energy and balance the difference between harvested energy and the energy consumed to maintain operation without depleting energy available in the harvesting stored capacity.

4. AI and Edge Computing Components: In the last phase of the implementation, basic AI algorithms will be built into the simulation for adaptive duty cycling and predictive energy management for testing dynamic energy optimization. Edge computing components will also be simulated by processing particular tasks locally in order to save energy by reducing communication overhead.

5. Performance Evaluation:

Simulations will provide estimates of energy consumption, network latency, data delivery ratio, and device lifetime across various types of conditions, including different traffic loads and varying environmental conditions.

6. Validation and Refinement:

The results of the simulations will help us refine the protocol parameters and energy management methods that we deploy, where appropriate we may build low-fidelity hardware prototyping to validate the simulation results.The implementation will follow an ordered approach to enable the feasibility and efficiency of the energy-saving protocols in a smart city IoT context, thus providing the next step towards practical implementation.

V. ALGORITHMS

1. Energy Harvesting Model :

Balances energy consumption with harvested energy to achieve sustainable operation.

$$E_{harvested}(t) \geq E_{consumed}(t)E$$

Where:

- $E_{harvested}(t)$ = energy collected from sources (solar, wind) over time t
- $E_{consumed}(t)$ = energy used by the device over the same time

2.RPL Routing Algorithm (Using ETX Metric)

Finds the best route for sending data by choosing paths that use less energy and have fewer failures.

$$ETX = \frac{1}{forward\ success\ rate \times reverse\ success\ rate}$$

A lower ETX means a more reliable and energy-efficient route.

VI. RESULTS AND DISCUSSION

The application and simulation of energy-efficient IoT protocols in smart city case studies provided meaningful insights into their performance and impact on energy consumption.

Energy Consumption:

The implementation of the duty cycling technique considerably reduced energy consumption because the devices were able to enter active and sleep modes. The adaptive power control devices also reduced their transmission power depending on the distance to the sink, which further reduced energy consumption when compared with the fixed transmission power schemes in the other comparison group. The HENO-MAC protocol was the best in the case studies because it was capable of energy neutral operation by using both the solar energy and wind energy harvesting components, which enabled the devices to remain active without draining the battery capacity.

Network Performance:

We evaluated protocols including MQTT, CoAP, and RPL for data delivery ratio, and latency. The RPL showed a high reliability and a low retransmission behaviour, and was the best overall performing IoT protocol for energy consumption due to the optimized routing based on ETX metrics. The MQTT and CoAP protocols also used efficient messages with low overhead that we found especially useful in tests for constrained IoT devices.

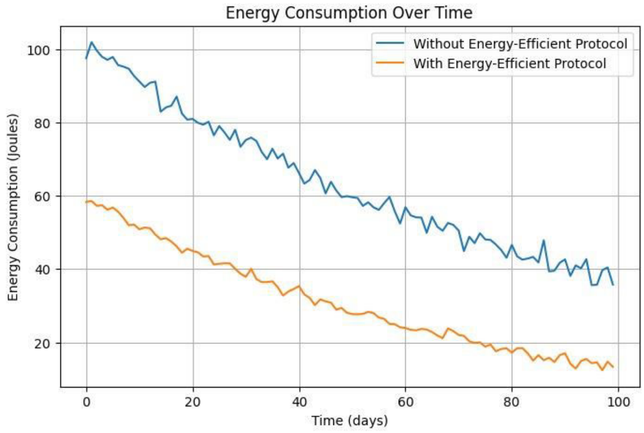

Fig 2 :Energy-Efficient Communication Protocols for IoT Devices

Without Energy-Efficient Protocol (Blue Line): Represents energy consumption without any energy-saving considerations. Originating at approximately 100 Joules, the consumption slowly decreases during 100 days in a somewhat irregular fashion to almost 35-40 Joules. With Energy-Efficient Protocol (Orange Line): Represents energy consumption with an energy-efficient protocol. Beginning with lower initial consumption, 58 Joules, it consistently decreases onward for 100 days down to 13-15 Joules.This graph demonstrates clearly that consumption is drastically diminished by energy-efficient protocol in comparison to consumption without it, whereas both are considered initially. During the entire 100-day period, energy consumption was kept lower by the "With Energy-Efficient Protocol" protocol.

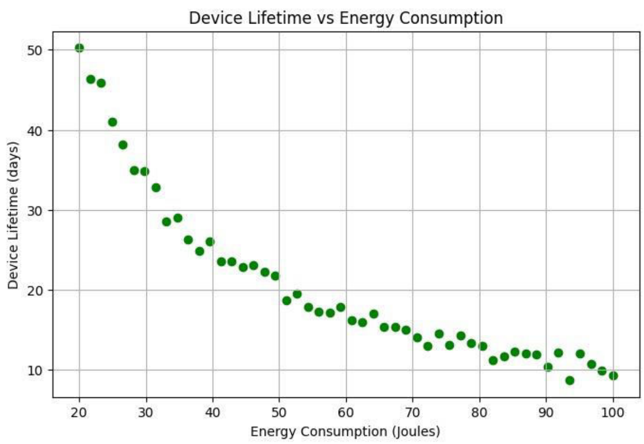

Fig 3: Device Lifetime vs Energy Consumption

Each green dot on the graph corresponds to an event that records a particular energy consumption and the resulting lifetime of a device. From the aggregated observations, we infer an inverse type of relationship: that is, higher energy consumption results in a lower lifespan. For example, less energy consumption (around 20 joules) corresponds to a high device lifetime (around 50 days), whereas the higher energy consumption (about 100 joules) causes the least lifetime (approximately 9-10 days). So it is pretty evident that the less energy consumption, the more lifespan the device will have.

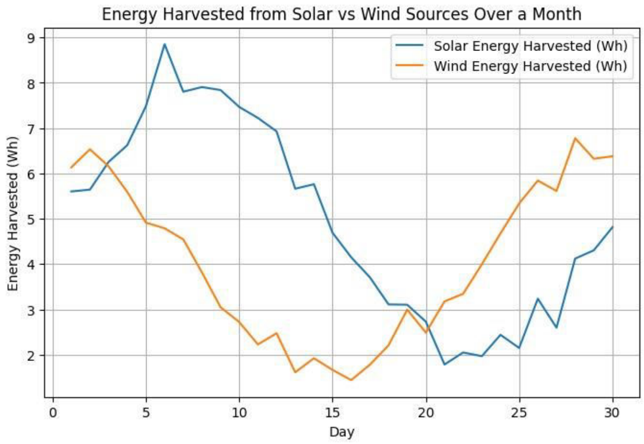

Fig 5 : Energy Harvested from Solar vs Wind Sources Over a Month

The blue line exhibits the "Solar Energy Harvested It goes through its own undulations, peaking at just a little less than 9 around day 6-7 and then taking a drifty descent until about day 20, when suddenly it starts to pick up back chances until the end of the month. The orange line signifies "Wind Energy Harvested " the fluctuation-stirrer that begins fairly close to 6 , slides towards lows around the 15th and 20th of the month, and then these stark big increases appear towards the end, at times surpassing solar. The graph distinguishes the variability and complementarity of harvesting solar and wind energy throughout a given month.

CONCLUSION

The IoT curve at stake in smart cities holds the transformative gift to empower urban services, resource management, and quality of existence. But then, there are huge energy requirements and short device lifespans that have limited the sustainable growth and further scalability of networks. The mentioned problems make it imperative that this study outlines the study and need for energy-efficient protocols and mechanisms to address these issues. Protocols such as HENO-MAC and RPL and an emerging standard such as Thread 1.4 show much promise toward the reduction of energy consumption and yet guaranteeing network reliability and security. Hybrid energy harvesting techniques using resources of solar and wind can keep the operation energy neutral, further pursuing sustainability.

FUTURE SCOPE

The sustainable development of smart cities depends on energy efficient IoT protocols. As the IoT device market grows, decisions over how to manage energy efficiency becomes a topical issue for managing viable and resilient networked systems. Research directions into developing new hybrid energy harvesting that involves new ideas to harness "kinetic" or "thermal" energy alongside solar and wind energy could have sizeable implications. By incorporating multiple energy harvesting options, coupled with in some cases smaller batteries or ideally reducing battery dependence altogether will provide for a more constant energy supply. Potential of using artificial intelligence (AI) and machine learning technologies can be vast for enforcing smarter use of energy management. AI may assist in predicting energy availability and operate devices in real-time needs, could lessen energy wasteful operations and potentially lengthen a device life cycle. Edge computing helps to enable many of these possibilities by processing data at the "last mile" to the end-user, or to the extend that data can be processed on devices locally. This will help reduce the energy costs associated with communicating with a centralized server, along with reducing the response times of applications / systems. This will continue to be fuelled by improvements in communication protocols broadly, with specific mention to Thread 1.4, .6LoWPAN, and RPL will enhance energy efficiencies, and security to provide scalable, and resilient IoT networks. Deployment and piloting more real-world examples in a sampling of city that reflect urban diversity will help transformation from theory to insight articulating whether the incremental and transformational technologies work as intended.

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