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Embedded Operating Systems in IoT Edge Computing

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ABSTRACT Embedded systems and Edge Computing in Internet of Things (IoT) represent a special approach to creating systems for collecting, processing and analyzing data in an unstable environment. This article examines the benefits of Linux in this context, highlighting its flexibility, robust software ecosystems, and scalability, which are critical for a variety of IoT applications. The question of the operation of devices in an environment with a weak and/or unstable network is also raised, the general development of IoT/Internet-of-Everything (IoE) as a technology in the conditions of various distribution of high-speed networks is considered. Edge Computing technology, its use and areas of application in the need for rapid adaptation to the environment are also taken into account. Because the ability to calculate and analyze data on a local network can be critical for simplifying infrastructure in remote areas or in environments where access to an external network is difficult or impossible. We focus on the Linux kernel because its versatility in IoT is highlighted by its ability to handle a variety of workloads and seamlessly integrate with services, increasing adaptability to changing environmental conditions and ensuring reliable data processing at the edge. This adaptability is critical to mitigating the challenges caused by unreliable network infrastructure, thereby facilitating real-time decision-making and increasing operational efficiency. In addition, the open nature of Linux fosters innovation, allowing developers to create solutions tailored to the specific needs of edge computing, from industrial automation to smart city initiatives. By allowing devices to operate autonomously and efficiently manage resources at the network edge, Linux significantly optimizes latency, resource utilization, and overall system performance. Use of edge computing with correctly set-up embedded operating system (OS) allows to avoid issues common in IoT field and related to environment change. Article provides insight into pros and cons edge computing, its implementation in IoT and IoE by embedded Linux based OS. We will go through most common use-cases and market shares of common OS options. While IoT takes part in most industries by storm, there are still problems common for new industry. The primary advantage of using embedded *nix OS is the agility and ease of incorporation of those devices into edge computing systems, allowing to deal with network issues. Due to IoT/IoE being a new industry where many technologies are combined there are a lot of different approaches and frameworks that are used in it, but some of them are more popular and common than other ones. While going through the IoT/IoE data in the article, we will focus on embedded edge computing as one of the most efficient ways in building IoT solutions. Especially in perspective of OS market changes now and in near future. The result of that study will provide insight into possible trends and positives of the use of embedded OS with edge computing.

KEYWORDS embedded operating systems, Linux kernel, system flexibility, IoT, IoE.

I. INTRODUCTION

Drones, smart appliances, and integrated systems have become widely used in many areas of life. Humanitarian demining, animal control, and crop monitoring are just a small fraction of the areas where the use of Internet of Things (IoT) devices has become commonplace.

That's why we are now faced with huge streams of data generated in real time and literally collected on the spot, from animal migration to terrain analysis. All of this requires fast network access so that the data can be processed and considered on the ground. However, it is not possible to use the 5G network and mobile communication terminals everywhere, which complicates the process of analyzing and processing the data.

To address this issue, many approaches have been created, including the use of local payment terminals and attempts to introduce Software as a service (SaaS) to implement the always online paradigm. However, all the above depends on the stability and efficiency of the connection, which is not always possible or worthwhile in some cases [1].

Nowadays, in the period of Internet-of-Everything (IoE), we are witnessing the rapid development of networks and ways to use them to integrate diverse systems, which often forces us to choose unexpected solutions to solve bandwidth and computing power problems, and one of these solutions is Edge Computing.

Edge Computing allows to reduce network bandwidth requirements and perform computations on-site or near it, which in turn allows to use the positive features of IoT in regions with poor connectivity or without serious preparation of the environment [2].

In general, network bandwidth is a key factor for fast data processing in most of the situations described above. However, since the start of technology mass adoption in 2019, 5G coverage is still rapidly increasing and will reach more than 50% of the Earth`s population in 2025. But still, the distribution remains atomized. While 89% of the population in developed countries is covered by 5G, availability in still developing ones remains limited. Europe provides the widest 5G coverage, with 68% of the population covered, followed by the Americas (59%) and Asia Pacific (42%). Coverage reaches 12% of the population in the Arab States region and less than 6% in Africa [3].

Ninety percent of the world's population is covered by 4G network only, that is still a solid option. But still, 55% of people without access to 4G live in developing countries. While 95% of the population in high- and middle-income countries is covered by 4G or higher, this share drops to 39% in low-income countries, where 3G remains the dominant technology and often the only technology available for Internet connectivity [4]. General coverage for 5G is sporadic by region as depicted in Fig. 1.

Today, 95% of the world's population has access to mobile broadband. Closing the "coverage gap" – that is, reaching the remaining percentage of people who are still not in availability zones – becomes a challenge: since passing the 90% threshold in 2018, global 3G network is widened only by 4%.

It is precisely because of the uneven coverage that Edge Computing has begun to gain popularity to reduce network bandwidth requirements. Edge Computing built on ideas of processing data near to an event to enable rapid analysis and response in near real time.

The basic idea is to process and analyze data directly on devices or equipment that are closer to the place of event avoiding data transition to data centers or nodes. This is suitable for cases where low latency is important, such as in manufacturing processes, autonomous transportation systems, and medical applications where every millisecond counts.

The main advantages of edge computing include increased speed and reliability of data transfer, as much of the processing takes place on-site. It also reduces the load on network equipment and centralized servers, which lowers infrastructure costs and increases overall system efficiency. In addition, edge computing helps to protect data privacy, as sensitive data does not need to be transmitted over large open networks [6].

Speaking about IoT and Edge Computing, it is worth noting that a large part of it is the use of specialized embedded operating systems that are optimized for calculations and data analysis. It is the use of embedded OSes that provides a whole list of positive characteristics [7]:

Resource management: Allocate and manage limited device resources such as memory, processing power, and network bandwidth;

Flexibility in peripherals: Work with a variety of network protocols and devices;

Security: Ensure data is not modified and is protected from external influence;

Concurrency: Support parallelization and provide option to use threads/greenlets/processes for general purposes;

Modularity: Provide an option to switch system components by current project needs, modify and update those components to control resources;

Configurability: Allow customization of system configuration to tailor performance and functionality;

Comon knowledge: Ensure that elements of project have an established community that can provide `howtos` and expand ecosystem;

Compatibility: Support different common platforms and be able to provide an ability to adapt new devices to use their specs for current tasks.

Now, it is the combination of a specialized OS, software packages, and local networks that allows us to cope with the main list of problems caused by an unstable or weak network. And in general, it makes the process of data analysis and response to changes in the environment easier, since data processing at the scene greatly simplifies the process of information exchange between all links of the device-operator-analyst [8].

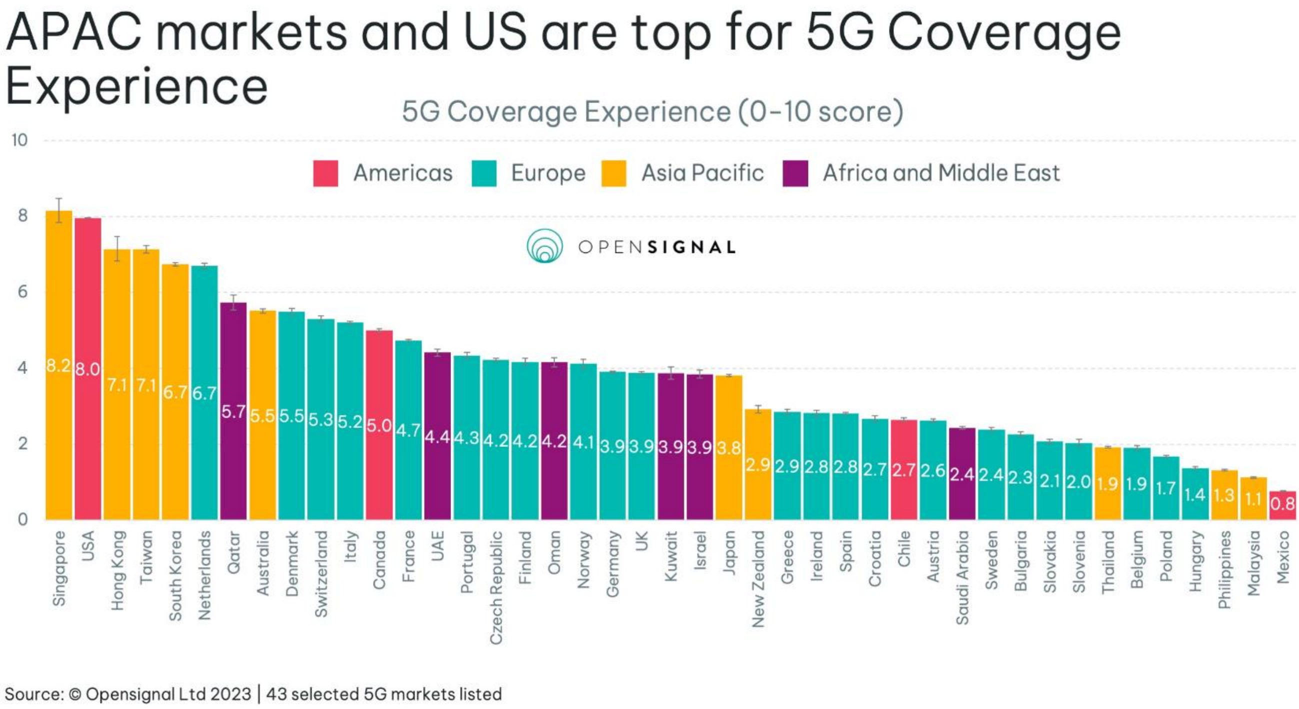

FIG. 1. 5G network coverage [5].

II. EMBEDDED LINUX OS FOR EDGE COMPUTING

Today's industry is undergoing a transformational stage with the adoption of newer system paradigms. Edge computing changes the way data is transformed and loaded in various subindustries due to its approach to minimizing data transporting and therefore requirements for network. In this article, we'll examine Linux's role in shaping the landscape of edge computing and IoT gateways, exploring its benefits, challenges, and prospects [9].

While it`s development started in 1991, now Linux outgrow all set expectations, becoming one of the pillars of information technology industry. Its adaptability and robust architecture have made it the preferred choice in server environments and now in edge computing [10]. Advantages of using Linux for peripheral computing can be briefly summarized as [11]:

Use Open Source: Linux's open-source model promotes innovation and collaboration by allowing developers to customize and optimize the OS for the specific needs of edge computing;

Which promotes easy adaptation: Kernel being highly adaptable gives an option to run it on most of the existent devices;

Fast adoption of security features: Linux offers powerful security features that are critical to ensuring that data cannot be modified by suspicious actors, especially if that data is processed near the event-producer;

Compatibility with peripherals: Linux-based OS can work with most of the peripherals or can be tailored to adapt to specific ones by creating specialized driver software;

General scalability and reliability: Having the ability to rapidly adapt to different environment, OS can provide a way to adapt and scale on rapid paces, while still having same reliable characteristics as before.

While still having those advantages, Linux usually has specific characteristics that must be accounted for:

Resource Boundaries: In most cases, embedded OS are heavily restricted in provided resources, which usually requires tailoring for each specific task;

Keeping updated: While over-the-air update approach is common – keeping whole system updated while avoiding over transferring data or keeping updated specific modules can require building specific pipelines;

Device Support: Integration and support of a wide list of platforms is complicated and can require custom drivers or even kernel-level modifications.

The use of embedded systems, regardless of what they are based on, is the basis for the implementation of the entire layer of IoE [12]. IoE includes three types of connections – machine-to-machine (M2M), man-machine (P2M) and man-man (P2P). Together, P2M and P2P connection will account for 69% of the total IoE cost for the public sector to 2025, while M2M connections will account for the remaining 31%. It is important to note that while M2M connections are quickly becoming a significant source of value, the result of these connections ultimately benefits people. The bottom line is that the IoT economy is an opportunity for people to be more productive and efficient. In the public sector, P2P communication includes, for example, telecommuting.

TABLE 1. Most used frameworks.

Framework	General Usage
Yocto Project	Yocto is a build system that allows developers to create custom Linux distributions for embedded devices. It provides tools and templates for building, deploying, and managing embedded Linux systems. Yocto is highly configurable and widely used in industrial applications requiring tailored Linux distributions.
Buildroot	Buildroot is a simple and efficient build system designed for embedded Linux systems. It automates the process of building cross-compilation toolchains, kernel images, root filesystems, and bootloader images. Buildroot focuses on simplicity and ease of use, making it suitable for smaller, resource-constrained devices often found at the edge of networks.
OpenEmbedded	OpenEmbedded is a build framework used to create Linux distributions for embedded systems. This framework is already integrated with most common platforms and provides tools for package management, cross-compilation, and configuration management. OpenEmbedded is flexible and can be customized to meet specific requirements of edge computing applications.
PTXdist	PTXdist is a build system tailored for creating embedded Linux distributions. It emphasizes simplicity, speed, and ease of customization. PTXdist is suitable for projects that require minimalistic and highly optimized Linux distributions for edge devices.
OpenEmbedded + Yocto	Some frameworks are based on both OpenEmbedded (OE) and Yocto Project technologies, offering a combined approach to building and managing embedded Linux systems. These frameworks leverage the strengths of OE and Yocto to provide comprehensive solutions for edge computing, including support for real-time applications, security, and scalability.

Bring your own device, distance learning, mobile collaboration and travel waivers. Examples of human-machine/human-machine communication include intelligent parking, disaster response and inpatient monitoring [13].

Although a significant percentage of the market is occupied by Linux, it should not be overlooked that RTOS is also widely used, although in a much smaller list of devices [14].

Operating systems in general can appear to be running multiple programs at the same time, which is called "multitasking". However, since central processing unit cores can only execute one thread or task at a time, true multitasking is not possible [15].

Therefore, this effect is achieved with the help of a scheduler – software that handles tasks execution, synchronization and switches between different processes or threads, implementing pseudo parallelism. Some OSes have different priority algorithms or flags that can change how the scheduler operates, so order of processes can differ and should be accounted for.

RTOS's main advantage is being deterministic. Tasks or jobs have deadlines, so RTOS is predictable. Embedded devices require real-time operation, which is why RTOSs are so popular in this sector [16].

Linux focuses on general performance, so scheduler prioritizes high-priority tasks to guarantee better performance. Because of that, Linux cannot be considered deterministic and so task order or lifetime cannot be ensured as reliable as it can be done using RTOS.

Types of RTOS can be divided into hard and soft deterministic subtypes.

Division between those subtypes is mostly defined inside community and industry, but as main rule considered system behavior after lifetime expectations were wrong. If OS crashes – it is hard, otherwise (e.g. the system degrades in performance) it is considered soft.

However, Linux based OS is considered go to for most developers due to being most common in different industries. The whole OS market is highly dynamic but generally split by a couple of OS types (Fig. 2).

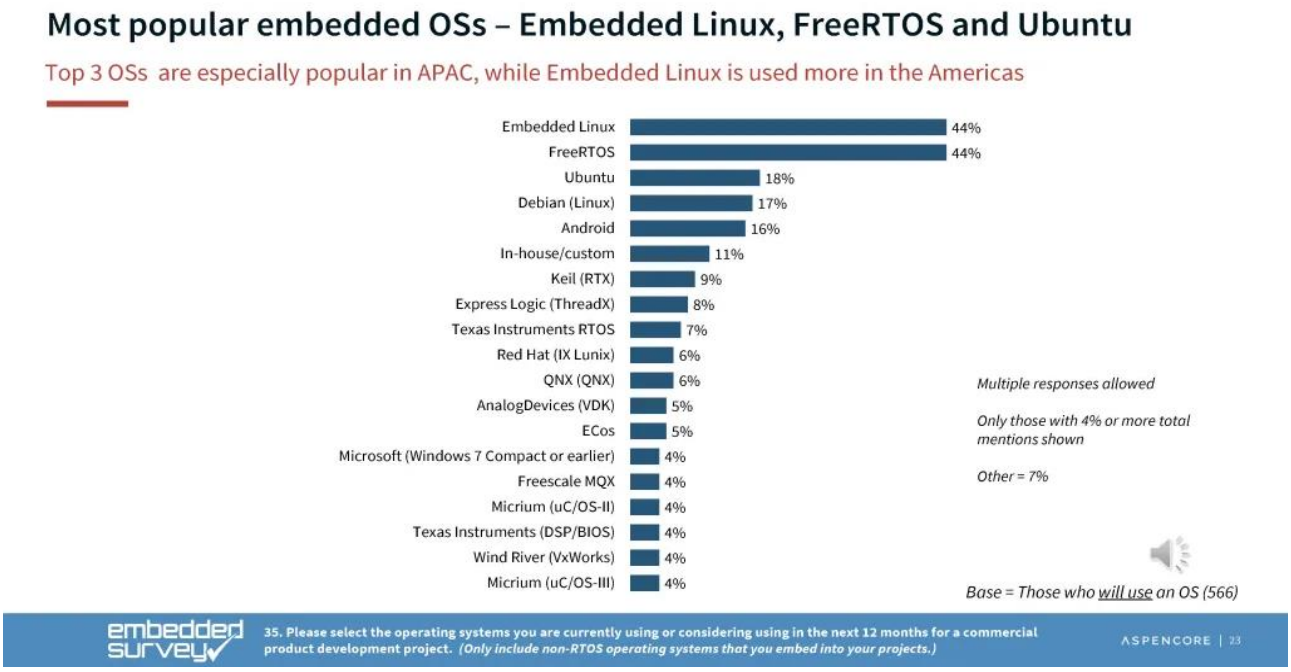

FIG. 2. OS market division [17].

Based on historical data it's predicted that the amount of active IoT devices will increase profusely, while having some trending differences in different regions.

Those trends can be seen in general community preference to use some specific Linux versions

Therefore, the percentage of Linux share will continue to grow [18].

III. CONCLUSION

In conclusion, the discussion of embedded systems for edge computing in the IoT has highlighted the key role of Linux operating systems, especially compared to RTOS. Embedded Linux offers a solid foundation for edge computing due to its flexibility, broad software support, and scalability, which are critical to meet the diverse and evolving needs of IoT applications.

In this research, it became clear that Linux's strengths lie in its ability to support a wide range of edge computing tasks, from data processing and analytics to connectivity and application management.

In addition, the integration of Linux into peripheral computing environments increases resistance to complex network conditions and facilitates rapid adaptation to environmental changes. This capability is particularly useful in remote or resource-constrained scenarios where reliable data processing and decision-making at the edge is a must.

Linux is a versatile and powerful choice for edge computing in IoT applications. Being able to incorporate wide number of peripherals and work on most platforms, combined with resilience to adverse network conditions, positions Linux as a cornerstone technology that drives progress while being efficient makes it main option for systems that implement edge computing and build IoE.

In our case, unfortunately, 5G was not implemented everywhere, and therefore the problem of network instability is still critically important when working with IoT/IoE devices. Therefore, our article considered ways to solve this problem using the embedded operating system.

The implementation of edge computing in IoT offers numerous advantages, but the convergence of these two computing paradigms creates new challenges that need to be solved in the future.

AUTHOR CONTRIBUTIONS

Yu.H., A.S. – conceptualization, writing-review and editing, supervision; Yu.H., H.L. – methodology, software, resources, writing-original draft preparation, visualization, validation, investigation.

COMPETING INTERESTS

The authors declare that they have no conflict of interest.

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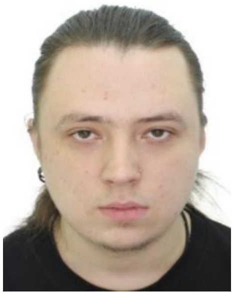
REFERENCES

[1] C. S. Inc., "The Internet of Things reference model," *Internet of Things WorldForum*, Chicago, IL, USA, Oct. 14, 2014, pp. 1–12.
[2] Cisco, "The Internet of Things: How the Next Evolution of the Internet Is Changing Everything," [Online]. Available: https://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf.
[3] D. Evans, *The Internet of Things How The Next Evolution of the Internet is Changing Everything*, [Online]. Available: https://www.researchgate.net/publication/30612290.
[4] X. Sun and N. Ansari, "Edge IoT: Mobile edge computing for the Internet of Things," *IEEE Commun. Mag.*, vol. 54, no. 12, pp. 22–29, Dec. 2016.
[5] Opensignal, "Understanding 5G and Overall Coverage Worldwide," [Online]. Available: https://www.opensignal.com/2023/05/17/understanding-5g-and-overall-coverage-worldwide.
[6] G. Carvalho, B. Cabral, V. Pereira, and J. Bernardino, "Edge Computing: Current Trends, Research Challenges and Future Directions," *Computing*, vol. 103, pp. 993–1023, 2021.
[7] M. Satyanarayanan, "The emergence of edge computing," *Computer*, vol. 50, no. 1, pp. 30–39, Jan. 2017.
[8] W. Shi, J. Cao, Q. Zhang, Y. Li, and L. Xu, "Edge computing: Vision and challenges," *IEEE Internet Things J.*, vol. 3, no. 5, pp. 637–646, Oct. 2016.
[9] Q. Qi and F. Tao, "A smart manufacturing service system based on edge computing, fog computing, and cloud computing," *IEEE Access*, vol. 7, pp. 86769–86777, 2019.
[10] J. Ren, H. Guo, C. Xu, and Y. Zhang, "Serving at the edge: A scalable IoT architecture based on transparent computing," *IEEE Netw.*, vol. 31, no. 5, pp. 96–105, Aug. 2017.
[11] S. Carlini, "The drivers and benefits of edge computing," Schneider Electric, Data Center Science Center, 2016.
[12] "Bare-Metal, RTOS, or Linux? Optimize Real-Time Performance with Altera SoCs," [Online]. Available: https://people.ece.cornell.edu/land/courses/ece5760/DE1_SOC/wp-01245-optimize-real-time-performance-with-altera-socs.pdf.
[13] D. Abbott, *Linux for Embedded and Real-Time Applications*, Oxford, UK: Butterworth-Heinemann, 2003.
[14] P. Raghavan, A. Lad, and S. Neelakandan, *Embedded Linux System Design and Development*, Taylor & Francis, 2019.
[15] A. Klinger, "Embedded linux – kernel, Aufbau, toolchain," *Embedded Software Engineering - Fachwissen*. [Online]. Available: https://www.embedded-software-engineering.de/embedded-linux-kernel-aufbau-toolchain-a-99d15279522f4d1fcd8b2d852a8f771b/.
[16] D. Guinard, "Operating Systems for IoT Embedded Systems – Web of Things," Webofthings.org, 2020. [Online]. Available: https://webofthings.org/2016/12/12/iot-os-embedded/.
[17] "Embedded Survey 2023," [Online]. Available: https://www.embedded.com/embedded-survey-2023-more-ip-reuse-as-workloads-surge/.
[18] "Real-time Operating System (RTOS) Market Size & Share, by Type (Soft RTOS, Hard RTOS, Firm RTOS) in 2024-2036," [Online]. Available: https://www.researchnester.com/reports/real-time-operating-system-market/5696.



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Вбудовані операційні системи в IoT Edge Computing

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АНОТАЦІЯ Вбудовані системи та Edge Computing в IoT представляють особливий підхід до створення систем для збору, обробки та аналізу даних у нестабільному середовищі. У цій статті розглядаються переваги Linux у цьому контексті, підкреслюючи його гнучкість, надійні екосистеми програмного забезпечення та масштабованість, які є критично важливими для різноманітних програм IoT. Також порушується питання роботи пристроїв у середовищі зі слабкою та/або нестабільною мережею, розглядається загальний розвиток IoT/IoE як технології в умовах різного поширення високошвидкісних мереж. Також враховується технологія Edge Computing, її використання та сфери застосування в необхідності швидкої адаптації до середовища. Оскільки здатність обчислювати та аналізувати дані в локальній мережі може бути критично важливою для спрощення інфраструктури у віддалених районах або в середовищах, де доступ до зовнішньої мережі ускладнений або неможливий. Ми зосереджуємося на ядрі Linux, оскільки його універсальність в Інтернеті речей підкреслюється його здатністю обробляти різноманітні робочі навантаження та легко інтегруватися зі службами, підвищуючи адаптивність до мінливих умов середовища та забезпечуючи надійну обробку даних на межі. Ця адаптивність має вирішальне значення для пом'якшення проблем, викликаних ненадійною мережевою інфраструктурою, що полегшує прийняття рішень у реальному часі та підвищує ефективність роботи. Крім того, відкритий характер Linux сприяє інноваціям, дозволяючи розробникам створювати рішення, адаптовані до конкретних потреб периферійних обчислень, від промислової автоматизації до ініціатив розумного міста. Дозволяючи пристроям працювати автономно та ефективно керувати ресурсами на межі мережі, Linux значно оптимізує затримку, використання ресурсів і загальну продуктивність системи. Використання підходу Edge Computing у поєднанні з правильно налаштованою вбудованою ОС дозволяє уникнути проблем, поширених у сфері IoT і пов'язаних зі зміною середовища. Стаття описує переваги та недоліки периферійних обчислень, їх реалізацію в IoT та IoE за допомогою вбудованих ОС на базі Linux. Ми розглянемо найпоширеніші випадки використання та частки ринку поширених варіантів ОС. Хоча IoT штурмує більшість галузей промисловості, все ще існують проблеми, характерні для нової галузі. Основною перевагою використання вбудованих *nix-систем є гнучкість і простота включення цих пристроїв в периферійні обчислювальні системи, що дозволяє вирішувати проблеми з мережею. Оскільки IoT/IoE є відносно новим поєднанням інформаційних і телекомунікаційних технологій, існує багато різних підходів і фреймворків, які використовуються в ньому, але деякі з них є більш популярними і поширеними, ніж інші – а отже більше практичної інформації доступно під час розробки. Розглядаючи дані про IoT/IoE в цій статті, ми зосередимося на вбудованих периферійних обчисленнях як одному з найефективніших способів побудови рішень IoT. Особливо в перспективі змін на ринку операційних систем зараз і в найближчому майбутньому. Результат цього дослідження дасть уявлення про можливі тенденції та позитивні сторони використання вбудованих ОС в об'єднанні із периферійними обчисленнями.

КЛЮЧОВІ СЛОВА вбудовані операційні системи, ядро Linux, гнучкі системи, Інтернет речей, Інтернет всього.