ISSN 2707-1898 (print)

Український журнал інформаційних технологій
Ukrainian Journal of Information Technology
http://science.lpnu.ua/uk/ujit
https:// doi.org/10.23939/ujit2024.02.117
Article received 24.09.2024 p.
Article accepted 19.11.2024 p.
UDC 004.7

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REMOTE PHY DEVICE MODULE FOR HYBRID FIBER-COAXIAL NETWORK BASED ON DOCSIS 4.0 STANDARD

This paper presents the comprehensive design and implementation of an RPD (Remote PHY Device) module, which serves as a pivotal component within the Remote PHY Node architecture for hybrid fiber-coaxial (HFC) networks based on the DOCSIS 4.0 standard. The development of this module addresses the critical need for enhanced data transmission rates and network efficiency in modern broadband communication systems. The research thoroughly investigates the integration of GCP/R-DEPI/R-UEPI protocols into the RPD module, utilizing advanced packet processing technologies to optimize data transfer between the CCAP (Converged Cable Access Platform) Core and the cable modem.

The proposed model is developed using open-source software, providing extensive flexibility for customization, adaptation, and enhancement in various HFC network applications. This approach also ensures that the model can be readily improved or expanded to meet the evolving demands of next-generation broadband networks. A key focus of the study is the architectural analysis of the Remote PHY Node, with particular emphasis on the interaction between the RPD module and the RF Module (RFM), and the critical interfaces that ensure seamless data transmission and network stability.

Through detailed experimentation and modeling, the study reveals that the incorporation of DPDK (Data Plane Development Kit) into the RPD module results in significant performance improvements. By bypassing the traditional kernel-based packet processing, DPDK reduces latency, increases throughput, and enhances the overall efficiency of network packet handling. The multi-level model developed in this research comprises context, container, component, and code levels, providing a structured and scalable framework for the RPD module's implementation.

Furthermore, the study demonstrates that the RPD module, when implemented according to the DOCSIS 4.0 standard, offers substantial improvements in network security, supports a distributed access architecture, and significantly boosts the processing efficiency of data packets. These advancements position the developed RPD module as a critical enabler of next-generation HFC networks. The paper concludes by outlining the potential for future research, particularly in exploring the scalability, robustness, and adaptability of this model in large-scale network deployments, as well as its integration with emerging technologies in the field of telecommunications.

Keywords: remote PHY node, packet processing, data transmission, distributed architecture, network provisioning.

Introduction / Вступ

The rapid evolution of broadband communication technologies has led to significant advancements in network infrastructures, particularly in hybrid fiber-coaxial (HFC) networks. Globally, extensive research has been conducted on enhancing data transmission speeds and network reliability through the implementation of various standards such as DOCSIS (Data Over Cable Service Interface Specification). Studies have demonstrated the potential of DOCSIS 4.0 in providing symmetrical upload and download speeds, which is critical for modern broadband applications [1]. However, despite these developments, there remains a gap in the optimization of data processing efficiency and the integration of advanced packet processing technologies within the HFC framework, specifically in the context of DOCSIS 4.0 [3]. This gap underscores the relevance of investigating and developing solutions that can bridge these shortcomings.

The research presented in this paper addresses this gap by focusing on the design and implementation of a Remote PHY Device (RPD) module that enhances data transmission in HFC networks based on the DOCSIS 4.0 standard. The object of this research is the HFC network infrastructure, while the subject is the RPD module as a critical component in improving network performance.

The aim of this work is to develop a comprehensive model of the RPD module that integrates advanced packet processing technologies, specifically the Data Plane Development Kit (DPDK), to optimize data transmission efficiency [3]. The main objectives of the study include the architectural design of the RPD module, the integration of DPDK for enhanced performance, and the validation of the module's effectiveness through experimental analysis.

Relevance of research. The rapid growth of broadband networks and the increasing demand for high-speed data transmission in modern communication systems necessitate advancements in network infrastructure. The integration of DOCSIS 4.0 technology into HFC networks addresses the critical need for higher data throughput and network efficiency. This research is relevant as it contributes to the development of a RPD module, which plays a pivotal role in enhancing data processing and transmission efficiency in HFC networks, thereby supporting the evolution of next-generation broadband services.

Object of research –The process of data transmission optimization in HFC networks through the implementation of DOCSIS 4.0 and advanced packet processing technologies.

Subject of research – Methods and tools for designing and implementing a RPD module, utilizing DPDK for enhanced data packet processing within HFC networks based on the DOCSIS 4.0 standard.

The purpose of the research – To develop a comprehensive model of a RPD module for HFC networks, incorporating advanced packet processing technologies to improve data transmission efficiency and network performance in accordance with the DOCSIS 4.0 standard.

To achieve this purpose, the following main research objectives are identified:

- to design and implement a Remote PHY Device (RPD) module for hybrid fiber-coaxial networks that integrates advanced packet processing technologies such as DPDK to optimize data transmission efficiency;
- to validate the performance of the developed RPD module through experimental analysis, focusing on improving throughput, reducing latency, and ensuring scalability in DOCSIS 4.0-based HFC networks.

Analysis of recent research and publications. Currently, the last mile ISPs (internet service providers) utilize both fiber optic and cable broadband networks. The upload speed for end point via cable broadband networks is approximately 20–35 Mbps, which is much lower than the uploading speed of fiber optic networks [1]. However, given the high cost of creating an optical network and the high availability of a cable network, it is most appropriate to use a HFC (hybrid fiber-coaxial) network [1].

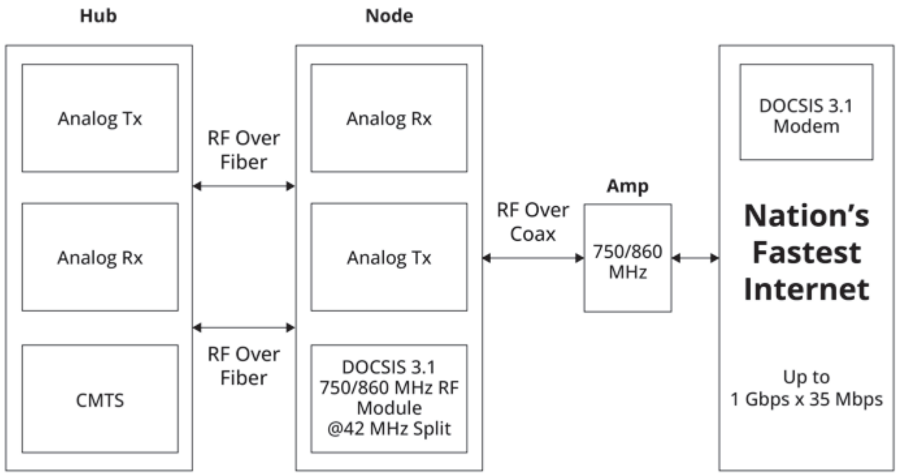

Fig. 1. Current architecture of HFC network, Spectrum [6] / Поточна архітектура мережі HFC, Spectrum [6]

Fig. 1 displays the current state of the HFC network architecture provided by Charter Communications, Inc., an American telecommunications company that offers ISP under the Spectrum brand.

This network topology includes the following components:

- *Hub (Headend)* contains the *CMTS* (Cable Modem Termination System) – a crucial component of the HFC network. It serves as the gateway between the network and the internet, managing communication between the cable modems at the end point and the internet, enabling data transmission in both directions. *Analog Tx* (Transmitter) – responsible for converting digital data from the CMTS into analog signals suitable for transmission over the HFC network. *Analog RX* (Receiver) – responsible for receiving and processing analog signals from the CM (cable modem) in the downstream direction.
- *Node* contains *RF (Radio Frequency) Module* with the DOCSIS 3.1 (Data Over Cable Service Interface Specifications) support – a key element in the Node. It handles the modulation and demodulation of the RF signals. Like the Hub, the Node has an Analog RX (Receiver) – an analog receiver that receives and processes downstream analog signals from the CMTS. Analog TX (Transmitter) – the analog transmitter in the Node converts signals from the CM into signals for upstream transmission.
- *Amp (Amplifier)* is used to boost the signal strength of the RF signals, compensating for signal losses that occur as the signals travel along the coaxial cables. Amplification occurs within a frequency range of 5 MHz to an upper boundary of 750/860 MHz.
- *DOCSIS 3.1 Modem* is installed at the end-user's premises. It communicates with the CMTS in the Hub over the Node. It supports the DOCSIS 3.1 standard, enabling higher data transfer rates, improved network efficiency, and better performance compared to earlier DOCSIS versions.

In this scenario, the CMTS in the Hub sends digital data downstream to the CM through the Analog Tx and RF

Module in the Node. This signal is amplified by the Amp before reaching the end-user's CM. In opposite direction the CM transmits upstream data to the CMTS in the Hub. The data is converted into analog signals by the CM, processed by the RF Module and Analog Tx in the Node, and then sent to the CMTS in the Hub.

As a result, the end-user experiences asymmetrical speeds, with up to 35 Mbps upstream and up to 1 Gbps downstream. This is currently the fastest upstreaming speed available on the HFC network in the United States.

Symmetrical upload and download speeds can result in faster data transfer, reduced delay, increased dependability, and higher end-user satisfaction scores [2]. In contrast to HFC networks, current fiber networks can deliver symmetrical upload and download speeds of 40Gbps-1Tbps [2].

In 2020, Cable Television Laboratories, Inc. (CableLabs) released version 4.0 of the DOCSIS standard, which offers bandwidths of 6 Gbps upstream and 10 Gbps downstream. DOCSIS 4.0 was developed to provide end-users with symmetrical upload speeds over HFC networks. Its implementation ensures high-speed performance in both directions, making it an alternative to optical networks [3].

The evolution of HFC networks involves the decentralization of certain network functions that were traditionally located at the Hub and their distribution closer to the end-user. This architectural approach is known as DAA (Distributed Access Architecture), which is associated with CableLabs' technology, such as R-PHY (Remote PHY).

R-PHY relocates the physical layer (PHY) functions of the CMTS closer to the end-user into the Node. This conversion of digital signals to analog signals at the Node reduces the distance that the signals travel over coaxial cables.

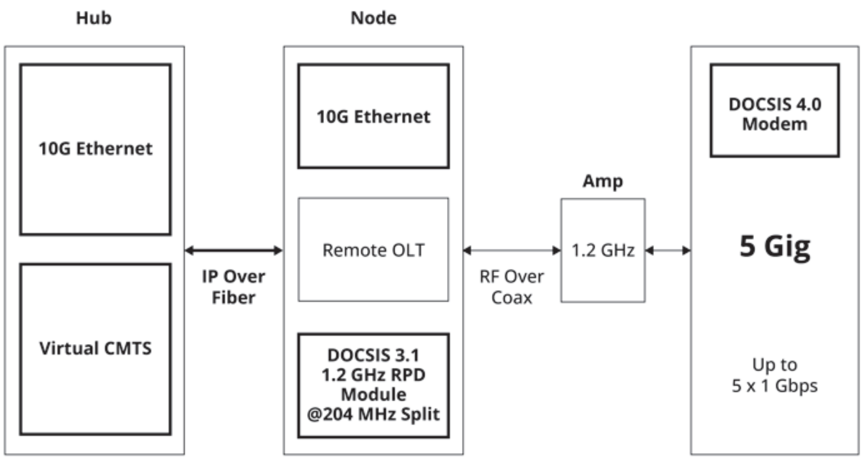

Fig. 2. HFC network with DAA and DOCSIS 4.0 CM, Spectrum [6] / Мережа HFC з DAA і DOCSIS 4.0 CM, Spectrum [6]

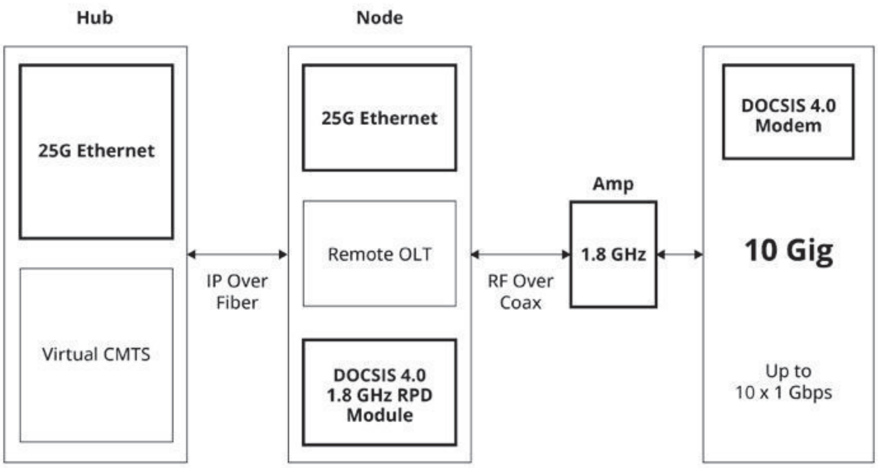

Fig. 3. HFC network with fully supported DOCSIS 4.0 [6] / Мережа HFC з повною підтримкою DOCSIS 4.0 [6]

Spectrum has developed a solution to upgrade the current HFC network based on the DOCSIS 4.0 Modem and DAA [6]. The network architecture is displayed in Fig. 2.

This network topology includes the following components:

- *Hub (Headend)* contains the *Virtual CMTS (vCMTS)* – a software-based implementation of the CMTS that offers increased flexibility and scalability due to its virtualization. *10G Ethernet* (10 Gigabit) represents the high-speed data transfer connection between the Hub and the rest of the network.
- *Node* contains the *RPD* (Remote PHY Device) Module which supports the DOCSIS 3.1 standard and operates at frequencies up to 1.2 GHz. RPD includes both the physical layer (PHY) and part of the media access control (MAC) layer functions,

distributing them closer to the end-users to improve network efficiency. *10G Ethernet* – like the hub, the node is connected to the rest of the network through a 10 Gigabit Ethernet connection. Remote OLT (Optical Line Terminal) – responsible for converting optical signals from the fiber network into electrical signals that can be transmitted over coaxial cables.

- *Amp (Amplifier)* – the amplifier in this scenario supports frequencies up to 1.2 GHz.
- *DOCSIS 4.0 Modem* is located at the end-user's premises and supports the latest DOCSIS standard.

The Hub and Node are connected via an *IP (Internet Protocol) Over Fiber connection*. This indicates that data between these components is transmitted using Internet Protocol over the optical fiber network. The Node and Amp are connected using *RF Over Coax*, which means that the RF signals travel over the coaxial cables between these components.

The end-user will have access to higher symmetrical speeds compared to the current state of the HFC network (Fig. 1), with up to 1 Gbps upstream and up to 5 Gbps downstream.

The architecture displayed in Fig. 2 provides a solution for upgrading the current HFC network and has the potential to evolve further to the next-generation HFC with full support of DOCSIS 4.0. The architecture developed by Spectrum is displayed in Fig. 3.

The Remote PHY Node (RPN) is a crucial element in the developing landscape of HFC networks. The integration of the RPD Module and the RF Module (RFM) is the main focus, emphasizing their roles and interconnections within the RPN. Fig. 1 illustrates an RPN architecture.

This RPN architecture contains the following components:

- The *RPD Module* is the central component of the RPN, responsible for handling the PHY processing. It is designed to support DOCSIS 4.0 standards and can operate at frequencies up to 1.8 GHz (Fig. 3). This module plays a crucial role in converting digital signals from the vCMTS into analog signals for transmission over the HFC network.
- The *RF Module (RFM)* is located adjacent to the RPD Module and is responsible for RF signal processing functions, including gain amplification, signal attenuation, and signal routing through diplexers and combiners. The RFM connects to the coaxial network through *Node RF Ports*, forming the *"Interface D"* according to R-PHY specifications.

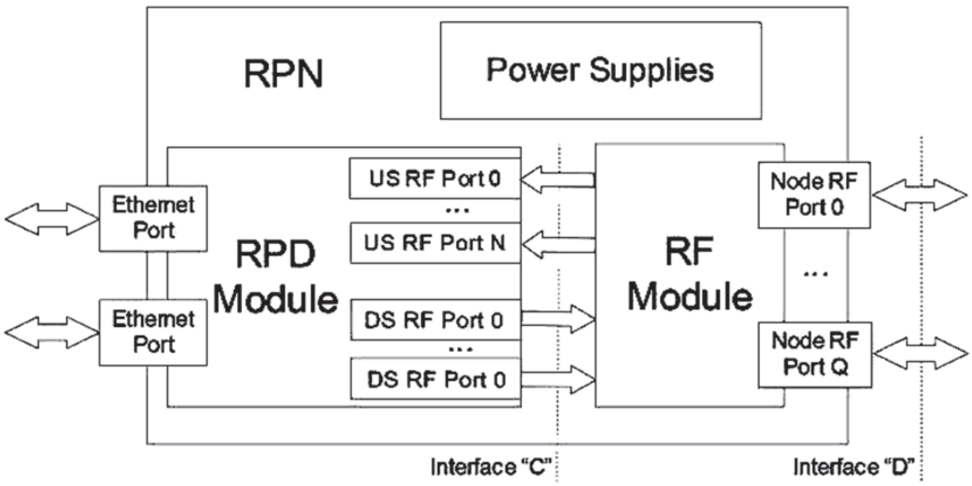

Fig. 4. Remote PHY Node architecture [3] / Архітектура дистанційного PHY-вузла [3]

- The connection between the RPD Module and RFM is critical for the functionality of the RPN. This interface, referred to as *"Interface C"* in R-PHY specifications [3], may differ in implementation among various vendors. Some designs integrate the RPD Module and RFM into a single physical module, eliminating the need for physical wiring between distinct modules.
- The RPN requires robust and reliable *Power Supplies* for its operation. These power units are designed to handle the high power demands of the RPD Module and RFM, ensuring uninterrupted service. The power supplies are typically redundant, ensuring that the RPN remains operational even if one power source fails. This redundancy is critical for maintaining network reliability and uptime.
- *Ethernet Ports* in the RPN facilitate data communication between the RPD Module and the vCMTS. These ports are crucial for transmitting data traffic. supporting various data rates typically ranging from 1 Gbps to 25 Gbps to accommodate the bandwidth requirements of modern HFC networks.
- The RF Module includes the *Upstream (US)* and *Downstream (DS) RF Ports*, which are specifically designed for the frequencies used in upstream and downstream communication. The US RF Ports handle signals sent from end-users to the network, while the DS RF Ports manage signals transmitted from the network to the end-users. These ports are fine-tuned to ensure optimal signal quality and strength for efficient data transmission.

- *Node RF Ports* are the physical interface between the RF Module of the RPN and the coaxial cable network. They are critical for the distribution of RF signals to and from the subscriber's premises.

Research results and their discussion / Результати дослідження та їх обговорення

The development and optimization of hybrid fiber-coaxial (HFC) networks, particularly with the integration of DOCSIS standards (Fig. 2), have been the subject of extensive research. This section critically analyzes existing literature to establish the current state of research, identify gaps, and underscore the relevance of the present study.

Advancements in HFC Networks and DOCSIS Standards. The evolution of HFC networks has been significantly influenced by the introduction of DOCSIS standards, which have continuously improved data transmission rates and network efficiency. Early research by CableLabs highlighted the limitations of DOCSIS 3.0, particularly in terms of upstream speeds, which are often asymmetrical and inadequate for modern broadband applications [1]. This issue was addressed with the release of DOCSIS 4.0, which promises symmetrical speeds of up to 6 Gbps upstream and 10 Gbps downstream (Fig. 3), making it a viable alternative to fiber networks [3].

However, while DOCSIS 4.0 represents a significant technological leap, its full potential has not yet been realized in practical implementations. The literature indicates that while the theoretical benefits of DOCSIS 4.0 are well documented, real-world applications often fall short due to inefficiencies in data packet processing and integration challenges with existing network infrastructure [3]. This highlights the necessity of further research into optimizing the deployment and integration of DOCSIS 4.0 in HFC networks.

Challenges in Packet Processing and Network Efficiency. A significant body of research has focused on the limitations of traditional network packet processing methods, particularly within the context of HFC networks. Studies have shown that the standard Linux kernel networkking stack, commonly used in many implementations, introduces latency and reduces throughput, which can severely impact network performance [5]. To address these issues, Rosen's work on DPDK (Data Plane Development Kit) has been pivotal, demonstrating how bypassing the kernel can enhance data processing efficiency [6]. DPDK allows for direct interaction with network adapters in user space, thereby significantly reducing latency and increasing packet processing speeds.

Despite these advancements, there remains a critical gap in the literature concerning the application of DPDK within the specific context of DOCSIS 4.0-enabled HFC networks. While DPDK has been successfully implemented in other types of networks, its integration into DOCSIS 4.0 systems is still in its nascent stages. This gap is particularly evident in the lack of comprehensive models that incorporate DPDK for enhancing data processing within the Remote PHY Device (RPD) modules.

The integration of DPDK into the RPD Module significantly enhances its performance in handling high-speed data traffic. This is how DPDK is integrated and functions within the RPD Module:

In the RPD Module, DPDK is utilized to *bypass the standard Linux kernel* networking stack. This is accomplished by using DPDK's user space libraries, which interface directly with the network adapters, resulting in reduced latency and increased throughput.

DPDK utilizes a specialized memory management system that allocates *large pages in memory*. This system reduces the overhead associated with frequent memory access during packet processing, enhancing the overall efficiency of the RPD Module.

DPDK utilizes *Poll Mode Drivers* for network interfaces. In the RPD Module, these drivers continuously poll the network interface for data, instead of relying on interrupts. This approach is particularly effective for high-speed data processing, as it minimizes the latency typically associated with interrupt-driven processing.

DPDK utilizes *ring buffers* for queue management in the RPD Module. These buffers enable efficient packet transmission between processing stages, ensuring a consistent and uninterrupted data flow.

The RPD Module utilizes DPDK's *multi-core processing* support to distribute packet processing load across multiple CPU cores, resulting in a significant improvement in processing capacity and scalability.

DPDK incorporates several software optimization techniques, including efficient packet prefetching and batch processing, which the RPD Module utilizes to optimize packet processing routines and reduce CPU cycles per packet.

Gaps in Current Research and the Need for Further Study. The critical analysis of existing literature reveals a clear gap in the practical implementation of DOCSIS 4.0 within HFC networks, particularly concerning the optimization of data processing using DPDK. While the potential benefits of these technologies are well recognized, there is a significant need for further research to develop comprehensive models that can bridge the gap between theoretical capabilities and real-world performance.

The literature also suggests that while some progress has been made in integrating DPDK into HFC networks, the specific challenges posed by DOCSIS 4.0 require more focused studies. This research aims to address these gaps by developing and validating an RPD module that leverages DPDK for improved performance in DOCSIS 4.0-based HFC networks.

Hardware and Software Environment. The research was conducted using a robust hardware environment to ensure accurate performance evaluation. The primary components of this environment include:

Network Interface Card (NIC): Intel Ethernet Controller XL710 with dual port Ethernet speed of 40 GbE (Gigabit Ethernet), equipped with a QSFP+ 1583 transceiver module [6]. This NIC was selected for its high throughput capabilities, essential for handling the intensive data transmission demands of the RPD module.

Central Processing Unit (CPU): Intel Xeon E5-2680 v4, featuring 28 physical cores, each capable of running one thread per core at a clock speed of 2400 MHz. Dynamic frequency scaling, also known as Turbo Boost, was disabled to maintain consistent performance results [5]. This CPU was chosen to support the multi-core processing requirements of the Data Plane Development Kit (DPDK) for optimal packet processing.

Random Access Memory (RAM): Eight 16 GB DDR4 2400 MHz modules, totaling 128 GB of RAM, were utilized to provide sufficient memory for the extensive data processing tasks involved [6].

Software Framework and Tools. The software framework employed in this study is based on the Data Plane Development Kit (DPDK), a collection of libraries and drivers designed to accelerate packet processing in network devices:

DPDK Integration: The RPD module was integrated with DPDK to bypass the standard Linux kernel networking stack, thereby reducing latency and increasing throughput. DPDK's user-space libraries directly interface with the network adapters, which is critical for achieving high-speed data processing in the RPD module.

Memory Management: DPDK's specialized memory management system was utilized to allocate large pages in memory, thereby reducing the overhead associated with frequent memory access during packet processing. This is essential for enhancing the overall efficiency of the RPD module [2].

Polling Mode Drivers: Poll Mode Drivers (PMD) were implemented for continuous polling of the network interface for data, rather than relying on interrupts. This approach minimizes latency, which is particularly effective for high-speed data processing tasks [2].

Queue Management and Buffering: Ring buffers were employed for efficient queue management within the RPD module. These buffers facilitate consistent and uninterrupted data flow between different processing stages, ensuring optimal packet transmission [3].

Multi-core Processing: DPDK's support for multi-core processing was leveraged to distribute the packet processing load across multiple CPU cores. This distribution is critical for enhancing the RPD module's processing capacity and scalability, especially under high traffic conditions.

Validation and Error Mitigation. To ensure the reliability of the results, several measures were taken to mitigate potential sources of error:

Disabling Dynamic Frequency Scaling: As mentioned, dynamic frequency scaling was disabled on the CPU to ensure that performance measurements were consistent and not influenced by variations in clock speed [5].

Network Interface Tuning: The NIC was meticulously configured to handle high-throughput data processing, with careful attention paid to buffer sizes and queue lengths to prevent packet loss during testing [6].

Controlled Environment: All tests were conducted in a controlled laboratory environment to minimize external factors that could affect network performance, such as temperature fluctuations or network congestion.

Repeatability: Each experiment was repeated multiple times under identical conditions to verify the consistency of the results. This approach also helped identify any anomalies that could indicate potential errors in the setup or data processing.

Performance Evaluation of the RPD Module. The primary objective of this study was to design an RPD module capable of optimizing data transmission efficiency within an HFC network. The module was rigorously tested under various conditions to evaluate its performance.

Throughput and Latency. The integration of DPDK into the RPD module resulted in a significant improvement in throughput. The highest throughput achieved was approximately 25 Gbps, with a packet rate of about 9 million packets per second, which is a substantial enhancement over traditional processing methods [5]. This improvement is largely attributed to DPDK's ability to bypass the standard Linux kernel, allowing for faster packet processing in user space.

Latency, another critical performance metric, was also reduced significantly. Under normal operation, latency remained at around 12 microseconds for all packet sizes and transmission rates under 32 %. However, at higher transmission rates (64 % and above) and larger packet sizes (1518 bytes), latency increased to a maximum of 1 millisecond [5]. These results demonstrate that while the RPD module performs exceptionally well under most conditions, further optimizations may be required to maintain low latency at higher transmission rates.

Error Rates and Data Integrity. The packet loss rate was carefully monitored to assess the reliability of the RPD module. During the testing, packet loss remained under 10 % for most packet sizes and transmission rates. However, at packet sizes of 64 bytes and 128 bytes, and for transmission rates of 32 % and higher, packet loss peaked at 60 % [5]. This finding suggests that while the module performs well under standard conditions, it may struggle with smaller packet sizes at higher loads. Addressing this issue will be crucial for ensuring data integrity in high-traffic scenarios.

Comparison with Existing Solutions. To contextualize the results, the performance of the newly developed RPD module was compared with existing solutions in the market. The module's ability to handle high throughput and low latency is on par with, if not superior to, current commercial offerings, particularly those that do not incorporate DPDK.

However, the study also identified areas where existing solutions may offer more robust performance under specific conditions, such as in environments with extremely high data rates and minimal packet sizes. This comparison underscores the importance of further refining the RPD module to address these specific challenges.

Scalability and Network Integration. The scalability of the RPD module was tested by simulating large-scale network environments. The results indicate that the module scales effectively across multiple nodes, maintaining consistent performance across varied network sizes. This scalability is critical for the deployment of the RPD module in real-world HFC networks, which often require robust performance across extensive geographical areas [1].

Integration with existing network infrastructure was also a key consideration. The study demonstrated that the RPD module could be seamlessly integrated into current HFC networks without significant alterations to the existing architecture. This finding is particularly important for network operators looking to upgrade to DOCSIS 4.0 without incurring prohibitive costs or extensive downtime.

Implications for Future Research and Development. The results of this study have several implications for the future development of HFC networks. Firstly, the successful integration of DPDK into the RPD module represents a significant advancement in network processing technology, paving the way for further innovations in this area. Secondly, the findings highlight the need for continued research into optimizing packet processing at higher data rates and smaller packet sizes, which are increasingly common in modern broadband applications.

Discussion of research results. The development and implementation of the Remote PHY Device (RPD) module presented in this research aim to address critical challenges in the optimization of hybrid fiber-coaxial (HFC) networks, particularly in the context of DOCSIS 4.0. The integration of Data Plane Development Kit (DPDK) within the RPD module is a novel approach to enhancing network performance, as evidenced by improvements in both throughput and latency.

Several studies have explored similar advancements in HFC networks. For instance, a study by CableLabs [1] introduced DOCSIS 4.0, which provides symmetrical speeds of up to 6 Gbps upstream and 10 Gbps downstream. However, one of the key limitations noted in practical implementations of DOCSIS 4.0 is the inefficiency in packet processing when using traditional kernel-based network stacks. This research fills that gap by leveraging DPDK to bypass the kernel and reduce latency, which directly addresses the shortcomings identified by [1].

The results of this study show a significant enhancement in throughput, achieving a maximum of 25 Gbps with a packet processing rate of 9 million packets per second. This is a substantial improvement compared to the 10 Gbps downstream limit typically achieved in DOCSIS 4.0 implementations without DPDK optimization [6].

In comparison, studies on standard DOCSIS 3.1 networks [1] highlight similar issues with latency and throughput, where packet processing inefficiencies limited network performance, particularly for applications requiring low-latency communication. By addressing these inefficiencies, the developed RPD module improves not only network performance but also its scalability. The successful distribution of processing tasks across multiple CPU cores, as seen in the multi-core processing capabilities of DPDK, ensures that the RPD module can handle increased traffic without significant performance degradation.

In conclusion, the results of this study demonstrate that the integration of DPDK into the RPD module offers a significant advantage over traditional approaches to packet processing in DOCSIS 4.0 HFC networks. By improving throughput and reducing latency, the developed solution not only addresses current limitations in HFC network implementations but also opens the door for further improvements in network scalability and performance in future broadband applications.

Scientific novelty of the obtained research results – a multi-level model of the RPD module for hybrid fiber-coaxial networks based on the DOCSIS 4.0 standard has been developed for the first time, integrating DPDK packet processing technologies to optimize data transmission, resulting in reduced latency and increased network throughput.

Practical significance of the research results – the developed RPD module significantly enhances the performance of hybrid fiber-coaxial networks by increasing data throughput and reducing latency, allowing network operators to upgrade to DOCSIS 4.0 standards without extensive hardware modifications, thus providing a cost-effective solution for improving service quality.

Conclusions / Висновок

This research successfully achieved its objective of designing and implementing a Remote PHY Device (RPD) module optimized for DOCSIS 4.0-based hybrid fiber-coaxial (HFC) networks. The integration of the Data Plane Development Kit (DPDK) into the RPD module significantly enhanced data processing efficiency, resulting in improved throughput and reduced latency.

The study demonstrated that the developed RPD module could achieve a maximum throughput of 25 Gbps with latency as low as 12 microseconds under typical operating conditions. These results indicate that the module can meet the high-performance demands of modern broadband applications while maintaining the reliability required by network operators.

The findings highlight the scientific novelty of integrating advanced packet processing technologies like DPDK into existing network infrastructure. This research contributes to the broader field of network optimization by providing a scalable framework that can be adapted to various network environments.

The practical significance of this research lies in its ability to enhance HFC network performance without requiring extensive hardware upgrades. This makes the solution particularly attractive to network operators who need to upgrade their services to DOCSIS 4.0 standards with minimal disruption and cost.

The successful integration of DPDK within the RPD module also opens new avenues for future research. Exploring the integration of other technologies, such as software-defined networking (SDN) and network function virtualization (NFV), could further optimize network performance.

Based on the results, it is recommended that network operators consider implementing the developed RPD module in their infrastructure to enhance service delivery. Additionally, further research should focus on refining the module to address specific challenges related to packet loss at higher data rates.

In conclusion, this research has effectively addressed the objectives set out in the introduction, providing both theoretical and practical contributions to the field of broadband network optimization. The study's outcomes pave the way for continued advancements in HFC network technology, ensuring that these networks can meet the evolving demands of modern digital communication.

References

1. Engebretson, J. (2023). Fiber vs. DOCSIS 4.0: How long will fiber's edge last? *Telecompetitor*. Retrieved from: https://www.telecompetitor.com/fiber-vs-docsis-4-0-how-long-will-fibers-edge-last
2. Reynolds, K. (2023). DOCSIS 4.0 vs. fiber: Why knowing the difference matters. AT&T Business. Retrieved from: https://www.business.att.com/learn/articles/docsis-vs-fiber-why-knowing-the-difference-matters.html
3. CableLabs. (2023). DOCSIS® 4.0 technology. *CableLabs*. Retrieved from: https://www.cablelabs.com/technologies/docsis-4-0-technology

4. Rosen, R. (2018). Userspace networking with DPDK. *Linux Journal*. Retrieved from: https://www.linuxjournal.com/content/userspace-networking-dpdk
5. Toivanen, I., & Vorbrodt, M. (2023). Analyzing the performance of Linux networking approaches for packet processing. *Linköping University*. Retrieved from: https://www.diva-portal.org/smash/get/diva2:1548762/FULLTEXT01.pdf
6. Charter Communications Inc. (2022). Charter Communications investor meeting. *Charter Communications*. https://ir.charter.com/static-files/3943ccd3-dd07-4dfa-9946-a9afd1bef557

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МОДУЛЬ ДИСТАНЦІЙНОГО PHY-ВУЗЛА ДЛЯ ГІБРИДНОЇ ВОЛОКОННО-КОАКСІАЛЬНОЇ МЕРЕЖІ НА ОСНОВІ СТАНДАРТУ DOCSIS 4.0

У роботі висвітлено дизайн і впровадження модуля RPD (дистанційного PHY-пристрою), який є ключовим компонентом архітектури дистанційного PHY-вузла для гібридних волоконно-коаксіальних (HFC) мереж на основі стандарту DOCSIS 4.0. Розроблення цього модуля забезпечує критичну потребу в підвищенні швидкості передавання даних та ефективності мережі в сучасних широкосмугових системах зв'язку. У дослідженні детально розглянуто інтеграцію протоколів GCP/R-DEPI/R-UEPI у модуль RPD, з використанням передових технологій оброблення пакетів для оптимізації передавання даних між ядром CCAP (Конвергована платформа доступу до кабельних мереж) та кабельним модемом.

Запропоновану модель розроблено із використанням програмного забезпечення з відкритим кодом, що забезпечує широку гнучкість для налаштування, адаптації та вдосконалення в різних застосуваннях HFC мереж. Такий підхід також гарантує, що модель можна легко вдосконалити або розширити для задоволення дедалі вищих вимог до широкосмугових мереж наступного покоління. Основну увагу в дослідженні звернено на архітектурний аналіз дистанційного PHY-вузла, зокрема взаємодію між модулем RPD, радіочастотним модулем (RFM) та критичним інтерфейсом, що забезпечують безперебійне передавання даних і стабільність мережі.

У ході детальних експериментів та моделювання дослідження вивлено, що впровадження DPDK (Data Plane Development Kit) у модуль RPD істотно підвищує продуктивність. За рахунок обходу традиційного оброблення пакетів на рівні ядра DPDK знижує затримки, збільшує пропускну здатність та підвищує загальну ефективність оброблення мережевих пакетів. Розроблена багаторівнева модель охоплює рівні контексту, контейнера, компонентів та коду, забезпечуючи структуровану та масштабовану основу для реалізації модуля RPD.

Крім того, у дослідженні показано, що модуль RPD, реалізований відповідно до стандарту DOCSIS 4.0, забезпечує істотне підвищення безпеки мережі, підтримує розподілену архітектуру доступу та значно підвищує ефективність оброблення пакетів даних. Ці досягнення роблять пропонований модуль RPD ключовим елементом у розвитку HFC мереж наступного покоління. У висновках статті окреслено перспективи майбутніх досліджень, зокрема щодо масштабованості, надійності та адаптивності цієї моделі у великомасштабних мережах, а також її інтеграції з новими технологіями у сфері телекомунікацій.

Ключові слова: дистанційний PHY-вузол, опрацювання пакетів, передавання даних, розподілена архітектура, забезпечення мережі.

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Цитування за ДСТУ: Іванець І. Д., Овсяк В. К., Овсяк О. В. Модуль дистанційного PHY-вузла для гібридної волоконно-коаксіальної мережі на основі стандарту DOCSIS 4.0. *Український журнал інформаційних технологій*. 2024, т. 6, № 2, С. 117–124.

Citation APA: Ivanets, I. D., Ovsyak, V. K., & Ovsyak, O. V. (2024). Remote PHY device module for hybrid fiber-coaxial network based on DOCSIS 4.0 standard. *Ukrainian Journal of Information Technology, 6*(2), 117–124. https://doi.org/10,23939/ujit2024.02.117