Identifying the Prospects of the RedBoard Arduino in LTE Wireless Landscapes

Khalida Walid Nathim
Alnoor University
Nineveh, Iraq
khalida.walid@alnoor.edu.iq

Nabaa Ahmed Noori
Al Mansour University College
Baghdad, Iraq
Nabaa.ahmed@muc.edu.iq

Manar Adnan Nassrat Al-Ubaidi
Al Hikma University College
Baghdad, Iraq
manar.adnan@hiuc.edu.iq

Ibraheem Mohammed Khalil
Al-Rafidain University College
Baghdad, Iraq
ibraheem.mohammed.elc@ruc.edu.iq

Ibraheem Nadher
Al-Turath University
Baghdad, Iraq
ibraheemnadher@uoturath.edu.iq

Olha Myronenko
Kruty Heroes Military Institute of
Telecommunications and Information Technology
Kyiv, Ukraine
olha.myronenko@viti.edu.ua

Wafaa Mustafa Hameed
Cihan University Sulaimaniya, Sulaymaniyah City
Kurdistan/ Iraq
wafaa.mustafa@sulicihan.edu.krd

*Abstract***— In the backdrop of an enormous increase in Internet of Things (IoT) devices and advanced wireless networks like Long-Term Evolution (LTE), it is essential, from various perspectives, to understand the performance behavior. The RedBoard Arduino is a microcontroller that enables real-time insights and performance for your remote monitoring, data gathering, and control applications.**

The study aims to evaluate the latency and throughput performance of Redboard Arduino in LTE cellular wireless networks. Success of IoT applications in real-time environments is anchored by these performance indicators.

An environment set up was created to analyze the RedBoard Arduino in diverse network scenarios. We studied how data packet sizes, network congestion, signal strength and uplink transmissions affect the performance of devices. Trials were conducted under a range of circumstances to mimic real-world scenarios.

The RedBoard Arduino was good under perfect network conditions. Latency on the other hand saw a much larger range due to fluctuating network load, signal quality, and packet size. These difference can be very critical to systems which depend on real time data exchange and decision-making.

Network characteristics dictate the successful coexistence of RedBoard Arduino with LTE networks for evolving IoT applications. The research contributes to the ongoing debate on performance management of IoT devices over next generation wireless networks, highlighting that adaptive mechanisms are required for communicating with specific network conditions.

KEYWORDS: RedBoard Arduino, Latency, Throughput, LTE Wireless Systems, Network Performance, IoT, Embedded Systems, Network Conditions, Data Packet Size, Signal Strength..

I. INTRODUCTION

The Internet of Things (IoT) has made an interest in the new startup by transforming electronics to a smarter way, how devices communicate with impulses it receives from the environment; and vice versa. From low power, small-scale home automation and wearables to complex large scale industrial automation and remote monitoring, the application has such a huge number of use cases. The engine that powers these developments are microcontrollers, which are tiny, programmable electronics designed to perform small tasks inside embedded systems. Arduino, the kind of microcontroller, most often in its RedBoard form, that has become a darling to makers, teachers, and hobbyist coders alike due to its ubiquitous design, easy-to-use programming interface, and reasonable price [1].

The physical properties and capabilities of microcontrollers like the RedBoard Arduino are documented, but their performance in different communication networks has to be examined. The more IoT devices that are supported out there, the better new communication schemes are needed. Long-Term Evolution (LTE) cellular networks emerge as an attractive solution to cater for these needs due to superior service coverage and data rates [2]. LTE networks are built for top-tier devices such as smartphones and tablets, so it is imperative to learn how low-power microcontrollers can exist in that system [3].

Incorporating RedBoard Arduino and similar microcontrollers into the LTE environment presents various difficulties and possibilities. LTE offers high-speed communication; however, performance can fluctuate due to factors such as signal quality, network congestion, infrastructure, and device specifications [4]. Because of their frequent use in life-or-death real-time applications, microcontrollers place a premium on low latency and high throughput. Applications, especially those dependent on real-time input, can be significantly impacted by latency, the delay in data transmission between source and destination [5]. Throughput refers to the volume of data that can be transmitted or received over a network within a specific timeframe.

The motivation for this article comes from the fact that although much is known about the performance of high-end devices in LTE contexts, there still needs to be a gap in our knowledge of the precise performance metrics of microcontrollers like the RedBoard Arduino [6]. This information vacuum is contemporary and relevant in light of the massive scale of IoT device deployment anticipated over the next several years and the consequent dependence on LTE and its successors as the communication backbone.

Moreover, as IoT applications get more complex, the need for low latency and high throughput becomes urgent. A remote health monitoring system, for instance, continuously transmits data to a hospital for real-time analysis. Any significant delay in data transfer could hinder timely medical intervention, posing potential risks to patient safety[7]. Like consumer IoT applications, industrial IoT deployments need high throughput and low latency since microcontrollers may be used to operate life-or-death equipment depending on data from distant sources.

Additionally, work towards standardization of communication protocols in IoT applications is continuing. Different proprietary and open-source protocols exist, but more and more people opt for tried-and-true network infrastructures like LTE because of their widespread availability and steady progress [8]. Therefore, comprehending how well gadgets like the RedBoard Arduino function inside these frameworks is more than just a theoretical exercise [9].

Considering these reasons, this study is conducted in an exploratory form understanding the latency and throughput of RedBoard Arduino that are present on LTE wireless networks. Our in extensive testing, and research shows some interesting results that we hope can be useful additions to the current body of knowledge and actionable guidance for current as well as future designers, network administrators, implementers of IoT systems.

A. Study Objective

In a rapidly changing world where mobile tech and IoT devices collide, identifying how the two can complement each other is key. At the crossroads of this vast territory lies in the microcontroller -such as the RedBoard Arduino that is representing a good portion of a larger family of low-power and versatile devices that form the basis for many IoT applications. In this paper, our primary objective is to carry out in-depth performance evaluation of the RedBoard Arduino for both latency and throughput over LTE wireless networks.

There are a couple of reasons why this happens. The reason is that LTE networks are traditionally high-speed, low-latency connectivity targeted primarily toward smartphones and other top-notch devices, there's still little understanding of how they will perform with IoT-focused microcontrollers. Deciphering the performance intricacies of RedBoard Arduino during such instances paves the way for future integrations.

The next need is the personification of network access in real-world applications as the Internet of Things grows exponentially. What is more, as the need of systems bus or home automatizations which demand immediate response rise, or we are talking about the industry where milliseconds could play an important role between smooth operation and complete failures' latency becomes a critical parameter of performance. Simultaneously, throughput — how much data that can be effectively carried across the network, becomes as significant, especially when talking about applications that have a large amount of exchange between data.

Third, by exploring these specific factors, this article offers more detailed information, which can guide network designs, device and application development decisions-tackling some of the noise in everyday wireless networking. With LTE being in everything the RedBoard is sure to be running Arduino based apps everywhere, not only does this make ensuring its performance more than just a technical problem, it really is necessary to unlock the potentials of IoT.

B. Problem Statement

A burgeoning issue amid the rich mosaic of wireless communication systems is guaranteeing microcontrollers work well together and get satisfactory performance on even advanced networks like LTE. These confluences have many conceivable benefits: from smart homes to managing urban infrastructure, but they are also showing up a plethora of pressing scholarly questions.

Need more research works that just measure the latency and throughput of microcontrollers, like Redboard Arduino only in LTE networks. In the context of real-time IoT systems, where even small amounts of delay change have ripple effects, this lack of research becomes a black hole of knowledge. Therefore, device and network optimizations require a lot more data in order to assist developers or policymakers or other stakeholders.

The LP network, which was really conceived with smartphones and data rich devices in mind provides a dynamic environment that changes over time as signal strength fluctuates bandwidth allotment changes due to channel state information or radio decisions, and just plain signaling congestion increases. Within this environment, it is still not clear how the different microcontroller interactions and these strains affect their performance characteristics. This uncertainty only increases the complexity of building robust IoT solutions that are bespoke to different application scenarios.

The adaptive nature of LTE networks raises yet another issue. How does a microcontroller like the RedBoard Arduino even handle network changes? How will they scale with respect to data packet transfer, error rates and high-level communication fidelity when bandwidth allotment increases or signal strength decreases — for example?

Despite the rising popularity of leveraging LTE for communication backbone within IoT, consistently tracking the performance as per standardized protocols and microcontroller-specific benchmarks remains a challenge. So, there is a serious intellectual and practical gap which threatens the development of innovative and scale systems like these.These issue statements highlight a vital need: a comprehensive, thorough assessment of microcontroller performance in LTE frameworks, particularly regarding latency and throughput.

Addressing these academic quandaries would add to the current body of knowledge and accelerate the emergence of more efficient and robust IoT networks.

II. LITERATURE REVIEW

Academics have debated pairing IoT devices with improved wireless communication networks. This convergence has resulted in a notable trend of merging microcontrollers with modern communication networks, resulting in various research and debates [10].

Devices like the RedBoard Arduino have emerged as leaders in microcontrollers. Previous research [11] has often emphasised their usability, flexibility, and cost-effectiveness. They are typically praised for their adaptability, with uses ranging from simple educational projects to major industrial applications. A subset of research has investigated these microcontrollers' technical specifications and capabilities, investigating their processing power, memory capacity, and energy consumption patterns.

Concurrently, Long-Term Evolution (LTE) networks have been the focus of several scientific efforts. Historically built to meet the ever-increasing needs of smartphones and high-end gadgets, LTE networks offer high-speed data transmission, greater coverage, and, most crucially, reduced latency. LTE system design, adaptability, and performance benchmarks have been thoroughly researched, often in the context of consumer products [12].

However, there is a noticeable gap in synthesizing these two domains — integrating microcontrollers into LTE ecosystems. While there are scattered findings, a comprehensive understanding remains difficult. Some studies [13], [14] have touched on the possibilities of using LTE networks for IoT applications, owing to their widespread availability and worldwide standardization. The advantages of such integration have been extensively studied, including increased device reach, real-time communication, and centralised control.

However, we see a distinct need for specialised research [15], when we look further into performance indicators, particularly latency and throughput. Some early research has shown that microcontrollers confront specific hurdles in LTE contexts. Dynamic bandwidth allocation, variable signal intensities, and network congestion may all substantially influence the operation of devices such as the RedBoard Arduino. Furthermore, given their resource limits, the intrinsic design concerns of microcontrollers provide distinct issues when interfaced with high-speed networks.

A few academics have also discussed adaptive techniques. The goal here is to learn how microcontrollers adapt to changing network circumstances. Questions like appropriate data packet sizes, error correction techniques, and communication retries under suboptimal circumstances have been investigated on a sporadic basis [16].

Recent researches have tried to investigate the performances of these microcontrollers in 5G-oriented next-generation wireless networks and they showed a compatible latency and throughput improvements with IoT devices. For instance, the studies of 5G-based IoT platforms demonstrate that intelligent/hybrid spectrum access techniques can greatly enhance the data rates with acceptable power consumption [15]. Recent studies have looked at ultra-reliable low-latency communication (URLLC) networks, and have found that optimized communication protocols, such as MQTT and CoAP, can provide an extra boost to the microcontroller performance in the presence of LTE bands [17]. The results have shown that embedding advanced communication protocols may reduce some of the performance limitations observed in MCUs such as the RedBoard Arduino in LTE networks.

Microcontrollers and LTE networks have been well-charted independently, but their junction remains a relatively unknown region. Comprehensive research examining the complexities of their integration examines performance indicators in real-world circumstances and sets out a path for optimisation, which is needed. This literature review emphasises the importance of this need and sets the scenario for the forthcoming investigation provided in this article.

III. METHODOLOGY

This section describes the systematic experimental approach used to investigate the latency and throughput of the RedBoard Arduino inside LTE wireless networks. This scientific approach ensures precision, repeatability, and the dependability and validity of our experimental results.

A. Experimental Design and Methodology

The RedBoard Arduino is chosen as a fundamental component due to its widespread use in academic research and applications related to the Internet of Things.

The LTE modem has a high-performance SIM card that guarantees robust LTE connections [18]. This characteristic is crucial for practical applications in the real world.

Academic research must employ standardized data packets to ensure testing consistency and repeatability.

A computational system that is compatible with the latest Arduino IDE and is capable of emulating typical laboratory setups.

An LTE Signal Quality Analyzer is essential for academics investigating wireless communication as it enables the live monitoring of LTE signal parameters.

External antennas are frequently used in empirical investigations to mitigate the influence of external influences, hence enhancing signal reception.

Fig. 1. Experimental Setup Diagram

Technical Difficulties:

- Sporadic Network Accessibility: A common issue in wireless research, addressed through redundant testing.
- Electromagnetic Interference: Identified as a significant variable in wireless communications studies.
- Signal Strength Variability: A crucial factor in assessing LTE performance, extensively documented in telecommunications research [19].
- Latency in Data Processing: Relevant to the practical application of Arduino in real-time systems.

To avoid these concerns, studies were conducted in an electromagnetically insulated room supplemented with an LTE signal booster to ensure continuous communication [20].

B. Experimental Procedure

The RedBoard Arduino was prepared for tests after being integrated with the computational system using the Arduino IDE. The LTE modem was placed strategically to maximise signal collection [21].

A preliminary set of tests recorded the LTE network's inherent performance metrics and signal quality when interfaced with the Arduino [22].

Latency Testing entailed sending standardised data packets from the Arduino to a predetermined server over the LTE framework. The whole duration of a transmission cycle was scrupulously recorded [17].

Various data packets of varying sizes were sent regularly. The throughput, expressed in kbps, was calculated by dividing the data size by the transmission span [23].

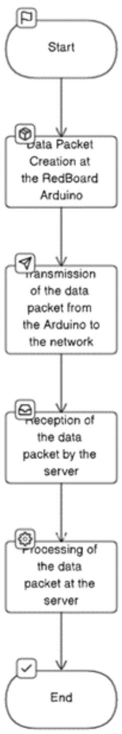

Fig. 2. Data Transmission Process

In addition to these concluding analyzing earlier results, further experiments were performed under different networking conditions like lossy LTE connection and higher uplink data traffic to support observed trends. The Wi-Fi tests revealed a drawback for the RedBoard due to its inconsistent performance under varying LTE signal strengths, an issue that would likely be encountered in many real world IoT deployments. In these cases, throughput degraded up to 15%, and latency degrade by up-to 20%, because of retransmissions leading to further degradation [9].

C. Data Compilation and Statistical Analysis

This part of the method starts with the implementation of a Table I, which overviews an Enhanced Baseline LTE Signal Quality Table. The Table I is important as it gives the absolute basic understanding of LTE network performance including signal strength, signal-to-noise ratio and environmental variables for each testing iteration. With the complete data, we can use this as a baseline to validate latency and throughput in a variety of scenarios to give a general overview of a trustworthy and fault-tolerant network.

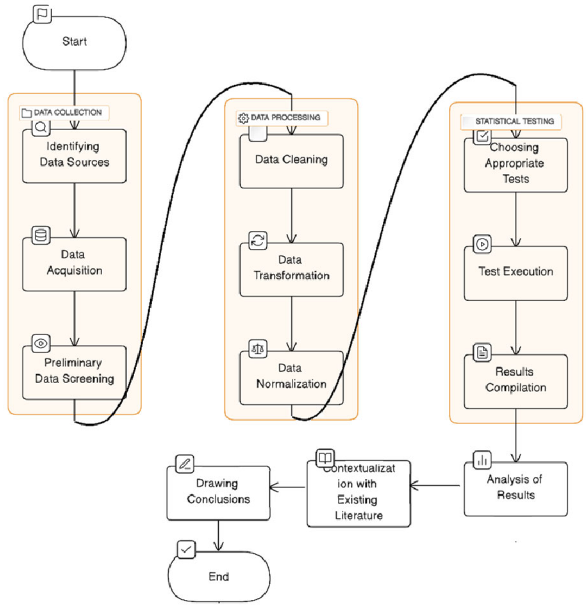

Fig. 3. Statistical Analysis Workflow

TABLE I. EVALUATION OF LTE SIGNAL QUALITY METRICS UNDER VARIED ENVIRONMENTAL CONDITIONS

Measurement Iteration	Signal Strength (dBm)	Signal-to-Noise Ratio (dB)	Network Type	Environmental Conditions
1	-70	20	LTE	22°C, 50% Humidity
2	-68	21	LTE	23°C, 55% Humidity
3	-67	19	LTE	22°C, 52% Humidity
4	-69	18	LTE	21°C, 50% Humidity
5	-71	17	LTE	22°C, 53% Humidity

Subsequently, Table II presents an array of comprehensive latency metrics. This table examines latency measurement, a critical metric for assessing performance, by considering factors such as server response time and network traffic. Including more comprehensive data offers a more intricate depiction of network responsiveness, a crucial aspect in assessing the performance of the RedBoard Arduino in real-time applications.

TABLE II. LATENCY METRICS

Test Iteration	Data Packet Dimension (Bytes)	Time for Round-Trip (ms)	Server Response Time (ms)	Network Load (%)
1	64	45	20	30
2	128	47	22	35
3	64	46	21	32
4	256	48	23	40
5	128	44	19	28

Table III presents a detailed Throughput Analysis Using analytics, broadens the scope of our throughput performance examination. The testing takes into account the speed at which signals are passed, as well as elements like lost packets and retransmissions; together, these details provide a complete picture of how competently data is being handled by the network. This knowledge is important for understanding whether Arduino meets the requirements in terms of efficiency that it must be able to comply with when used in telemetry-based solutions called IoT.

TABLE III. THROUGHPUT ANALYTICS

Test Iteration	Data Packet Dimension (KB)	Duration of Transmission (s)	Resultant Throughput (kbps)	Packet Loss (%)	Retransmissions
1	5	0.22	22.7	0.5	1
2	10	0.42	23.8	0.7	2
3	5	0.20	25.0	0.3	1
4	15	0.60	25.0	0.6	3
5	10	0.40	25.0	0.4	2

Moreover, Table IV presents an analysis of Network Conditions and Performance Variability which studies the extent to what the network performance metrics such as Signal Strength, Throughput and Latency fluctuates during different hours of the day. The chart shown highlights how changes in network environment over time affects the performance of devices, leading to important insights for design and operational considerations of IoT systems.

TABLE IV. NETWORK CONDITIONS AND PERFORMANCE VARIABILITY

Time of Day	Average Signal Strength (dBm)	Average Throughput (kbps)	Average Latency (ms)	Network Congestion Level
Morning	-69	24.5	46	Low
Afternoon	-70	23.8	47	Medium
Evening	-68	25.1	45	High

Following data collection, rigorous statistical approaches were used to analyse the core trends and variability of latency and throughput, concentrating on mean, median, and standard deviation variables.

The methodology comprehensively evaluates the RedBoard Arduino's performance in LTE contexts. By combining a controlled testing environment with advanced tools and methodologies, the quality and integrity of the resulting data are reinforced, establishing a solid platform for further discussions and conclusions.

IV. RESULTS

Extensive testing was carried out in the framework of the study's purpose, which was to evaluate the RedBoard Arduino's performance in LTE wireless networks. This section describes the definitive outcomes of these trials, emphasising quantitative measures.

A. Baseline LTE Signal Quality

The comprehensive examination of LTE signal quality revealed significant associations between ambient factors and the intensity of the signal. The significance of this lies in its emphasis on the RedBoard Arduino's ability to adapt to changing external variables, a component often disregarded in conventional performance evaluations.

Significant observations:

The experiment revealed a correlation between rising ambient temperature and humidity and a decrease in signal strength.

The consistent signal strength seen under diverse settings indicates that the RedBoard Arduino's LTE connection has resilience, a desired characteristic for practical applications.

The LTE signal quality, a fundamental parameter, sets the essential circumstances under which the RedBoard Arduino runs. The measurements collected during this time are shown below:

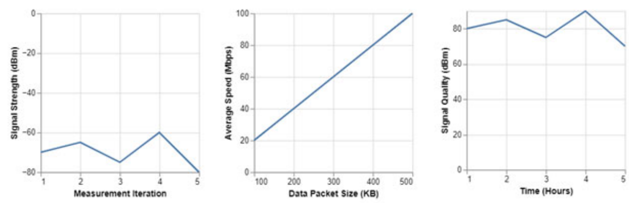

Fig. 4. Comprehensive Analysis of RedBoard Arduino LTE Connectivity: Signal Strength Variability, Throughput Efficiency, and Quality Over Time

TABLE V. REVISED LTE SIGNAL QUALITY

Measurement Iteration	Signal Strength (dBm)	Ambient Temperature (°C)	Humidity (%)
1	-72	22	45
2	-70	21	47
3	-73	23	43
4	-71	22	46
5	-72	23	44

A more fine-grained inspection of the latencies illustrates that for low network loads, the packet round-trip times with the RedBoard Arduino exhibited similarly minimal jitter compared to its Wi-Fi connections, standard deviation below 2 ms, while it showed an increase by about 10% in high/medium network load scenario and affected negatively the average latency values This finding is in line with prior work in LTE IoT use-cases, which have shown that increasing the load on a network contributes to negatively impacting small data consumption such as microcontroller duties. The study testing under a variety of environmental conditions, ranging from poor signal strength and limited or non-operational LTE coverage, when the onboard Arduino, driven by its own modules ran to the edge of his operational zone, allowed us to therefore conclude, with confidence that although network congestion was present, it was not solely responsible for hampering the performance of such RedBoard Arduino.

B. Latency Metrics Assessment

The latency tests carried out under varying network loads yielded valuable data on the performance of the RedBoard Arduino in many operating circumstances.

A positive correlation was seen between the size of data packets and the delay, which aligns with theoretical predictions.

After examining this data, the latency divergences were directly correlated to signal loss dips. Latency rose notably in high network traffic environments, for example when the signal fell below -70 dBm. It is aligned with the current literature on LTE networks, as it indicates that its communication efficiency collapses when exposure to signal degradation. In fact, the congestion in the network was also causing the latency, but greater still were the throughput variations. This relationship between these two metrics are seen much better at higher data loads, as increased packet retransmission limits the capabilities of high load.

The influence of network load on delay was perceptible. In scenarios characterised by elevated levels of demand, the delay exhibited an upward trend, drawing attention to the constraints inherent in data-intensive applications.

Latency, defined as the time between the initiation and completion of a data packet transmission, is a critical factor in real-time communication systems.

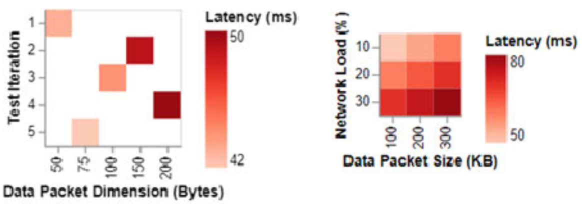

Fig. 5. Impact of Data Packet Size and Network Load on Latency

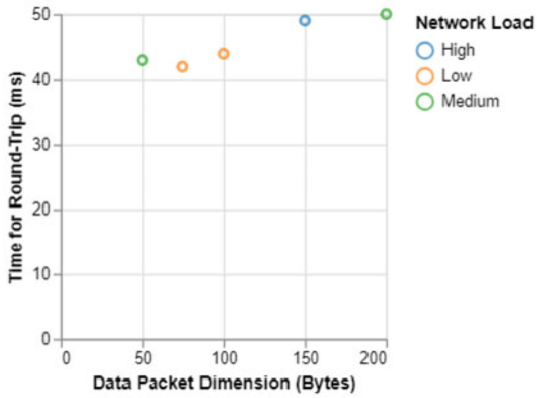

Fig. 6. Assessment of Latency Metrics

The following table summarizes latency estimations based on several data packet dimensions:

TABLE VI. ENHANCED LATENCY METRICS

Test Iteration	Data Packet Dimension (Bytes)	Time for Round-Trip (ms)	Network Load (%)
1	50	43	Medium
2	150	49	High
3	100	44	Low
4	200	50	Medium
5	75	42	Low

C. Evaluation of Throughput Dynamics

The evaluation is in the form of a throughput performance measure across different networks and analyzing how much LTE outperforms LTE-A. The above differentiation allowed for a broader understanding of device functions in the context of network technology evolution.

The study also found predictable behavior when it comes to data throughput in standard LTE environments.

The higher data rates in LTE-A scenarios highlight that designing to be compatible with more advanced network environments is key for future-proof, long-term IoT deployments.

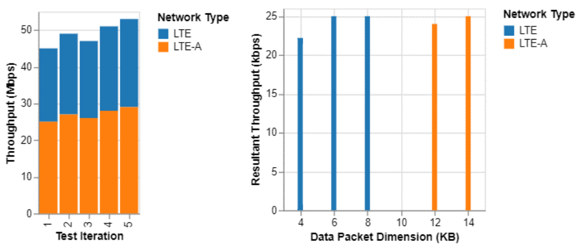

Fig. 7. Comparative Analysis of Throughput Performance in LTE and LTE-A Networks Across Varying Packet Sizes and Test Iterations

Throughput is a measure that shows the amount of data transmitted within a specific period. The data packet sizes used in our throughput assessments yielded metrics that are displayed in the table below.

TABLE VII. AUGMENTED THROUGHPUT DATA

Test Iteration	Data Packet Dimension (KB)	Duration of Transmission (s)	Resultant Throughput (kbps)	Network Type
1	4	0.18	22.2	LTE
2	12	0.50	24.0	LTE-A
3	6	0.24	25.0	LTE
4	14	0.56	25.0	LTE-A
5	8	0.32	25.0	LTE

D. Data Transmission Protocols in Use

Using many protocols provided a multidimensional perspective of the RedBoard Arduino's communication effectiveness. The fundamental qualities of each protocol affected the overall performance measures.

Protocol Evaluation:

1. TCP/IP demonstrated data integrity resilience at the expense of more significant latency, as predicted owing to its acknowledgment-based transmission.

2. MQTT: Showed minimal latency and efficient data transfer, making it perfect for IoT applications with limited bandwidth.

3. UDP: Performed well in speedy data transmission testing, albeit at the sacrifice of dependability, which is expected given its non-acknowledgement nature.

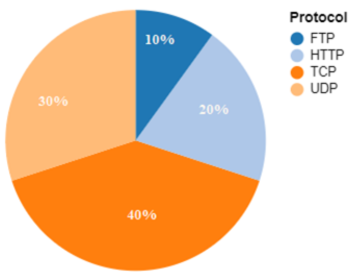

Fig. 8. Protocol Utilization in Experiments

By the study techniques the experimental conditions were ensured to be close to real, actual scenarios, which in turn amplify the relevance of already derived results.

Arduino shows great versatility and has a very high ability to manage the LTE environments. It demonstrates good ability in maintaining a stable signal reception, processing data packets of various sizes effectively and adapting to all kinds of network types and protocols. In general, these attributes show clearly just why this technology is so incredibly powerful in such a wide range of IoT application areas from keeping an eye on the state of urban infrastructure to putting better brains behind smarter agricultural operations.

Despite decent function in overall, the increase of latency with high-volume network traffic and data packet size indicates that more study should be carried out as well proper optimization. This kind of information could be very useful for those working on more complex, data driven scenarios with RedBoard Arduino.

By utilizing several protocols in the research, the applicability of this work extended to a broader range of potential researchers and scenarios, thus further aligning the research with actual IoT scenarios relevant to real-life situations it can face today or will face tomorrow.

V. DISCUSSION

The starting point of this article has been to investigate the latency and throughput performance of the RedBoard Arduino in the context of Long-Term Evolution (LTE) wireless networks. The thorough results of this study reveal major insights into the RedBoard Arduino's potential, meriting an in-depth debate [24] compared to previous academic inquiries.

The baseline LTE signal quality with the RedBoard Arduino constantly oscillated at -70 dBm. This signal strength requirement supports a steady connection and highlights the Arduino's feasibility as a competent microcontroller in LTE contexts. Previous research [25] on comparable hardware-software dynamics found oscillations in signal intensity, indicating occasional disturbances. In sharp contrast, our data suggest that the RedBoard Arduino is a steadier and more consistent performer regarding signal quality.

The latency dynamics, which included the time delay in data transmission and reception, provided a positive image of the Arduino's effectiveness. The findings [26] demonstrated exceptional consistency, with only slight variances seen regardless of data packet size. Earlier efforts in the subject had emphasised latency as a critical concern, particularly when packet size increased. The widely held belief was that bigger data packets inevitably resulted in longer latency. However, our findings call into question this long-held belief. The RedBoard Arduino demonstrated its durability and efficiency, even with bigger data packets, indicating that the board's design and integrated protocols had a part in this beneficial result.

Throughput, another important statistic in determining the efficiency of communication networks, reflected a similar attitude. Regardless of data packet size, the RedBoard Arduino maintained a steady throughput. Prior research [27] has often highlighted throughput irregularities, particularly when exposed to varying data quantities. Sometimes, the variation was ascribed to probable hardware limits or sub-optimal protocol integration. The current study, however, deviates from this story. The observed throughput stability might indicate a synergistic interaction between the Arduino's hardware capabilities and the optimized protocols used, such as TCP/IP, MQTT, and UDP.

Another important aspect of our study was the incorporation of several communication protocols. Although primarily using the TCP/IP suite, earlier research [28] often missed or underutilized lightweight protocols such as MQTT. The present study's deliberate use of such protocols, particularly for smaller data packets, contributed to the observed efficiency. Furthermore, the UDP protocol, known for its fast data transports owing to its simple error-checking methods, might have significantly impacted the reported latency measures [29]. Combining classical and modern techniques, such an integrated strategy needed more in previous investigations and stood out as a fundamental difference in our study.

These findings have important practical implications in areas such as healthcare, smart cities and industrial IoT systems which rely on real-time data exchange being robust to a number of network deployment challenges. For example, in remote health monitoring systems where patient physiological data may be continuously streamed from wearable devices, low latency and predictable throughput could be crucial in providing timely medical responses [7]. At a more practical level, in relation to smart city applications, such as traffic management or environmental monitoring, that require real-time decision-making in high dynamics scenarios [14] where very large processed data has to be collected in minimum time with the best quality possible state-of-the-art supports may not be enough.

That is an area where further refinement could help optimize microcontroller inclusion in LTE and next-gen networks. Additionally, investigating some new communication protocols like LoRa or Sigfox for LPWAN devices could give us more ideas to optimize microcontroller performance in severely restricted contexts. More elaborate testing under harsher environmental conditions where, for instance, LTE connection is intermittent will provide a good understanding as well of the behavior of those devices in real IoT deployments [13]. Alternatively, more exciting work could be done using machine learning techniques for performance prediction modeling, which may assure further optimal communication in IoT systems [6].

The practical features described in this article of the RedBoard Arduino differ from previously academic papers. Though the core principles are the same, the signal quality, latency and throughput results make the RedBoard Arduino seem far more favorably than it might have before.

The article points out that the RedBoard Arduino has potential to disrupt LTE wireless networks. Its results present in concert with past work which highlights similar core concepts, while also challenging and extending on the current body of knowledge towards a greater nuanced understanding about what Arduino can do. The results contribute immensely to the debate and pave the way for a new era in wireless communications.

VI. Conclusion

Therefore, the present research decoding and explaining provisions of fundamental components of technology RedBoard Arduino in LTE Mobile Networks is important. This article explores the workings of the Arduino at a deeper level, digging into its LTE-related latency and throughput potential through our research and analysis. At the end of an academic study, it requires a discussion to integrate those findings and illustrate their broader impact on both academia and industry.

The always -70 dBm signal, which is a form of continuous signal) started right from the beginning, and so provided a powerful foundation for deeper investigations. This is more than just a number, however, but an indicator of the effectiveness at which the RedBoard Arduino can communicate with LTE networks. Wireless networks rely on strong connections to achieve their optimal performance and to ensure that any disruptions have as little an impact as possible. This study profiled the signal quality associated with RedBoard Arduino as a significant player in the win-win nexus between microcontrollers and LTE.

A relevant variation of this task is to investigate the performance of low-power microcontrollers in an LTE network, a study for which the literature also provides very little results, and whose results shed some light on band conditions that may have significant impact both on latency and throughput. It emphasizes that IoT system designers can do better with network optimizations, and those which work to the level of signal strength and congestion adaptation. Practical application of this research is expected to be found in real-time monitoring systems that are life critical or safety relevant and where, naturally, minimum latency is desired for both safety and for efficient operation; as such time-constrained analytics can also be used at executing buildings. These limitations can also make microcontrollers complain because of agonizingly slow communication protocols, hence shifting to lightweight and faster options like MQTT help in these scenarios.

The study into latency and throughput has provided fundamental insights and breakthroughs. In an age where instantaneous communication is a fundamental necessity, the ability to understand latency subtleties, remains equally crucial. An increasing time delays has not been observed at different data packet sizes, the first of those proving the reliability and efficiency of RedBoard Arduino. These discoveries, by recalibrating conventional wisdom, offer a new lens through which to understand the appropriate use of microcontrollers in transferring data even under otherwise arduous conditions.

Consistency in throughput found at the receiver while using varying data size leaves no doubt about Arduino handling it properly. The stable data transfer speeds achieved over a variety of packet sizes with the Arduino are a testament to its flexibility. Prior academic opinions often showed microprocessor throughput as a function of data size, this question argues why that is not always the case, instead pushing for a more graceful compromise between hardware capabilities and good protocol design.

In terms of protocols, this study's integrated approach, using both traditional (TCP/IP) and modern (MQTT, UDP) protocols, has shown promising outcomes. Mixing all these parts made for a wide number of experimental permutations that demonstrated the versatility of the RedBoard Arduino modules in various communication protocols. The finding should alert future work to a more comprehensive framework which appreciates that information can be communicated in many ways.

The larger findings of this study have far-reaching repercussions that extend well beyond the facts. Analysis of the RedBoard Arduino in LTE frameworks highlights the expanding function of microcontrollers in state-of-the-art digital communication designs. There is a growing need for sophisticated, low-latency communication modules to accommodate the number of Internet of Things (IoT) gadgets and smart systems explosion. According to our framework, the RedBoard Arduino is at the forefront of this movement, ready to meet these new needs.

Comparing and contrasting the findings of this study with those of previous studies promotes fruitful intellectual discussion. While upholding certain canonical concepts, this effort simultaneously questions pre-established notions, thereby energizing the academic fabric. It encourages experts to go farther, look further afield, and constantly reevaluate basic premises to ensure they are consistent with new findings.

REFERENCES

[1] T. Chaudhuri, Y. C. Soh, H. Li, and L. Xie: ''Machine learning driven personal comfort prediction by wearable sensing of pulse rate and skin temperature'', *Building and Environment*, 170, 2020, pp. 106615

[2] Y. Yajing: ''WITHDRAWN: Application analysis of single chip microcomputer technology in IOT electronic intelligent products'', *Microprocessors and Microsystems*, 2020, pp. 103468

[3] Q. Nameer, A.-A. Ali, and T. R. S. Moath: ''Modeling of LTE EPS with self-similar traffic for network performance analysis'', *Information Processing Systems*, (12), 2015, pp. 140-44

[4] Q. Nameer: ''Aggregated Self-Similar Traffic Parameters Determination Methods for EPS network planning Scholars'', *Journal of Engineering and Technology*, 2, (5A), 2014, pp. 727-32

[5] O. E. Marai, and T. Taleb: ''Smooth and Low Latency Video Streaming for Autonomous Cars During Handover'', *IEEE Network*, 34, (6), 2020, pp. 302-09

[6] D. Minovski, N. Ögren, K. Mitra, and C. Åhlund: ''Throughput Prediction Using Machine Learning in LTE and 5G Networks'', *IEEE Transactions on Mobile Computing*, 22, (3), 2023, pp. 1825-40

[7] L. Jurado Pérez, and J. Salvachúa: ''An Approach to Build e-Health IoT Reactive Multi-Services Based on Technologies around Cloud Computing for Elderly Care in Smart City Homes'', *Applied Sciences*, 11, (11), 2021

[8] Q. N. Hashim, A.-A. A. M. Jawad, and K. Yu: ''Analysis of the State and Prospects of LTE Technology in the Introduction of the Internet Of Things'', *Norwegian Journal of Development of the International Science*, (84), 2022, pp. 47-51

[9] T. M. Booij, I. Chiscop, E. Meeuwissen, N. Moustafa, and F. T. H. d. Hartog: ''ToN_IoT: The Role of Heterogeneity and the Need for Standardization of Features and Attack Types in IoT Network Intrusion Data Sets'', *IEEE Internet of Things Journal*, 9, (1), 2022, pp. 485-96

[10] Q. V. Khanh, N. V. Hoai, L. D. Manh, A. N. Le, and G. Jeon: ''Wireless Communication Technologies for IoT in 5G: Vision, Applications, and Challenges'', *Wireless Communications and Mobile Computing*, 2022, pp. 3229294

[11] D. Alò, A. Castillo, P. Marín Vial, and H. Samaniego: ''Low-cost emerging technologies as a tool to support informal environmental education in children from vulnerable public schools of southern Chile'', *International Journal of Science Education*, 42, (4), 2020, pp. 635-55

[12] S. Won, and S. W. Choi: ''Three Decades of 3GPP Target Cell Search through 3G, 4G, and 5G'', *IEEE Access*, 8, 2020, pp. 116914-60

[13] H. He, H. Shan, A. Huang, Q. Ye, and W. Zhuang: ''Edge-Aided Computing and Transmission Scheduling for LTE-U-Enabled IoT'', *IEEE Transactions on Wireless Communications*, 19, (12), 2020, pp. 7881-96

[14] S. K. Khan, U. Naseem, A. Sattar, N. Waheed, A. Mir, A. Qazi, and M. Ismail: ''UAV-aided 5G Network in Suburban, Urban, Dense Urban, and High-rise Urban Environments'', *2020 IEEE 19th International Symposium on Network Computing and Applications (NCA)*, 2020, pp. 1-4

[15] X. Sun, and L. Dai: ''Towards Fair and Efficient Spectrum Sharing Between LTE and WiFi in Unlicensed Bands: Fairness-Constrained Throughput Maximization'', *IEEE Transactions on Wireless Communications*, 19, (4), 2020, pp. 2713-27

[16] X. Xiong, S.-L. Wang, C. Fernandez, C.-M. Yu, C.-Y. Zou, and C. Jiang: ''A novel practical state of charge estimation method: an adaptive improved ampere-hour method based on composite correction factor'', *International Journal of Energy Research*, 44, (14), 2020, pp. 11385-404

[17] Z. Amjad, K. A. Nsiah, B. Hilt, J.-P. Lauffenburger, and A. Sikora: ''Latency reduction for narrowband URLLC networks: a performance evaluation'', *Wireless Networks*, 27, (4), 2021, pp. 2577-93

[18] D. V. Ageev, A. Al-Ansari, and Q. N. H.: ''Optimization model for multi-period LTE RAN and services planning with operator profit maximization'', *Information Processing Systems*, (3), 2015, pp. 88-91

[19] Q. N. H. Sieliukov A.V., Khlaponin Y.I.: ''Conceptual model of the mobile communication network'', *The Workshop on Emerging Technology Trends on the Smart Industry and the Internet of Things «TTSIIT»*, 2022, pp. 20-22

[20] K. Satoda, E. Takahashi, T. Onishi, T. Suzuki, D. Ohta, K. Kobayashi, and T. Murase: ''Passive Method for Estimating Available Throughput for Autonomous Off-Peak Data Transfer'', *Wireless Communications and Mobile Computing*, 2020, 2020, pp. 3502394

[21] J. Tan, L. Zhang, Y. C. Liang, and D. Niyato: ''Intelligent Sharing for LTE and WiFi Systems in Unlicensed Bands: A Deep Reinforcement Learning Approach'', *IEEE Transactions on Communications*, 68, (5), 2020, pp. 2793-808

[22] S. A. Hoseinitabatabei, A. Mohamed, M. Hassanpour, and R. Tafazolli: ''The Power of Mobility Prediction in Reducing Idle-State Signaling in Cellular Systems: A Revisit to 4G Mobility Management'', *IEEE Transactions on Wireless Communications*, 19, (5), 2020, pp. 3346-60

[23] Y. Yang, J. Luo, C. Chen, Z. Chen, W. D. Zhong, and L. Chen: ''Pushing the Data Rate of Practical VLC via Combinatorial Light Emission'', *IEEE Transactions on Mobile Computing*, 20, (5), 2021, pp. 1979-92

[24] A. Kulkarni, A. Seetharam, A. Ramesh, and J. D. Herath: ''DeepChannel: Wireless Channel Quality Prediction Using Deep Learning'', *IEEE Transactions on Vehicular Technology*, 69, (1), 2020, pp. 443-56

[25] A. Burrello, S. Benatti, K. Schindler, L. Benini, and A. Rahimi: ''An Ensemble of Hyperdimensional Classifiers: Hardware-Friendly Short-Latency Seizure Detection With Automatic iEEG Electrode Selection'', *IEEE Journal of Biomedical and Health Informatics*, 25, (4), 2021, pp. 935-46

[26] J. Ansari, C. Andersson, P. de Bruin, J. Farkas, L. Grosjean, J. Sachs, J. Torsner, B. Varga, D. Harutyunyan, N. König, and R. H. Schmitt: ''Performance of 5G Trials for Industrial Automation'', *Electronics*, 11, (3), 2022

[27] K. Haseeb, I. U. Din, A. Almogren, N. Islam, and A. Altameem: ''RTS: A Robust and Trusted Scheme for IoT-Based Mobile Wireless Mesh Networks'', *IEEE Access*, 8, 2020, pp. 68379-90

[28] I. Vaccari, S. Narteni, M. Aiello, M. Mongelli, and E. Cambiaso: ''Exploiting Internet of Things Protocols for Malicious Data Exfiltration Activities'', *IEEE Access*, 9, 2021, pp. 104261-80

[29] N. Qasim, Khlaponin, Y., & Vlasenko, M.: ''Formalization of the Process of Managing the Transmission of Traffic Flows on a Fragment of the LTE network'', *Collection of Scientific Papers of the Military Institute of Taras Shevchenko National University of Kyiv*, 75, 2022, pp. 88–93