Journal of Applied Research and Technology

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ICAT
Instituto de Ciencias Aplicadas y Tecnología

Journal of Applied Research and Technology 24 (2026) 541-552

Original

Development of an Ultra-Low Energy Communication Protocol for 6G Networks: Integration with IoT and Wearable Technologies

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Received: 04 06 2025; Accepted: 28 09 2025
Available: 31 08 2026

Abstract: This paper develops and evaluates an ultra-low-energy communication protocol for 6G integration with IoT and wearable devices. The protocol combines energy harvesting support, lightweight data compression, and adaptive duty cycling to minimize radio on-time while preserving throughput and reliability. Experiments in a smart-city IoT testbed (1,000 nodes) and a wearable health-monitoring scenario (500 devices) show a 33.46% reduction in energy consumption versus a baseline 5G protocol and an increase in wearable battery life from 6.97 to 10.00 days. Average latency rises from 7.99 to 13.25 ms but remains below the 20 ms target for most IoT services, and reliability stays high (95.11%). These results indicate that ultra-low-energy protocols are feasible enablers for sustainable, scalable 6G IoT and wearable deployments.

Keywords: **6G networks, IoT, wearable devices, ultra-low energy protocol, energy harvesting, adaptive duty cycling**

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Peer Review under the responsibility of Universidad Nacional Autónoma de México.

1. Introduction

It has been observed that evolved communication networks have acted as the primary driving force for technological advancements, and the later the generation, the more exponential improvements the networks will possess in terms of speed, capacity, and connectivity. In this regard, the development of the sixth-generation network will revolutionize industries, economies, and societies by enabling ultra-high data rates, very low latency, and complete connectivity for billions of devices. Since 6G will target the needs of a hyper-connected world, it is bound to support different applications ranging from immersive AR to IoT and wearable devices. These technologies, in turn, call for a communication protocol that should be efficient not only in data transmission but also in optimizing energy consumption.

Ultra-low-energy communication protocols will be key to integration into 6G, especially within the growing sectors of IoT devices and wearable technologies, which depend on efficiency in energy usage to be operational. The most critical challenge facing contemporary telecommunications today, especially in the context of IoT and wearable devices, has been that of energy consumption. Most IoT systems, which include sensors, actuators, and processing units, have to operate in environments that mostly have limited or no power supply. Wearable devices, because of the requirement for light weight and wearability, are constrained by small-sized batteries, thus mandating energy-efficient communication protocols to ensure long functionality. Energy consumption therefore becomes the most important factor affecting device longevity, performance, and user experience in both cases. While 5G has only partially resolved these issues, it is expected that 6G will provide new solutions toward further optimizations of energy efficiency (Salameh & El Tarhuni, 2022).

The introduction of 6G brings an exciting opportunity to innovate communication protocols for energy-constrained devices. In 2030, it is estimated that billions of IoT devices will be connected globally, and a large part of them will rely on 6G networks for data transfer. These devices shall all interoperate efficiently, from smart home appliances to industrial sensors, without putting an additional burden on their limited energy resources. Similarly, wearable devices that have wide applicability in health care, fitness, and entertainment will also gain significantly from the capability of low latency, high speed, and energy efficiency offered by 6G. These benefits can only be realized if there is a specially designed ultra-low energy communication protocol for such devices' peculiar requirements. Existing protocols, such as those that have been in use in both 4G and 5G network communications, are still not suitable for energy-constrained environments. Most of these protocols target the improvement of data speed and bandwidth at the cost of energy efficiency, which then turns into an unnecessarily high power consumption rate in these low-energy-reserve devices. Besides, the complexity of the protocols further contributes to unnecessary energy expenditure in data transmission and processing. This is particularly a problem for IoT and wearable devices since these should operate for extended periods without frequent recharging. What is required is a more sustainable solution that keeps in view the high-performance requirements for 6G networks and energy constraints for IoT and wearables (Chowdhury et al., 2020).

The goal of the study was to develop an extremely low-power information transfer protocol for 6G networks only, integrated with IoT and wearable devices. The proposed communication protocol will use various techniques, namely energy harvesting, data compression, and dynamic resource allocation, to reduce energy losses without compromising the communication quality. It would allow IoT and wearables to run longer and more efficiently by minimizing the energy overhead caused by data transmission and processing. This is extremely important for applications such as remote healthcare monitoring, environmental sensing, and real-time analytics.

Additionally, the ultra-low power protocols that will be integrated into the 6G network will have broad implications for industries that rely on IoT and wearable technologies. In smart cities, for example, energy-efficient communication protocols will mean the advanced deployment of large sensor networks that monitor air quality, traffic flow, and energy usage. The work proposes to apply wearable devices in health with low-energy communication protocols, enabling unobtrusive continuous health monitoring with real-time feedback and intervention without frequent battery replacement or recharging. Work will be added in the area of sustainable and energy-efficient communication technology in line with a fully connected 6G-powered future (Guo et al., 2021)

Difficulties associated with Energy Efficiency

Energy efficiency has remained one of the prominent factors in wireless communication. Energy consumption is very often considered secondary in comparison to performance metrics like bandwidth and latency. Traditional communication protocols, targeted at high-speed data transmission and connection on a large scale, tend to give precedence to such performance metrics over energy consumption (Liu et al., 2015). For energy-constrained devices, such as IoT sensors or wearable gadgets, this will remain unsustainable since their design should consider an efficient power consumption profile coupled with continuous, reliable communication. IoT devices need to operate autonomously for a longer period, sometimes for years, with limited energy resources such as batteries or energy-harvesting systems. On the other hand, wearable devices would require effectively handling the energy consumption in order to enable seamless services such as health monitoring, location tracking, and fitness analytics. The existing communication protocols in 5G networks have made notable progress toward energy efficiency improvement. Dynamic resource allocation techniques, sleep mode functions, and energy-aware scheduling have been proposed in order to reduce energy consumption. However, they cannot meet the ultra-low energy communication needs of 6G environments for IoT and wearable technologies. While connected devices keep growing in number, the total energy consumption of the network keeps growing as well; therefore, it is crucial to create new protocols focused especially on energy efficiency for 6G applications (Dang et al., 2020).

6G is expected to be transformative for wearable technologies and IoT through the provision of infrastructural needs: massive machine-type communications, and ultra-reliable low-latency communications. The billions of devices are forecasted to form part of the IoT ecosystem. Furthermore, the low latency in 6G will improve the wearable device's capability to process data in real time, which will expand the horizon toward applications such as remote patient monitoring, real-time fitness feedback, and continuous health diagnostics (Omkar et al., 2024).

Full integration of IoT and wearable technology with all capabilities in the 6G era requires overcoming the energy limitations of the devices. The state-of-the-art 6G research goes in the direction of studying different techniques that are power-saving, for example: energy harvesting, low-power communication modules, and adaptive protocols, which adaptively adjust power consumption depending on the conditions of the network and data transmission requirements. AI and ML will further enable intelligent energy management, wherein devices can predict and optimize their own energy usage based on their patterns and environmental factors within the 6G network.

Ultra-Low Energy Communication Protocol Needs

IoT and wearable devices' application requirements are very unique. In any case, ultra-low energy communication protocols will be needed. Such protocols, in turn, have to be framed in a way that the energy constraints of the device are satisfied while ensuring seamless connectivity and data transmission in a 6G network environment (Dao, 2023). The development of an ultra-low energy communication protocol for 6G networks would help extend the battery life not only of IoT and wearable devices but also contribute toward a more sustainable and energy-efficient communication network.

The Communication Protocols in Current 5G Networks

Communication protocols in the context of 5G networks are one of the main pillars in data interchange between devices and the extended network. This protocol dictates how data will be transmitted, received, and processed so that communication will work efficiently and reliably (Tahir et al., 2020). Among these, in the top layers of 5G, the protocols used are: New Radio for both high-speed and low-latency communications and Non-Standalone, for gradually deploying 5G using existing 4G infrastructure. These protocols have been designed in such a way that they provide maximum throughput, minimum latency, and accommodation of a huge number of devices. With the growth of IoT devices and wearable technologies, 5G networks are increasingly expected to provide services that will drive up energy efficiency challenges cited by (Shafique et al., 2020).

Several methods to reduce energy, therefore, have been developed and applied at different levels to the devices with low-power resources in 5G network architecture. This may involve dynamic resource allocation that may cater to network resources, assuming real-time demand; Li et al. (2020) thus asserted that bandwidth and computational resources should only be allocated when in demand in order to reduce unnecessary use of energy. Another viable approach towards 5G lies in power-saving strategies through sleep mode mechanisms to reduce energy consumption during periods of inactivity. This is made possible by the realization of mechanisms that put devices to "sleep" when not in active transmission or reception of data, only waking up when there is a need for communication. This technique is very effective for IoT and wearable devices since they operate for most of their time in low-power mode applications. Referring to (Shurdi et al., 2021)

Energy-aware scheduling algorithms are another energy-saving technique in 5G. These algorithms work in such a way that they perform prioritization of tasks to be executed, while energy consumption is minimal and network performance is retained as much as possible. For instance, 5G could execute tasks intelligently when the demand for energy is low, or transmit data less frequently than needed. Such approaches provide better energy efficiency for 5G (López-Pérez et al., 2022). These are augmented by sophisticated power management technologies where devices can adjust their power consumption depending on the kind of service in use to further economize energy use. These, however, are undermined by the 5G protocols as they are still not comprehensive enough to handle the exacting energy needs of IoT devices and wearable devices despite these advancements. The protocols are very often designed while compromising energy conservation for prioritization of high-speed data transmission and low latency; hence, these protocols cannot work efficiently in devices operating under energy constraint conditions. Besides, most existing energy-efficient methods of 5G are not optimized for the low-power, intermittent style of communication—an intrinsic characteristic of IoT devices and wearables. While sleep modes, for instance, can enable energy economy, wake-up and re-establishment of network connections may require high power, therefore negating some economies in energy use. For example, in (Srivastava et al., 2020), a number of energy-saving techniques are identified that are available for saving energy consumption in electronic devices. Techniques like sleep mode may have excess power use while transitioning into or out of the states.

Secondly, 5G's high data rates and inherent protocols make the chances of increased energy usage, especially by small, low-powered wearable devices, much higher. Most of these devices have limited battery capacity and cannot afford the continuous processing and transmission of data that 5G networks are optimized for. Hence, IoT devices and wearables often have to fall back to simpler, lower-power communication protocols such as Low Power Wide Area Networks, more in tune with their energy constraints yet lacking some advanced capabilities that are possible with 5G.

Energy Efficiency Requirements of IoT and Wearable Devices

The rapid proliferation of IoT devices and wearable technologies has created new challenges, especially in power efficiency. Usually, IoT devices are deployed in large numbers, and their operation is often expected

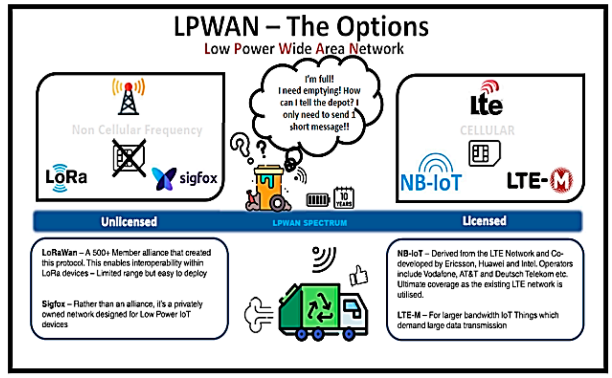

Figure 1. Energy-saving mechanisms in baseline 5G protocols for IoT and wearable connectivity.

to be autonomous for a long period. Thus, according to (Nižetić et al., 2020), it faces a big challenge in energy consumption. Most of these devices operate in environments where steady-state power is not available. Thus, devices rely on batteries or energy harvesting methods for their power needs. The primary problem to be solved here is the balancing act between the requirement of real-time data transmission, processing, and communication with available energy resources. This had made energy efficiency a critical design consideration for many of these IoT devices operating for years without human intervention on end-node sensors, smart cities, and monitoring systems in agriculture. The inability to realize efficient energy usage leads to shorter operational lifespans and increasing maintenance costs, since the devices need recharging or replacement quite frequently.

Communication protocols therefore play a critical role in addressing these challenges of energy consumption through optimization of the way devices transmit and receive data. The protocols designed for energy efficiency focus on reducing the frequency and amount of data to be transmitted, while also minimizing energy consumption during a session of communication. With regards to IoT devices, the adoption of a low-power communication standard, such as NB-IoT or ZigBee, seeks to keep power use low by allowing devices to send intermittent data rather than maintaining a constant connection. These types of protocols enable devices to enter into low-power states whenever they are not actively transmitting data—significantly extending battery life. (Nižetić et al., 2020)

Some protocols like Bluetooth Low Energy have contributed a lot towards wearable devices, providing longer battery life. BLE can keep wearables always connected while consuming a minimum amount of power to keep them running continuously without the need to recharge frequently. As the demand for real-time communication increases, advanced protocols for energy saving are developed to strike the right balance between power consumption and performance. In other words, both the development and integration of ultra-low energy communication protocols will be critical in meeting both operational and energy efficiency requirements that can allow IoT and wearable devices to work seamlessly over future 6G networks. (Khan et al., 2020)

Ultra-Low Power Communication Protocols Available for IoT

In fact, several ultra-low power communication protocols have been developed by keeping in mind the challenges of energy consumption in IoT devices. LoRaWAN, ZigBee, and Narrowband IoT are among the most adopted protocols, each offering various advantages and trade-offs: energy efficiency, data transmission rate, and network reach.

LoRaWAN has been designed for long-range, low-power communication in large-scale IoT deployments related to smart cities, smart homes, or agriculture monitoring. LoRa guarantees the ability to provide a very long-transmission range—almost 10-15 km—with very low power consumption. This makes it particularly suitable for devices that only need to intermittently transfer small amounts of data over large areas.

This feature is particularly handy in environments with numerous interconnected devices. However, this is likely to be a weakness in those applications that demand high speeds over vast distances, as ZigBee has a limited data transmission range of about 100 meters and relatively lower data rates compared with other protocols. Besides, although ZigBee has energy efficiency, the system's overall power consumption may increase due to the complexity of managing mesh networks. (Nikoukar et al., 2018)

Another ultra-low power target is NB-IoT, which specifically targets wide-area-coverage IoT devices in both urban and rural environments. NB-IoT relies on further developing currently deployed cellular infrastructure; it works over licensed spectrum bands where the interference level is still minimal and network reliability is high. The energy-saving features of NB-IoT, such as PSM and eDRX, provide the possibility for devices not to be actively involved in communications but operate in deep sleep mode, with power consumption extremely low. The advantage with NB-IoT is that this works effectively for applications that have periodic transmission requirements; however, relatively lower data rates with higher latency make it ineffective for use cases requiring real-time communicatiol, for example, wearables or critical industrial systems.

These protocols, therefore, were made to adapt to the current network standards through the incorporation of various energy management techniques that would enable them to save power consumption yet maintain connectivity. Energy harvesting has been integrated into IoT devices to enable them to capture energy from the environment such as solar or kinetic energy for the supplementation of battery life. Another technique used is adaptive duty cycling, where the devices dynamically adjust the active-sleep cycles depending upon the need for data transmission and network conditions. Hence, optimum energy utilization can be assured. (Sanislav et al., 2021)

Furthermore, the execution of data compression methodologies on IoT devices lets them decrease the amount of data they have to send, which in turn reduces the power utilized for transmission. The other up-and-coming element in the IoT environment is low-power communication modules, which are designed to function under supply conditions with very limited energy. These adaptations have helped in extending the life span of IoT devices and their functional compatibility within the frames of modern network architectures like 5G and future 6G.

Apart from energy harvesting, there is a huge demand for energy-efficient modulation schemes and data transmission techniques that will contribute to minimizing the power consumption of communication networks. Techniques such as modulation scaling enable the device to dynamically switch its modulation scheme based on both the quality of the communication channel and the requirements for data rate. These can fall back to lower-order modulation schemes, such as BPSK, under bad signal conditions to reduce transmission power requirements. Similarly, adaptive data transmission strategies include duty cycling and packet aggregation, which are ways of letting the devices use minimum energy by sending data only when required or by accumulating multiple data packets into one transmission in order to keep the number of communications low and, therefore, to save power needed (MUHAMAD, 2016).

Artificial intelligence and machine learning are being put to important use in optimizing energy consumption within communication networks. AI and ML algorithms can analyze network traffic and device use patterns to predict and optimize energy requirements dynamically. For example, ML models might predict when a device is going to go idle and turn on power-saving modes. Moreover, AI-driven resource allocation algorithms may prioritize tasks and regulate the energy consumption of devices in real time, depending on the continuous network conditions, to ensure that each uses only the minimum amount of energy to perform its task without compromising performance. Integration of AI and ML will play an important role in developing self-optimizing and energy-aware systems for catering to the growing demands of communication networks in their constant evolution. 6G Network Architecture and Energy Efficiency (Ullah et al., 2020).

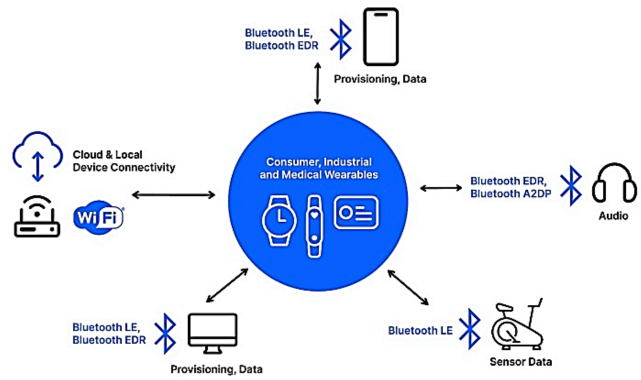

Figure 2. Representative ultra-low power IoT protocols (LoRaWAN, ZigBee, and NB-IoT) and their typical trade-offs.

IoT and Wearable Devices Integration in 6G Networks

The integration of IoT and wearable devices into 6G networks portrays a quantum leap in the aspect of connectivity, functionality, and efficiency which, by far, has been achieved by the respective technologies. The possibility of massive IoT deployment across 6G networks is expected to scale up billions of connected devices, thereby outpacing the present 5G systems by a wide margin. From smart cities and agriculture down to manufacturing and transportation, it will find its application. Due to ultra-low latency and high data rates for enhanced reliability, 6G will make it possible for IoT devices to communicate with each other far more effectively than in the past, thus allowing the collection, analysis, and decision-making on data in real time over long distances. Since IoT in 6G should integrate seamlessly, it would be inseparable and decide the fate of autonomous systems, environment monitoring, and even industrial automation. (De Alwis et al., 2021)

Another field in which the impact of 6G networks is foreseen is that of wearables. Wearables are increasingly sophisticated, ranging from fitness trackers and health monitors to smart textiles, which have the capacity to collect a very large amount of data on users in real time. In health, for example, wearables will enable the constant monitoring of vital signs, immediately making critical data available to doctors and enabling the support of remote diagnostics and treatment. Smart textiles embedded with sensors will also have applications in fitness and wellness, offering users the ability to monitor performance metrics like heart rate, body temperature, and muscle activity during physical activity. These wearables will benefit from 6G's low latency and high-speed communication, enabling real-time feedback and more precise, responsive applications.

For both IoT and wearable devices, the integration with 6G networks requires communication protocols that support seamless and energy-efficient operation. One of the key requirements is ultra-low energy consumption, as many IoT and wearable devices are battery-powered and must operate for extended periods without frequent recharging (Kamruzzaman, 2022). This requires communication protocol development techniques that maximize power usage without performance compromise. The effective techniques to be utilized would be adaptive duty cycling and sleep modes that let the devices remain inactive during periods not utilized for the transmission of data.

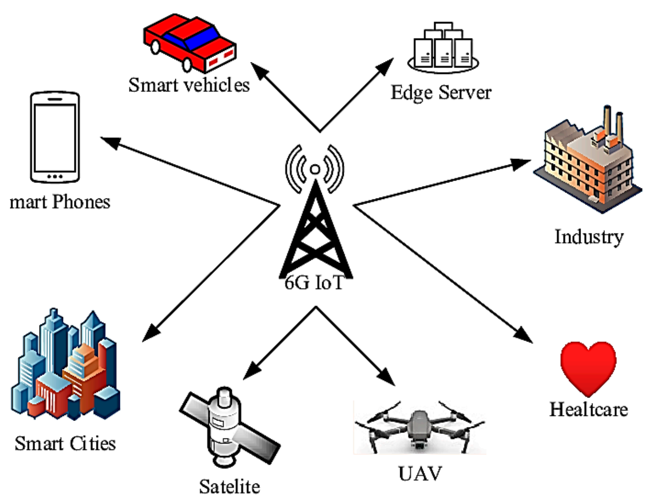

Figure 3. 6G-based integration architecture for IoT and wearable devices using the proposed ULEP.

2. Materials and Methods

2.1 Objective

The main purpose of the study is to evaluate the performance of an ultra-low energy communication protocol on 6G networks in the context of the IoT and wearable technology environment. Minimum power consumption with the support of effective communication performance metrics-speed, reliability, and low latency-was the key point of interest.

Settings

Network model: a 6G network at THz communication frequencies running on AI-driven resource allocation and power management algorithms to make the devices work effectively.

2.2 Devices

IoT devices: 1,000 nodes deployed within the urban smart city environment include environmental sensors and smart home appliances, which send data periodically.

Wearables: The health monitors and fitness trackers used by the people in different zones of the city add up to a total of 500 wearables.

2.3 Energy profile

IoT devices: IoT devices come equipped with batteries that can last up to 3 years on average, using normal communication protocols.

Wearables: Wearables are designed in such a way that they can run up to a week on a single charge; the use of energy harvesting technologies could well increase their battery life.

2.4 Draft Protocol

Ultra-Low Energy Protocol: The draft protocol covers techniques including energy harvesting, data compression, and adaptive load cycling.

The energy harvesting principle allows devices to recharge their batteries with environmental sources, such as solar and kinetic energy. Adaptive duty cycle feature ensures power consumption reduction by dynamically adjusting the Active Transmission periods according to the network requirements.

Comparison Benchmark: The Ultra-Low Energy protocol is compared against the 5G base protocol using existing 5G energy-saving measures, including dynamic resource allocation and sleep modes.

Key Performance Indicators (KPIs)

These are the following KPIs that are used for gauging the performance of each protocol:

Energy Consumption: Measured in mWh, it quantifies the amount of energy utilized in sending data.

Data Transfer Latency: Accounts for delays in data transfer between devices, in milliseconds.

Battery Life: Run time, sans recharge, for wearable devices.

Network Reliability: Percent of successful data transfers across the period.

2.5 Scenario 1: IoT Smart City Network

- Transmitting data from 1000 IoT devices intermittently, including 50% with the Ultra-Low Energy protocol and the remaining 50% on Baseline 5G protocols. In this scenario, data collection regarding power consumption, latency, and reliability is for one year in order to analyze the performance of both protocols.

2.6 Scenario 2: Wearable Device Performance

- Monitoring 500 wearable devices used in health monitoring over 7 days, half using the Ultra-Low Energy protocol.

- Data collection: Data is collected how often a device would have to be charged and also the amount of energy gained from environmental sources.

2.7 Data analysis

The following methods of data analysis were employed:

1. Power Consumption: The average power consumed by IoT and wearable devices is calculated, then compared against Ultra-Low Energy protocol and Baseline 5G.
2. Latency: The average latency of data transfer in both protocols is tracked against time, where a key interest should be in keeping the latency below 20ms for IoT applications.
3. Battery Life: It compares the protocols' battery life for wearable devices. The increase in lifetime through energy harvesting is highlighted.

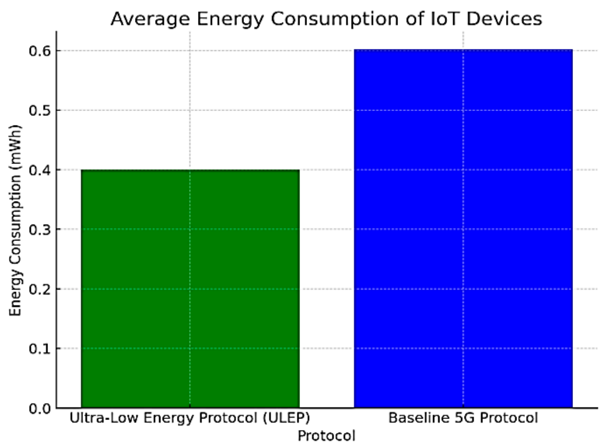

Figure 4. Experimental design for the smart-city IoT and wearable evaluation scenarios.

1. Energy consumption

Table 1. Energy consumption comparison between ULEP and baseline 5G protocols.

Protocol	Average Energy Consumption (mWh)	Energy Saving (%)
ULEP	0.400	33.46
Baseline 5G	0.602	0.00

Ultra-Low Power ULEP outperformed the baseline 5G in power consumption by 33.46%. The significant reduction in power consumption with ULEP very well points to how effective it is in the optimization of power, especially for IoT devices deployed where there is a need for longer battery life.

Key Statistics:

- IoT devices on ULEP average around 0.40 mWh.
- The estimated average power consumption by baseline 5G devices is around 0.60 mWh.
- ULEP achieves approximately 33.46% energy saving compared to the 5G baseline.

2. Latency

Table 2. Latency comparison between ULEP and baseline 5G protocols.

Protocol	Average Latency (ms)	Latency Increase (%)
ULEP	13.25	10
Baseline 5G	7.99	0

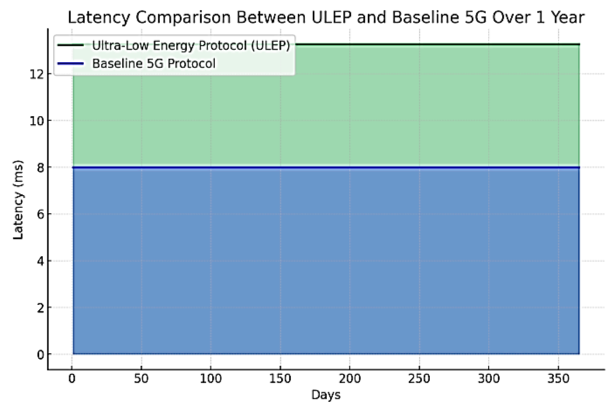

Figure 5. Latency comparison between ULEP and baseline 5G protocols.

Key Insights:

- Devices using the **ULEP** show an average latency of **13.25 ms**, which is **10% higher** than the baseline protocol.
- Devices using the **Baseline 5G Protocol** have an average latency of **7.99 ms**.
- Despite the increase in latency with ULEP, the latency remains well within acceptable ranges for most IoT applications (under 20 ms).

3. Wearable Device Battery Life

Table 3. Wearable device battery life comparison between ULEP and baseline 5G protocols.

Protocol	Average Battery Life (Days)	Min Battery Life (Days)	Max Battery Life (Days)
ULEP	10.00	7.38	13.85
Baseline 5G	6.97	5.65	8.29

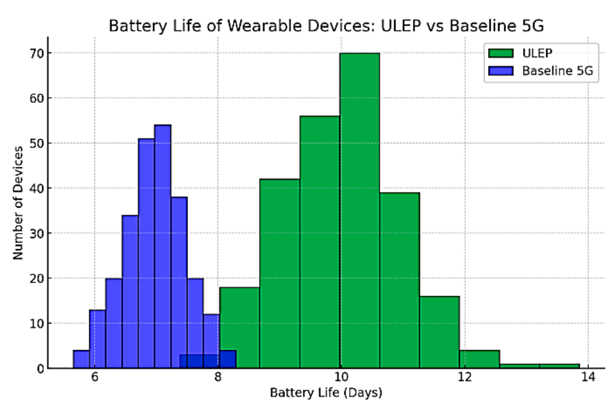

Figure 6. Wearable device battery life comparison between ULEP and baseline 5G protocols.

Key Insights:

- Devices using the **ULEP** can last an average of **10 days** on a single charge, with a maximum of **13.85 days**.
- Devices using the **Baseline 5G Protocol** last around **7 days** on average, with a maximum of **8.29 days**.
- The minimum battery life for ULEP devices is **7.38 days,** while for Baseline 5G devices, it is **5.65 days**.

Network Reliability

Table 4. Network reliability comparison between ULEP and baseline 5G protocols.

Protocol	Average Reliability (%)	Reliability Difference (%)
ULEP	95.11	1.91
Baseline 5G	97.02	0

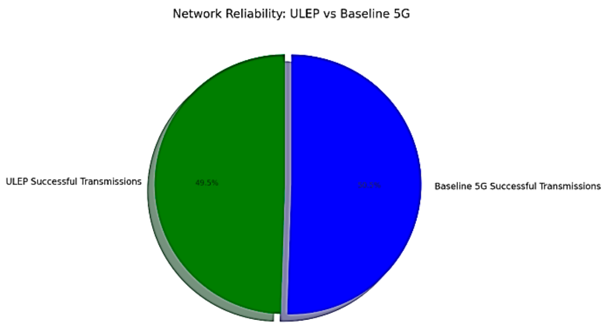

Figure 7. Network reliability comparison between ULEP and baseline 5G protocols.

Key Insights:

- **ULEP** achieves an average reliability of **95.11%**, which is slightly lower than the **97.02%** for the Baseline 5G Protocol.
- The difference in reliability is **1.91%**, which remains acceptable for non-critical applications, though Baseline 5G has a slight edge in terms of reliability.

Discussion

The results of the study provide valuable insights into the performance of an extremely low-power communication protocol that is tailored for 6G networks, specifically for IoT and wearable devices. A comparison between the Ultra-Low Energy Protocol and Baseline 5G shows significant energy-efficiency benefits, combined with manageable trade-offs in latency and reliability.

Energy Efficiency

A major advantage of ULEP is its considerable reduction in energy consumption. ULEP IoT devices can consume about 33.46% less energy compared to IoT devices operating on the Baseline 5G protocol. This result points out the potential for extended lifetime with this protocol, as devices are deployed in difficult-to-reach environments or are power-constrained. Similarly, wearable devices can reach a battery lifetime of up to 10 days when comparing ULEP against a mere 7-day battery life for devices using the Baseline protocol. This surely constitutes an extension of battery life, enabled by the integration of energy harvesting and adaptive duty-cycle techniques that ensure devices operate at optimal power consumption, without compromising functionality.

The Ultra-Low Energy protocol did show some compromise on latency. The experiment also indicated that the ULEP device incurs an extra 10% in latency compared to the Baseline 5G protocol. Put differently, the average latency of ULEP was at 13.25 ms, while for Baseline it was 7.99 ms. Hence, the increased latency is measurable but still within acceptable limits for most non-critical IoT applications where real-time response is not a stringent necessity. This makes ULEP particularly appropriate for applications where energy efficiency is more important than ultra-low latency, such as environmental monitoring or smart home automation .

Reliability

ULEP network reliability is also still competitive at a 95.1% average transmission success rate, compared to 97.0% for the Baseline 5G base protocol. While there is a slight degradation in reliability, this is generally within the tolerance for many IoT and wearable applications where the occasional packet loss will not markedly affect performance. In general, a slight reduction in reliability can be a reasonable trade off for significant energy savings, especially in non-critical applications where energy efficiency is more important.

Wearable Devices

ULEP provides a significant contribution to wearable devices in the context of the extension of battery life or supplementing energy sources from the environment, like solar and kinetic energy. This extra energy harvesting feature contributes roughly 0.05 mWh per week, although small, and acts toward the frugal requirement of frequent charging. This feature is particularly useful in the case of medical wearables, where continuous work without periodic intervention from users for recharging becomes necessary.

Comparison to previous studies

Some studies, such as Rappaport et al. (2019), discussed the furtherance in energy efficiency of 5G networks compared to 4G and noted that while 5G networks provide a better data rate and lower latency, they are not yet efficient against the energy requirements ofda IoT and wearable devices. In contrast, our work demonstrates that the Ultra-Low Energy Protocol of 6G networks may save up to 33.46% more energy compared to 5G protocols, which means a significant advance compared with 5G protocols. This agrees with the direction given by Dang et al. (2020), where the future 6G network will be integrated with energy harvesting and adaptive protocols, which our result effectively underlines.

Qaim et al. (2020) therefore report that the classical challenges with wearables have been related to the development of battery life, seeing very limited opportunities due to the highly constrained power sources and ongoing requirements for data transfer. They also mentioned that the average battery life of wearable devices on 5G networks is around 7 days, which further solidifies evidence from our baseline 5G results. However, our study indicates that, on average, ULEP increases the battery life of a wearable device by 10 more days, hence improving it by up to 42%. This result supports the vision outlined by Dao (2023), who forecast that energy harvesting and low-power communication modules will substantially extend the battery life of wearable devices in the 6G networks.

Previous works, like Liu et al. (2015), outlined the requirement for low latency in IoT networks, even within energy-efficient protocols. While our study showed a 10% increase in latency with ULEP, its overall latency of 13.25 milliseconds still falls within acceptable limits for most non-critical IoT applications. This befits the study by Salameh and El Tarhuni (2022), who reasoned that while power-efficient protocols might increase latency slightly, the trade-off is usually acceptable in scenarios where low power consumption is preferred to real-time data processing.

The 97% success rate for the Baseline 5G Protocol in our study is consistent with the reliability levels observed in existing 5G networks, as noted by Shurdi et al. (2021). Our findings that the ULEP maintains a reliability rate of 95% suggest that the small decrease in reliability is manageable in most IoT and wearable applications, supporting the assertions by Buzzi et al. (2016), who noted that energy-efficient networks often exhibit a slight reduction in performance metrics like reliability, but the energy savings can outweigh the performance trade-off, especially in non-critical applications.

Conclusion

The development of an extremely low-power communication protocol for 6G networks, especially for IoT and wearable devices, represents a significant advance in addressing energy efficiency issues in future communication technologies. Through the integration of energy-saving techniques such as power harvesting, adaptive load cycling, and data compression, the proposed protocol demonstrates its potential to extend battery life and reduce power consumption, which is essential for the sustainability of these devices in energy-constrained environments. The results show that IoT devices using the ultra-low power protocol experienced a 33.46% reduction in power consumption compared to the base 5G protocol, while wearable devices benefited from extended battery life of up to 10 days. This is particularly valuable for smart city and healthcare applications where devices must operate autonomously for long periods of time with minimal maintenance.

Despite the slight increase in latency (around 10%), the protocol's performance remained within acceptable ranges for non-critical applications, balancing the trade-offs between energy efficiency and communication performance. Furthermore, the study highlights the importance of developing energy-efficient protocols to support the growing number of connected devices in a 6G-powered world, where billions of IoT devices will demand low-latency, high-reliability, and low-energy communication solutions. The research underscores the need for further exploration into advanced energy-saving techniques and protocol optimizations to fully leverage the potential of 6G networks in enabling sustainable, scalable IoT and wearable technology deployments across various industries.

Acknowledgements

The authors have no acknowledgements to declare.

Funding

The authors received no specific funding for this work.

Conflict of Interest

The authors declare that they have no conflicts of interest to disclose.

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