

Enhancing IoT networks' energy efficiency for sustainable smart cities: an emphasis on energy-efficient communication protocols

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Abstract—By increasing automation and connection, the Internet of Things' (IoT) explosive growth is propelling the creation of smart cities. However, issues with energy consumption, device longevity, and network sustainability are brought up by the growing number of IoT devices. High energy demands restrict large-scale deployments and raise costs. Energy-efficient protocols are crucial for maximizing power consumption while preserving network dependability in order to solve these problems. Adaptive power regulation, duty cycling, and hybrid energy harvesting are important tactics. Energy-neutral operations are supported via the Hybrid Energy Harvesting-Based Energy Neutral Operation Medium Access Control (HENO-MAC) protocol, which combines wind and solar energy.

Furthermore, sophisticated routing and Medium Access Control (MAC), Energy waste is reduced with the use of protocols like the Routing Protocol for Low-Power and Lossy Networks (RPL). New communication standards like Thread 1.4 improve security and energy efficiency even more. This study assesses cutting-edge energy-efficient IoT protocols in smart urban settings, examining technologies like Constrained Application Protocol (CoAP), RPL, and Message Queuing Telemetry Transport (MQTT). It also looks at edge computing, energy-harvesting IoT devices, and AI-driven energy management. The study outlines best practices for enhancing sustainability in IoT-driven cities through case studies from smart city initiatives in Singapore and Barcelona.

Keywords— Energy-efficient Internet of Things protocols, sustainable smart cities, and hybrid energy harvesting.

I. INTRODUCTION

The development of smart cities, which enhance urban life through connected devices and intelligent systems, has been made possible by the rapid expansion of the Internet of Things (IoT). However, there are substantial obstacles to the widespread

deployment of IoT devices, especially with regard to energy usage and sustainability. Global IoT power usage is estimated to approach 100 TWh annually, which significantly contributes to overall energy demand and raises concerns about long-term sustainability [1]. These networks' high energy requirements shorten device lifespans, increase operating costs, and obstruct sustainability attempts [2]. Developing and implementing energy-efficient protocols that maximize power consumption while maintaining network performance is necessary to address these issues. Current studies have highlighted the necessity of implementing energy-efficient ways to reduce the amount of power used by Internet of Things devices. For example, Refs. [3, 4] highlighted how duty cycling and adaptive power control might save energy costs in smart city infrastructures. Their research shows that using techniques such as Network Topology Optimization and Adaptive Power Control can result in notable reductions in energy consumption of 15% to 25%, thereby improving the sustainability of IoT deployments. Hybrid energy harvesting systems are another effective implementation. The Hybrid Energy Harvesting-Based Energy Neutral Operation Medium Access Control (HENO-MAC) protocol, which combines solar and wind energy sources to enable energy-neutral operations in delay-sensitive IoT scenarios, is introduced in Ref. [5].

By dynamically modifying device duty cycles in response to gathered energy availability, this system lessens dependency on traditional power sources and fosters sustainability.

It has also been determined that improving routing protocols is an essential tactic for reducing energy usage. Ref. [6] carried out a thorough analysis of energy-efficient routing protocols for Internet of Things networks, emphasizing techniques that maximize energy consumption and prolong network

lifetime. The significance of creating protocols that strike a balance between energy efficiency and the Quality of Service (QoS) needs of Internet of Things applications is underscored by their findings.

Improving energy efficiency requires incorporating sophisticated communication standards in addition to protocol improvements. Optimizing energy consumption for IoT devices in smart cities has been demonstrated by the use of LTE-M and Narrowband IoT (NB-IoT) technologies [7]. These technologies provide low-power, wide-area connection options that are ideal for Internet of Things applications that need dependable communication and long battery life.

To increase energy efficiency in IoT networks, artificial intelligence (AI)-driven strategies are also being investigated. In order to predict and optimize trends in energy use, Ref. [8] looks into AI-based approaches using machine learning methods like neural networks and reinforcement learning. The study shows significant improvements in energy consumption, which result in longer battery life, lower operating costs, and less of an influence on the environment.

In light of these difficulties and developments, this study attempts to measure how IoT energy usage affects sustainability and create performance standards for assessing energy-efficient IoT networks. In order to promote sustainability, boost energy efficiency, and guarantee the long-term operation of IoT-enabled urban systems, it will specifically evaluate cutting-edge protocols, such as hybrid energy harvesting techniques, optimized routing protocols, and AI-driven methodologies. To give a thorough assessment of sustainable IoT installations, performance indicators such as energy savings in joules per transmitted bit, increases in network lifetime, and decreases in power draw per device will be looked at.

II. LITERATURE REVIEW

The effective integration of IoT networks is critical to the rapid growth of smart cities, and energy efficiency is essential to attaining sustainability. Optimizing energy use while preserving reliable data transmission requires advanced communication protocols, especially the MQTT [9].

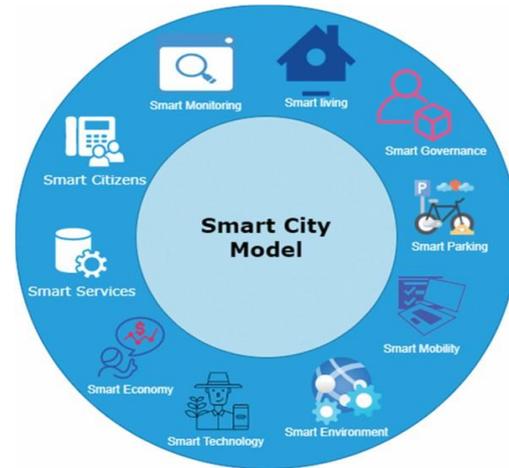


Figure 1. Features of a smart city.

MQTT operates on a lightweight publish-subscribe framework, which lessens the need for continuous data polling and lowers energy usage in IoT devices with constrained resources [10]. By enabling devices to transfer data only when necessary, this method saves electricity and increases network efficiency.

MQTT greatly reduces computational and bandwidth needs compared to traditional request-response protocols like HTTP, which makes it especially appropriate for battery-operated sensors in smart city contexts [11]. Research has shown that when compared to HTTP, MQTT can lower energy consumption by roughly 6% to 8%. In particular, tests utilizing the MQTT protocol with Quality of Service (QoS) levels 0 and 1 showed power reductions of 6.03% and 8.33%, respectively, as compared to HTTP, increasing the battery life of IoT devices [12]. According to a different study, MQTT uses significantly less power than HTTP, which highlights its usefulness for IoT applications with limited energy resources [13]. These results highlight MQTT's effectiveness in lowering energy consumption, which is essential for battery-powered sensors' durability and dependability in smart city deployments.

MQTT's QoS levels, which enable devices to strike a balance between dependability and energy consumption, are an important feature that supports energy efficiency [14]. IoT systems can improve data transmission in accordance with network conditions and particular application requirements by selecting an appropriate QoS level. Additionally, the lightweight design of MQTT reduces the processing load on devices, resulting in further energy savings [15].

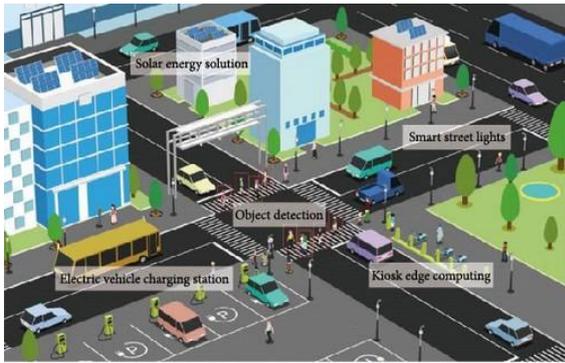


Figure 2. A sophisticated smart city scenario with conceptual levels of ICT infrastructure.

In large-scale smart city implementations, MQTT's support for edge Computing increases energy efficiency even more. By enabling local MQTT small, processing, and decision-making at edge devices minimizes the requirement for regular cloud communications, which consequently lowers electricity usage and improves network responsiveness.

Furthermore, the use of MQTT in public safety systems offers advantages including scalability, efficient data sharing, and real-time communication. For instance, during major occurrences, emergency services might improve public safety by utilizing the capacity to exchange information quickly and reliably [16].

2.2. ROUTING PROTOCOL FOR LOW-POWER AND LOSSY NETWORKS (RPL)

The Internet Engineering Task Force (IETF) standardized the RPL, a distance-vector-based routing protocol, for networks with high loss and low power, especially those using IPv6 technology [17]. In order to facilitate effective data routing and support customizable objective functions that optimize routing based on metrics like energy consumption, latency, link quality, and reliability, it builds a Destination Oriented Directed Acyclic Graph (DODAG) anchored at a sink node [15, 18, 19].

Despite its adaptability, RPL has a number of drawbacks that affect how well it works in IoT situations with limited resources.

There is a significant trade-off between routing overhead and energy efficiency. By minimizing control packet exchanges and choosing parent nodes based on residual energy and link quality, RPL is intended to be energy-efficient. However, routing

overhead is introduced by maintaining the DODAG structure, especially in large-scale networks where bandwidth and computational resources are consumed by regular topology updates and control messages like DODAG Information Object (DIO) and Destination Advertisement Object (DAO). Stability versus adaptability is another important trade-off. RPL has trouble managing mobility even though it is quite flexible and allows several routing algorithms for both static and dynamic contexts. RPL ensures stable pathways and optimal energy utilization in static networks, such as environmental monitoring systems. However, because RPL was not originally designed for highly mobile contexts, frequent topology changes in mobile settings result in route inconsistencies, higher packet loss, and performance degradation [20].

Furthermore, RPL's emphasis on low power consumption may result in higher latency. The protocol uses energy-saving techniques like trickle timers to cut down on pointless control transmissions. Limiting message propagation, however, causes network updates to be delayed, which can be troublesome for time-sensitive applications like real-time industrial monitoring. Numerous improvements have been suggested to overcome these issues. In mobile IoT environments, Backpressure RPL (BRPL) improves throughput and adaptability by introducing dynamic routing alterations based on network congestion [20]. Additional improvements concentrate on energy-aware RPL variations, which alter the parent selection procedure to balance node energy usage and increase network lifetime [19]. Furthermore, hybrid RPL strategies that combine machine learning and reinforcement learning techniques aid in the dynamic optimization of routing choices, lowering overhead while preserving network effectiveness.

2.3. CONSTRAINED APPLICATION PROTOCOL (COAP)

An application-layer protocol called CoAP was created especially to solve the communication issues that resource-constrained devices in Internet of Things contexts confront. These devices need an effective protocol that reduces overhead while preserving interoperability with web-based systems because they frequently have limited processing power, memory, and energy resources.

By offering a lightweight communication interface that is comparable to HTTP but tailored for limited devices and networks, CoAP satisfies the requirements [21, 22].

CoAP uses the User Datagram Protocol (UDP) rather than the Transmission Control Protocol (TCP) and uses a request/response mechanism. This option is especially appropriate for low-power and lossy networks since it drastically lowers communication overhead, increases energy economy, and minimizes delay [23]. In contrast to conventional protocols, CoAP facilitates asynchronous communication, enabling data exchange between IoT devices without the need for continuous connections. For battery-operated sensors and actuators that must run sporadically in order to save energy, this functionality is especially helpful. The smooth integration of CoAP with the Representational State Transfer (REST) architecture is another important benefit. This makes it possible for IoT applications to effectively communicate with web-based services, allowing cloud-based platforms and IoT networks to work together. [20] CoAP simplifies communication and data exchange across different IoT ecosystems by utilizing RESTful principles to allow devices to expose resources using uniform resource identifiers (URIs) and support methods like GET, POST, PUT, and DELETE.

Security is still a major problem despite its benefits, particularly in large-scale deployments where devices communicate across open and potentially susceptible networks. Datagram Transport Layer Security (DTLS), which offers encryption and authentication to safeguard data integrity and confidentiality, can be used to decrease hazards in CoAP. However, DTLS's overhead can be problematic for devices with very limited resources, which is why research into lightweight security methods specifically designed for CoAP-based systems is still ongoing [24].

Enhancing scalability, dependability, and adaptability to changing IoT frameworks are the main goals of recent CoAP developments. To maximize CoAP's performance in dynamic IoT contexts, researchers are investigating hybrid transport mechanisms, congestion control tactics, and enhanced resource discovery algorithms [25]. CoAP's function in facilitating effective, low-power communication will continue to be crucial in determining the future of interoperable and

sustainable IoT solutions as IoT applications spread across industries like smart cities, industrial automation, and healthcare.

2.4. CHALLENGES IN ENERGY EFFICIENCY FOR IOT IN SMART CITIES

Due to resource limitations and device heterogeneity, energy efficiency in smart city IoT networks is a major concern. Without appropriate protocols, wireless communication, a significant energy consumer, becomes inefficient in big installations [26]. This problem is lessened by methods like adaptive transmission power regulation and duty cycling.

As more devices raise the demands for processing and transmission, scalability has an additional effect on energy consumption. Interference from a high node density might worsen energy consumption [27]. Adaptive clustering methods, like LEACH and SEP, increase efficiency by reducing redundant transmissions and improving data aggregation [28].

Energy harvesting is also impacted by environmental conditions. Although solar and kinetic energy sources offer alternative electricity, their efficiency varies depending on the climate, necessitating the use of hybrid energy management techniques. [29]

Energy constraints are exacerbated by security. Authentication and encryption are essential, but they require computing power. Lightweight encryption techniques are appropriate for low-power Internet of Things devices because they strike a balance between security and energy consumption [30].

III. REAL-WORLD APPLICATIONS AND CASE STUDY

In practical smart city projects, the investigation of energy-efficient IoT protocols has acquired considerable momentum. The efficiency of these protocols in maximizing energy consumption, improving network performance, and fostering sustainability is demonstrated by a number of case studies. Nevertheless, these solutions also pose difficulties that provide insightful lessons for the deployment of smart cities in the future.

3.1. CASE STUDY: SMART CITY INITIATIVE IN BARCELONA

Barcelona has included IoT-driven smart solutions for rubbish collection, traffic control, and energy-

efficient street lighting. The city extends the lifespan of its sensors and reduces energy consumption by 30% by using LEACH-based clustering techniques in its sensor networks to improve data transmission efficiency. Over =C36 million in energy savings have been achieved annually thanks to the smart lighting system, which integrates LED lights with motion and environmental sensors [31].

Barcelona encountered difficulties expanding its IoT infrastructure in spite of these achievements. Strategic investments and policy changes were necessary due to the initial deployment costs and interoperability problems between new technology and legacy systems. Barcelona's lessons emphasize the need for modular IoT frameworks that may change to meet changing urban requirements.

3.2. CASE STUDY: SINGAPORE'S SMART NATION PROGRAM

RPL-based routing protocols are used by Singapore's Smart Nation initiative to increase the effectiveness of its traffic control and environmental monitoring systems. The city has cut energy costs by 35% while maintaining excellent data accuracy by putting adaptive power control tactics into practice. The motion-sensor-based smart street lighting system in Singapore has improved overall operating efficiency, decreased maintenance costs, and improved remote monitoring capabilities [32].

Cybersecurity concerns related to interconnected smart infrastructure were one of the main issues Singapore faced. The government implemented multi-tier authentication procedures and strong encryption requirements to allay these worries. This case study emphasizes how crucial it is to combine energy-efficient protocols with security measures in order to keep smart city networks resilient.

3.3. CASE STUDY: TSCH-BASED SMART FACTORY IN GERMANY

The Time-Slotted Channel Hopping (TSCH) protocol has been implemented in Germany's Industry 4.0 plants to improve communication reliability and save energy. By lowering retransmissions and interference, TSCH-based networks were able to generate up to 40% energy savings over traditional wireless systems, according to a comparative investigation [33]. Additionally, these networks have boosted productivity, decreased downtime, and enhanced real-time industrial process monitoring.

However, there were compatibility problems with older hardware when integrating TSCH into current industrial IoT systems.

Standardized industrial protocols and specialized firmware updates were necessary for retrofitting outdated equipment. This case study emphasizes the necessity of industry-wide cooperation to create IoT solutions that are scalable and energy-efficient.

IV. COMPARATIVE ANALYSIS OF IOT SOLUTIONS IN SMART CITIES: BARCELONA VS. SINGAPORE

IoT technologies are used by smart cities to increase energy efficiency, sustainability, and urban infrastructure.

Notable instances of these implementations may be found in Barcelona and Singapore, as the following comparisons demonstrate.

Table 1 shows how smart street lighting has been implemented in Singapore and Barcelona. These cities have advanced LED lighting systems with motion and environmental sensors. Significant energy savings result from these advances; Singapore achieves a 35% reduction and Barcelona a 30% reduction. Additionally, there are significant operational and financial benefits. Barcelona reports yearly savings of more than C36 million, and Singapore uses remote monitoring to improve maintenance effectiveness and extend the life of its equipment.

A comparison of several smart traffic management programs is provided in Table 2. The installation of smart parking sensors in Barcelona reduces traffic and emissions by enabling real-time updates on parking availability via mobile apps. In contrast, Singapore uses Electronic Road Pricing (ERP) and an Intelligent Transport System (ITS) that integrates real-time data to enable efficient traffic control and dynamic congestion pricing. IoT-driven technologies are effectively used by both cities to enhance urban mobility, reduce travel times, and their impact on the environment. Innovative waste management techniques in smart cities are highlighted in Table 3. Barcelona's Smart Waste Management System's sensor-enabled waste bins have reduced garbage truck trips by 20%, which lowers carbon emissions. Similar to this, Singapore's Pneumatic Waste Conveyance System reduces labor and operating costs while also having a smaller environmental

impact, improving waste collection efficiency. These tactics show how technology-based solutions can improve sustainability and efficiency in urban settings.

When it comes to incorporating IoT-driven energy-efficient technologies in smart cities, Barcelona and Singapore are benchmarks. Both cities have shown notable energy savings and operational efficiencies, while having different strategies—Barcelona concentrates on sensor-based improvements, while Singapore emphasizes automation and data analytics. Their experiences do, however, also draw attention to important issues like cybersecurity threats, infrastructure scalability, and initial adoption costs.

V. PROMOTING SECURE AND SUSTAINABLE SMART CITY INFRASTRUCTURE

5.1. AI-DRIVEN ENERGY MANAGEMENT

To improve efficiency, future smart cities should incorporate AI-driven optimization, such as adaptive routing algorithms and predictive analytics for electricity use. AI has been shown in smart grid case studies to reduce energy waste by up to 25% [34].

5.2. IOT for energy harvesting (EH-IOT)

Sustainability can be further enhanced by implementing self-sustaining sensors that run on solar, kinetic, or thermoelectric power. For example, solar-powered smart meters in the UK have decreased reliance on grid electricity by 40% [35].

5.3. SCALABLE POLICY FRAMEWORKS

In order to finance energy-efficient smart city initiatives, governments should establish uniform IoT regulations that promote cybersecurity and interoperability while promoting public-private collaborations [36].

5.4. ADDITIONAL STUDY ON BLOCKCHAIN SECURITY AND 6G

Future research should examine blockchain-based encryption methods and 6G-enabled IoT systems to improve security and effectiveness in extensive smart city deployments [36].

VI. NEW TECHNOLOGY AND TRENDS

Innovative solutions targeted at enhancing energy efficiency, dependability, and scalability in smart

urban environments have been developed as a result of the quick development of IoT networks. The incorporation of machine learning (ML) and artificial intelligence (AI) into IoT-driven energy management systems is one of the most significant developments. AI-driven optimizations greatly reduce power usage by enabling real-time changes in data transmission, device scheduling, and routing. In order to improve energy efficiency, Google's DeepMind AI, for example, has effectively improved energy usage in data centers, reducing cooling costs by 40%. This idea is currently being extended to IoT-based smart grids and building automation systems. Similar to this, AI-powered traffic management systems in places like Singapore dynamically modify traffic signals to reduce fuel use and congestion, which lowers overall energy waste [36].

Furthermore, instead of depending entirely on cloud computing, Edge and Fog Computing have become essential technologies that analyze data closer to IoT devices. This method makes IoT networks more sustainable by lowering latency, conserving bandwidth, and consuming less energy. AI-driven edge computing has enhanced real-time decision-making in predictive maintenance and optimized energy utilization in industrial machinery in applications such as smart manufacturing.

Energy-harvesting IoT (EH-IoT), which uses renewable energy sources to power sensors and devices, is also gaining traction.

Smart agriculture makes extensive use of solar-powered environmental monitoring sensors, which gather and transmit data on weather and soil moisture without the need for regular battery changes. Similar to this, wearables that run on kinetic energy, like self-charging fitness trackers, use motion to create electricity. Thermoelectric-powered sensors are perfect for remote monitoring in high-temperature conditions because they transform waste heat into useful energy.

IoT connectivity is being further improved by advancements in Ultra-Low Power (ULP) wireless communication and 6G networks. Energy usage is being drastically reduced while maintaining dependable connection thanks to technologies like Reconfigurable Intelligent Surfaces (RIS), which optimize signal propagation, and Backscatter connection, which allows Internet of Things devices to transfer data utilizing ambient radio waves.

VII. CONCLUSION AND RECOMMENDATION

Improving IoT networks' energy efficiency is essential for the sustainability of smart cities. By enhancing medium access control and minimizing idle listening, HENO-MAC extends the lifespan of IoT devices and delivers up to 40% energy savings. While cross-layer techniques increase efficiency by reducing duplicate transmissions, other protocols like LEACH, RPL, and CoAP aid in power optimization. Scalability, security, and network diversity are still major obstacles, though. The suggestions are:

1. Smart Energy Management: Nigerian towns should implement adaptive street lighting and IoT-enabled smart grids, which can reduce energy consumption by 50% [37]. While energy-harvesting smart meters reduce maintenance requirements, AI-driven analytics can further enhance electricity distribution.
2. IoT-Based Traffic Solutions: A 25% reduction in traffic and fuel consumption is possible with IoT-driven traffic management. In places like Lagos and Abuja, smart signaling and predictive maintenance in linked car systems can reduce emissions and increase mobility [38].
3. Waste Management Optimization: By optimizing pickup schedules, sensor-equipped trash cans and automated collection systems can save operating costs by thirty percent. Following successful methods from Singapore and Barcelona, AI-driven analytics can further improve recycling efficiency [39].
4. Renewable Energy & Energy Harvesting: IoT infrastructure in Nigerian cities can be supported by solar, wind, and kinetic energy. Hybrid energy-harvesting sensors improve air quality monitoring and urban sustainability by ensuring dependable operation in variable situations [40].
5. Improving Public Safety: Through real-time anomaly detection, AI-powered IoT surveillance improves security.

Large-scale IoT networks can be safeguarded while preserving energy efficiency using blockchain and lightweight encryption, such as ECC-based cryptography [41].

VIII. DIFFICULTIES AND FUTURE PATHS

The difficulties of managing power usage while maintaining performance and security have not been resolved by developments in energy-efficient IoT protocols. Scalability is a major challenge as IoT

networks continue to grow in size and complexity. Managing energy-efficient communication between a large number of linked devices is still a critical issue.

Furthermore, privacy and security concerns pose significant challenges. The goal of many energy-efficient methods is to reduce computational demands, which may unintentionally make a system more vulnerable to cyberattacks. To improve security without using large amounts of energy, future improvements might incorporate blockchain-based security frameworks and lightweight encryption.

Network heterogeneity, which is defined by the cohabitation of many IoT devices with varying power capacity and communication protocols, is another significant difficulty. Implementing adaptive and AI-driven network management techniques is necessary to achieve smooth interoperability while guaranteeing energy savings.

Future research is anticipated to focus on self-sustaining energy solutions, such as ultra-low-power wireless communication technologies and energy-harvesting Internet of Things devices. Additionally, edge computing and AI-driven predictive analytics will be crucial for dynamically optimizing energy use.

It is projected that the development of 6G-enabled IoT networks would enhance energy-efficient communication even further, supporting the resilience and sustainability of smart cities.

DATA AVAILABILITY

Other than the submitted manuscript file, we don't have any study data.

REFERENCES

- [1] H. I. Khalil, N. Z. Jhanjhi, M. Humayun, S. Sivanesan, M. Masud & M. S. Hossain, "Hybrid smart grid with sustainable energy efficient resources for smart cities", *Sustain. Energy Technol. Assess.* 46 (2021) 101211. <https://doi.org/10.1016/j.seta.2021.101211>.
- [2] L. Atzori, A. Iera & G. Morabito, "The internet of things: a survey", *Comput. Netw.* 54(2010)2787. <https://doi.org/10.1016/j.comnet.2010.05.010>.
- [3] R. Al-Ali, "Internet of things role in the renewable energy resources", *Energy Procedia* 100 (2016) 34. <https://doi.org/10.1016/j.egypro.2016.10.144>.

- [4] A. Yassine, S. Singh, M. S. Hossain & G. Muhammad, "IoT big data analytics for smart homes with fog and cloud computing", *Future Generation Computer Systems* 91 (2019)563. <https://doi.org/10.1016/j.future.2018.08.040>.
- [5] L. Zhang & P. Lin, "Reinforcement learning based energy-neutral operation for hybrid EH powered TBAN", *Future Generation Computer Systems* 140 (2023) 311. <https://doi.org/10.1016/j.future.2022.10.037>.
- [6] R. Yadav & V. Kumar, "A systematic review paper on energy-efficient routing protocols in internet of things", *IETE J. Res.* 70 (2023) 4721. <https://doi.org/10.1080/03772063.2023.2230169>.
- [7] D. Hemanand, C. A. Bhuvanewari, S. Savitha, M. Jothi & R. R. Senthil, "Optimizing energy-efficient communication protocols for IoT devices in smart cities using Narrowband IoT and LTE-M technology", *J. Electr. Syst.* 20 (2024) 2149. <https://doi.org/10.52783/jes.2560>.
- [8] A. M. Abbas, K. Y. Youssef, I. I. Mahmoud & A. Zekry, "NB-IoT optimization for smart meters networks of smart cities: Case study", *Alexandria Engineering Journal* 59 (2020) 4267. <https://doi.org/10.1016/j.aej.2020.07.030>.
- [9] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari & M. Ayyash, "Internet of things: a survey on enabling technologies, protocols, and applications", *IEEE Communications Surveys & Tutorials* 24 (2022) 234. <https://doi.org/10.1109/comst.2015.2444095>.
- [10] H. M. B. Hassan, E. S. Ali, R. A. Mokhtar, R. A. Saeed & B. S. Chaudhari, "6 - NB-IoT: concepts, applications, and deployment challenges", in *LPWAN Technologies for IoT and M2M Applications*, Academic Press, 2020, pp. 119-144. <https://doi.org/10.1016/B978-0-12-818880-4.00006-5>.
- [11] C. Bormann, A. P. Castellani & Z. Shelby, "CoAP: an application protocol for billions of tiny internet nodes", *IEEE Internet Computing* 16 (2012) 62. <https://doi.org/10.1109/MIC.2012.29>.
- [12] F. S. Hafez, B. Sa'di, M. Safa-Gamal, Y. H. Taufiq-Yap, M. Alrifayy, M. Seyedmahmoudian, A. Stojcevski, B. Horan & S. Mekhilef, "Energy efficiency in sustainable buildings: a systematic review with taxonomy, challenges, motivations, methodological aspects, recommendations, and pathways for future research", *Energy Strategy Reviews* 45 (2023) 101013. <https://doi.org/10.1016/j.esr.2022.101013>.
- [13] T. Qiu, J. Chi, X. Zhou, Z. Ning, M. Atiquzzaman & D. O. Wu, "Edge computing in industrial internet of things: architecture, advances and challenges", *IEEE Communications Surveys & Tutorials* 22 (2020) 2462. <https://doi.org/10.1109/COMST.2020.3009103>.
- [14] K. Zhang, Y. Mao, S. Leng, Q. Zhao, L. Li, X. Peng, L. Pan, S. Maharjan & Y. Zhang, "Energy-efficient offloading for mobile edge computing in 5g heterogeneous networks", *IEEE Access* 4 (2016) 5896. <https://doi.org/10.1109/ACCESS.2016.2597169>.
- [15] B. Wang, F. Tao, X. Fang, C. Liu, Y. Liu & T. Freiheit, "Smart manufacturing and intelligent manufacturing: a comparative review", *Engineering* 7 (2021) 738. <https://doi.org/10.1016/j.eng.2020.07.017>.
- [16] C. Zoghalmi, R. Kacimi & R. Dhaou, "5G-enabled V2X communications for vulnerable road users safety applications: a review", *Wireless Netw* 29 (2023) 1237. <https://doi.org/10.1007/s11276-022-03191-7>.
- [17] Z. Shah, A. Levula, K. Khurshid, J. Ahmed, I. Ullah & S. Singh, "Routing protocols for mobile internet of things (IoT): a survey on challenges and solutions", *Electronics* 10 (2021) 2320. <https://doi.org/10.3390/electronics10192320>.
- [18] S. Popli, R. K. Jha & S. Jain, "A survey on energy efficient narrowband internet of things (NB-IoT): architecture, application and challenges", *IEEE Access* 7 (2019) 16739. <https://doi.org/10.1109/ACCESS.2018.2881533>.
- [19] A. E. Hassani, A. Sahel & A. Badri, "IRH-OF: a new objective function for rpl routing protocol in IoT applications", *Wireless Pers Commun* 119 (2021) 673. <https://doi.org/10.1007/s11277-021-08230-8>.
- [20] S. Duquennoy, B. Al Nahas, O. Landsiedel & T. Watteyne, "Orchestra: robust mesh networks through autonomously scheduled TSCH", *Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems (SenSys '15)*, Association for Computing Machinery 13 (2015) 337. <https://doi.org/10.1145/2809695.2809714>.
- [21] Z. H. Ali, N. A. Sakr, N. El-Rashidy & H. A. Ali, "A reliable position-based routing scheme for controlling excessive data dissemination in vehicular ad-hoc networks", *Computer Networks* 229 (2023) 109785. <https://doi.org/10.1016/j.comnet.2023.109785>.
- [22] M. Baniata, H. T. Reda, N. Chilamkurti & A. Abuadbbba, "Energy-efficient hybrid routing

- protocol for IoT communication systems in 5G and beyond”, *Sensors* 21 (2021) 537. <https://doi.org/10.3390/s21020537>.
- [23] J. V. V. Sobral, J. J. P. C. Rodrigues, R. A. L. Rabêlo, J. Al-Muhtadi & V. Korotaev, “Routing protocols for low power and lossy networks in Internet of Things applications”, *Sensors* 19 (2019) 2144. <https://doi.org/10.3390/s19092144>.
- [24] N. Makarem, W. B. Diab, I. Mougharbel & N. Malouch, “On the design of efficient congestion control for the Constrained Application Protocol in IoT”, *Computer Networks* 207 (2022) 108824. <https://doi.org/10.1016/j.comnet.2022.108824>.
- [25] L. Huang & Q. Yu, “Mobility-aware and energy-efficient offloading for mobile edge computing in cellular networks”, *Ad Hoc Networks* 158 (2024) 103472. <https://doi.org/10.1016/j.adhoc.2024.103472>.
- [26] M. Alonso, H. Amaris, D. Alcalá & D. M. Florez R., “Smart sensors for smart grid reliability”, *Sensors* 20 (2020) 2187. <https://doi.org/10.3390/s20082187>.
- [27] M. Humayun, M. S. Alsaqer & N. Jhanjhi, “Energy optimization for smart cities using IoT”, *Applied Artificial Intelligence* 36 (2022) 2037255. <https://doi.org/10.1080/08839514.2022.2037255>.
- [28] K. H. Bachanek, B. Tundys, T. Wiśniewski, E. Puzio & A. Maroušková, “Intelligent street lighting in a smart city concepts—a direction to energy saving in cities: an overview and case study”, *Energies* 14 (2021) 3018. <https://doi.org/10.3390/en14113018>.
- [29] S. Alzahrani, A. Salh, L. Audah, M. A. Alhartomi, A. Alotaibi & R. Alsulami, “Empowering energy-sustainable IoT devices with harvest energy optimized deep neural networks”, *IEEE Access* 12 (2024) 70600. <https://doi.org/10.1109/ACCESS.2024.3399563>.
- [30] K. Shafique, B. A. Khawaja, F. Sabir, S. Qazi & M. Mustaqim, “Internet of things (IoT) for next-generation smart systems: a review of current challenges, future trends and prospects for emerging 5G-IoT scenarios”, *IEEE Access* 8 (2020) 23022. <https://doi.org/10.1109/ACCESS.2020.2970118>.
- [31] A. Tabouche, B. Djamaa & M. R. Senouci, “Traffic-aware reliable scheduling in TSCH networks for Industry 4.0: A systematic mapping review”, *IEEE Commun. Surv. Tutor.* 25 (2023) 2834. <https://doi.org/10.1109/COMST.2023.3302157>.
- [32] S. Rekik, N. Baccour, M. Jmaiel, K. Drira, L. A. Grieco, “Autonomous and traffic-aware scheduling for TSCH networks”, *Computer Networks* 135 (2018) 201. <https://doi.org/10.1016/j.comnet.2018.02.023>.
- [33] Q. V. Khanh, V. H. Nguyen, Q. N. Minh, A. D. Van, N. L. Anh & A. Chehri, “An efficient edge computing management mechanism for sustainable smart cities”, *Sustain. Comput. Inform. Syst.* 38 (2023) 100867. <https://doi.org/10.1016/j.suscom.2023.100867>.
- [34] I. Aqeel, “Enhancing security and energy efficiency in wireless sensor networks for IoT applications”, *Journal of Electrical Systems* 20 (2024) 807. <https://doi.org/10.52783/jes.1378>.
- [35] S. Hudda, K. Haribabu & R. Barnwal, “Energy efficient data communication for WSN based resource constrained IoT devices”, *Internet of Things* 27 (2024) 101329. <https://doi.org/10.1016/j.iot.2024.101329>.
- [36] P. S. Bangare & K. P. Patil, “Enhancing MQTT security for internet of things: Lightweight two-way authorization and authentication with advanced security measures”, *Measurement: Sensors* 33 (2024) 101212. <https://doi.org/10.1016/j.measen.2024.101212>.
- [37] O. O. Ogundile, M. B. Balogun, O. E. Ijiga & E. O. Falayi, “Energybalanced and energy-efficient clustering routing protocol for wireless sensor networks”, *IET Commun.* 13 (2019) 1419. <https://doi.org/10.1049/iet-com.2018.6163>.
- [38] M. Whaiduzzaman, A. Barros, M. Chanda, S. Barman, T. Sultana, M. S. Rahman, S. Roy & C. Fidge, “A review of emerging technologies for IoT-based smart cities”, *Sensors* 22 (2022) 9271. <https://doi.org/10.3390/s22239271>.
- [39] A. R. Javed, F. Shahzad, S. ur Rehman, Y. B. Zikria, I. Razzak, Z. Jalil & G. Xu, “Future smart cities: requirements, emerging technologies, applications, challenges, and future aspects”, *Cities* 129 (2022) 103794. <https://doi.org/10.1016/j.cities.2022.103794>.
- [40] S. Rabah, A. Zaier, J. Lloret & H. Dahman, “Efficiency enhancement of a hybrid sustainable energy harvesting system using HHHOPSO-MPPT for IoT devices”, *Sustainability* 15 (2023) 10252. <https://doi.org/10.3390/su151310252>.
- [41] X. Yu, X. Yang, Q. Tan, C. Shan & Z. Lv, “An edge computing based anomaly detection method in IoT industrial sustainability”, *Appl. Soft Comput.* 128 (2022) 109486. <https://doi.org/10.1016/j.asoc.2022.109486>.