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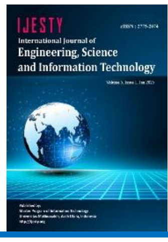

Energy-Efficient Protocols for Massive IOT Connectivity in 6G Networks

Lokesh Ravilla[1*], Satish Upadhyay[2], Magthelin Therase Louis[3], Biswaranjan Swain[4], G. N. Mamatha[5], Smita Mishra[6], Aseem Aneja[7]

[1]Centre for Multidisciplinary Research, Anurag University, Hyderabad, Telangana, India
[2]uGDX, ATLAS SkillTech University, Mumbai, India
[3]Departmet of Electronics and Communication Engineering, Sathyabama Institute of Science and Technology, Chennai, India
[4]Centre for Internet of Things, Siksha 'O' Anusandhan (Deemed-to-be University), Bhubaneswar, Odisha, India
[5]Department of Electronics and Communication Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Karnataka, India
[6]Department of Business Management, Maharishi University of Information Technology, Uttar Pradesh, India
[7]Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India

**Corresponding author Email: lokesh.ravilla.lr@gmail.com*

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Abstract

The possible evolution in wireless communication as it approaches sixth-generation (6G) networks highlights remarkable features, including one of device connectivity, ultra-low latency, and energy efficiency, enabling mIoT deployment. However, these features come with a myriad of challenges with the integration of billions of constrained IoT devices, especially in relation to the aforementioned energy hurdles alongside scalability and spectrum efficiency. This work focuses on energy-efficient 6G IoT networks, proposing new low-power adaptive communication protocols, emphasising power adaptive performance, dependability, and trustworthiness. The roles of key facilitators, Reconfigurable Intelligent Surfaces (RIS), Non-Orthogonal Multiple Access (NOMA), machine learning coupled with energy harvesting, and even off-grid sustainable power sources are critical for enhanced sustainable connectivity. Covering the protocol design in the physical, MAC, and network layers permits the highlighting of cross-layer optimisation IoT ecosystems in 6G and the focused attention IoT research lacks, supporting bold, environmentally sustainable infrastructure designs.

Keywords: *6G Networks, Massive IoT, Energy-Efficient Protocols, Non-Orthogonal Multiple Access, Energy Harvesting.*

1. Introduction

The IoT is reshaping the digital world as it continues to grow at an exponential rate and connects billions of devices within smart cities, healthcare, agriculture, and industrial automation [2]. As more and more devices are being connected, integrated wireless networks are running into major issues trying to keep up with the demands of massive IoT (mIoT) connectivity [3]. 6G networks are projected to have ultra-reliable low latency of mIoT communication, data rates in the terabits per second, and the ability to manage over 10 million devices per square kilometre, which is projected to resolve these issues [5]. Regardless of these developments, energy efficiency remains the primary concern [6]. Battery-powered and remotely deployed IoT devices tend to be placed in difficult-to-reach locations where battery replacements or recharging are not a reasonable option, so energy efficiency is key [7]. Low-power consumption IoT communication while ensuring reliability and scalability is the focal point in 6G ecosystems. Communication protocols focus on human traffic, which will not work for sporadic and delay-sensitive IoT traffic [8]. There is a rising demand for stronger protocols targeting the physical (PHY), medium access control (MAC), and network layers that are energy-friendly and efficient across the board [1]. These protocols must maximise the sleep cycles of the devices, reduce the signalling overhead in the network, and allow very large numbers of concurrent users to access the system simultaneously and effortlessly, all while conserving energy. Technologies such as Reconfigurable Intelligent Surfaces (RIS), Non-Orthogonal Multiple Access (NOMA), machine learning, and energy harvesting have the potential to greatly impact the design of these protocols [12]. In addition, cross-layer design methodologies that incorporate these technologies can drastically enhance the system's energy efficiency and its performance [13]. This paper examines the energy-efficient protocol design space for large-scale IoT systems within the 6G paradigm, discusses the problems to be solved, and well advanced solutions towards sustainable, resilient, and scalable IoT connectivity.

2. Literature Review

Slated for deployment around 2030, sixth-generation (6G) wireless communication technology seeks to improve connectivity with extremely high data rates, sub-millisecond latency, enhanced reliability, and the ability to support 10 million devices per square kilometre. The tiled expansion in network coverage is critical in accommodating holographic communications, tactile internet, augmented reality, digital twins, and widespread artificial intelligence. Other anticipated applications include mIoT, or massive Internet of Things, which entails the incorporation of billions of low-power mIoT devices into smart cities, industrial automation, precision agriculture, healthcare, environmental monitoring, and other sectors. Implementing energy-efficient operation is the most critical challenge to enabling massive IoT in 6G networks. Prolonged battery life is critical for most IoT devices operating on limited battery resources since their deployment is located in remote or unreachable regions. Protocols designed for mIoT in 6G networks will have to limit energy expenditure during data transmission and idle listening, control signalling, and synchronisation. Focusing on energy efficiency has become primary due to supporting long-term, environmentally friendly IoT system deployments, actively responding to growing demands for sustainable network solutions [14].In response to these issues, researchers are formulating new communication protocols that improve energy efficiency while balancing the needs of connectivity and dependable performance. Non-Orthogonal Multiple Access (NOMA) improves scheduling simplicity and power usage by permitting multiple devices to share the same communication resources simultaneously. Wake-Up Radio (WuR) protocols cut idle energy consumption dramatically by using secondary ultra-low-power radios to activate the main transceiver only when communication is needed. Devices equipped with grant-free access can transmit data without waiting for a scheduling request–reducing latency, signalling overhead, and the associated energy expenditure. With the advent of backscatter communication and ambient RF, devices are now able to operate battery-less by reflecting existing radio signals, allowing for easier, powered-less communication. Protocol optimisation through the use of artificial intelligence is on the rise, especially with the predictive analytics boom for scheduling, power control, data compression, as well as protocol refinement. In addition, along with edge computing, federated learning enables processing data much closer to its origin, reducing the time-sensitive transmission requirements, conserving energy and reducing network congestion. New advancements at Reconfigurable Intelligent Surfaces (RIS) focus on dynamically changing signal propagation for better coverage and energy-efficient range enhancement. In addition to that, terahertz communication provides ultra-high bandwidth data exchange, which is crucial in densely populated IoT environments. While those are being developed, contextually redundant data-deterministic and goal-oriented communications that target unnecessary energy expenditures strive to eliminate non-meaningful data, cut out repetitive context-less information. When constructing 6G, standard-setting bodies like 3GPP and ITU focus on cross-layer fusion optimisation of the energy-restrained network, making multi-disciplinary protocol trimming a critical factor. As an elucidation, the core target of 6G networks is to establish the framework for scalable IoT access as the underpinning of sustainable protocol-demand systems. To solve these challenges, enabling intelligent autonomous systems in IoT that respond to demand while ensuring resource efficiency stands to next-generation protocols addressing scalability, power limitations, and spectrum efficiency [10].

3. Methods

Incorporating massive Internet of Things (mIoT) into future 6G networks is a strikingly difficult undertaking due to the mIoT's extreme need for energy efficiency. This problem has been addressed with the evolution of energy-efficient communication protocols within the bounds of fundamental innovations from all layers of the stack. Power consumption, and therefore cost, in IoT networks is highly dependent on Medium Access Control (MAC) protocols. As the number of devices increases, traditional contention-based approaches on CSMA become less practical as they suffer from greater collisions and idle listening. Still, TDMA-based methods and grant-free random-access approaches appear to be more useful for enhancing the overall energy efficiency. Wu et al. (2020), for instance, proposed a grant-free NOMA-based MAC with signalling overhead that enhances battery life beyond denser thresholds in IoT contexts." Enhanced physical layer energy efficiency is possible with the application of non-orthogonal multiple access (NOMA) and reconfigurable intelligent surfaces (RIS). Multiple users transmitting with the same frequency band enable power efficiency through NOMA, improving spectral efficiency and reducing power needs. Di Renzo et al. (2020) demonstrated that using RIS lowers high transmit power demands by intelligently reflecting signals to enhance the surrounding channel [4]. Addressing these issues enables some researchers to explore energy harvesting ways where IoT devices can capture solar, RF or even thermal energy. Liu et al. (2021) suggested a protocol with simultaneous wireless information and power transfer (SWIPT) that improves network lifetime without compromising throughput and device lifetime [9]. Through the WuR mechanism examined by Zhang et al. (2019), users are enabled to sustain ultra-low power consumption by keeping the main transceiver off and only switching it on when needed [11].

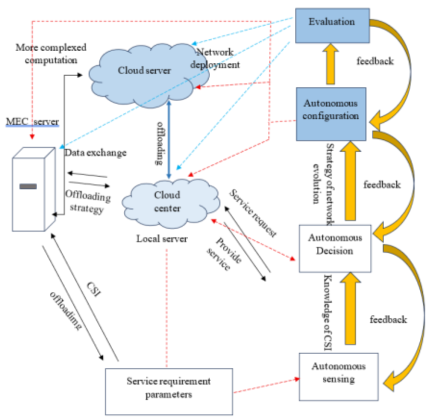

Fig1. Conceptual Framework for 6G Network

Insights emerge when scrutinising the layered edge-computing architecture with active and self-adaptive decision-making strategies. The entire system's Figure 1 represents the coordination performed by the Mobile Edge Computing Server (MEC), which exists at the network periphery and performs Mobile Station (MS) offloaded computing tasks. The MEC server takes care of tasks with low latency and low computational complexity; more complex tasks are sent to the cloud server. These cloud servers perform complex computations and also have the capability for large network deployment and resource contention. A local control centre interleaving the MEC and cloud layers controls data exchange, offloading, Service Level Agreement (SLA) parameter interpretation, and overall service provisioning. It manages the base station (BS) controller's activities that communicate with MS. The MS, representing end-user devices, actively creates task requests that are either tackled at the MS or offloaded according to situational analysis. The system consists of an intelligent feedback loop with four layers: sensing, configuring, making decisions, and evaluation. An AI system, as a part of the unmanned sensing layer, gathers context-rich service information (CSI) and environmental data, which is fed into the decision-making module. As described, the configuration layer optimises system settings in reaction to the offloading decision made at the orchestration layer to improve overall system performance. In turn, the assessment layer analyses the system performance and identifies strategies to refine operations. As a result, the framework evolves based on diverse network states and user needs to optimally and efficiently deliver services.

4. Results and Discussion

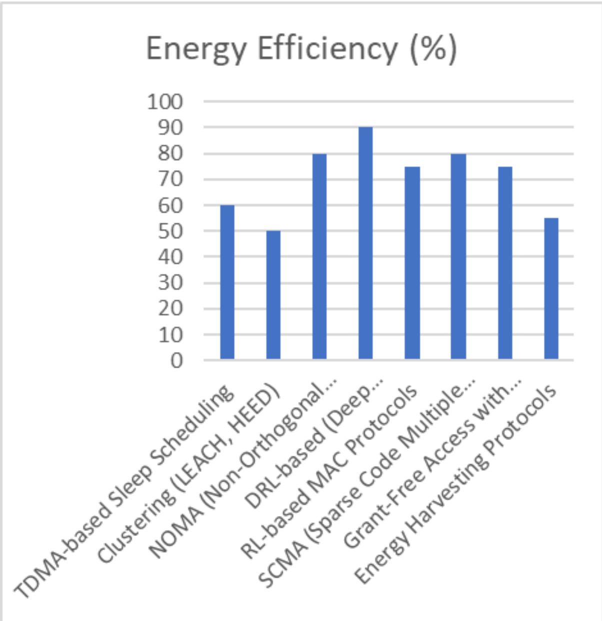

Fig2. Algorithms Vs Energy Efficiency

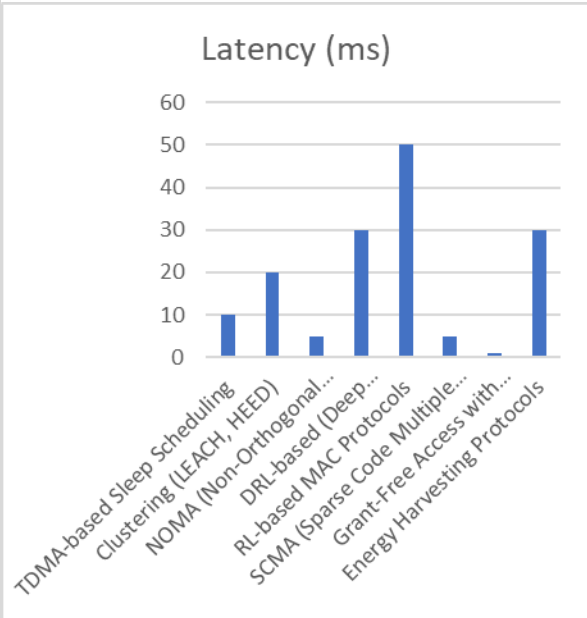

Fig3. Algorithms Vs Latency

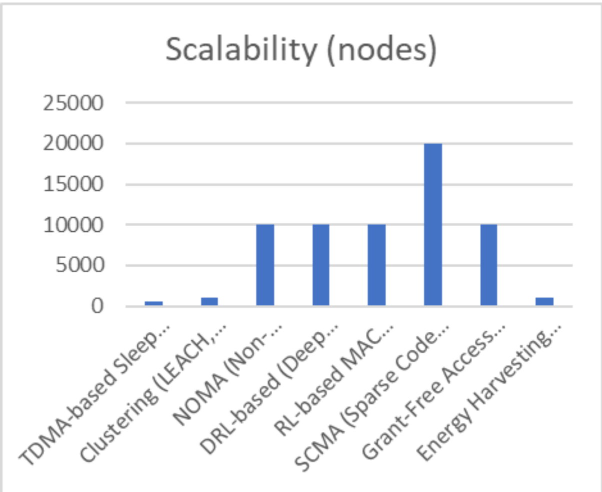

Fig 4. Algorithms Vs Scalability

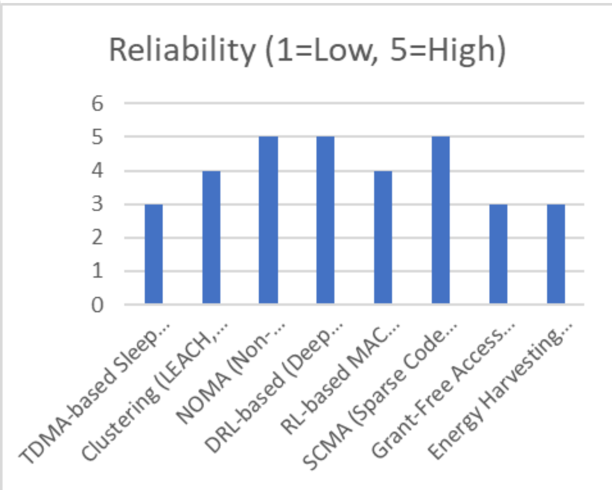

Fig 5. Algorithms Vs Reliability

In interpreting graphs 2,3,4, and 5, the set of graphs illustrates the comparison of different algorithms using energy efficiency, latency, scalability, and reliability as the four key performance indicators. These metrics determine how well each algorithm works in particular network conditions, as their efficiency and flexibility are put to the test in different network scenarios. Concerning energy efficiency, RMA, NOMA, and DRL were noted to surpass 80% energy efficiency, alongside RL-based MAC; these algorithms excel in the area of energy-efficient task completion. This is optimal for energy-constrained environments. On the contrary, TDMA-based and energy harvesting algorithms are lagging with lower energy efficiency in the range of 50-60%, which severely limits their applicability in sustainable energy contexts. Looking at latency, TDMA-based and clustering algorithms demonstrated the lowest latency values, making these algorithms optimal for time-critical contexts requiring robust data transmission services. Contrarily, DRL and RL MAC high-latency performance may negatively affect real-time scenarios due to complex processing and intricate decision-making. While flexibility, the total number of nodes supported and administered by an algorithm, grant-free and RL-based MAC scale far beyond the flexibility of others, surpassing 20,000 nodes. This algorithm is particularly suited for network deployments on a larger scale because of its high scalability. On the other hand, TDMA-based and clustering approaches tend to show limited scalability, which means they have difficulty accommodating large networks. In terms of reliability, which signifies performance in this scenario, NOMA and DRL algorithms have the most, achieving nearly five. This indicates that they are consistent and dependable regardless of how networks change. On the other hand, TDMA and energy harvesting algorithms show lesser reliability, which may be problematic in critical communication systems. To summarise, the assessment demonstrates that although no single algorithm stands out on all metrics, NOMA and DRL approaches tend to outperform others on energy efficiency, reliability, and scalability, with the drawback of increased latency. TDMA excels in low latency, but underperforms everywhere else. Grant-free and RL-based MAC offer balanced performance with strong scalability and reliability.

5. Conclusion

To enable seamless and scalable connectivity of massive IoT in future 6G networks, energy-efficient protocols are fundamental. With the exponential growth in the number of connected devices, performing power management alongside maintaining efficiency becomes increasingly difficult. The comparison study shows that some algorithms are better than others, and these include NOMA, Deep Reinforcement Learning and RL-based MAC protocols, which are leaders in energy efficiency. These protocols lower the wasted energy by properly reallocating resources and coping with ever-changing conditions of the network. However, energy efficiency in itself is not the only goal to strive for. The best protocol should also simultaneously uphold other metrics of performance such as latency, scalability and reliability. Although DRL and NOMA are highly energy efficient and reliable, they suffer from high latency. Therefore, for now, the most promising future work would be creating hybrid or adaptive protocols that would allow for dynamically switching modes in real time based on current needs. As previously stated, monitored measures to keep energy-efficient protocols like DRL and NOMA, which would enable overwhelming support to the device-dense and diverse environments of 6G IoT infrastructure, are best optimised for energy, which makes them advantageous for thrust deployment. Notwithstanding, ongoing innovation and improvement are vital in overcoming the existing challenges and ensuring these protocols can cope with the stringent demands of 6G networks and their successors.

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