https://www.sworldjournal.com/index.php/swj/article/view/swj31-01-036
DOI: 10.30888/2663-5712.2025-31-01-036

UDC 004.732

COMPARATIVE ANALYSIS OF THE EFFICIENCY OF ENERGY EFFICIENT ETHERNET (EEE) TECHNOLOGY IN ETHERNET NETWORKS

ПОРІВНЯЛЬНИЙ АНАЛІЗ ЕФЕКТИВНОСТІ ТЕХНОЛОГІЇ ENERGY EFFICIENT ETHERNET (EEE) В ETHERNET-МЕРЕЖАХ

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Abstract. *The energy efficiency features of the Energy Efficient Ethernet (EEE) technology and the impact of transitions to the low power idle mode with subsequent return to the active state on the frame transmission time of an Ethernet channel in EEE mode at different transmission rates depending on the channel utilization are investigated. The operating parameters of the IEEE 802.3az standard for various transmission rates are presented, as well as analytical expressions for calculating the power consumption of the channel and the average frame transaction time in EEE mode. Based on the calculations, graphs are constructed showing the power consumption of the port in different operating modes and the average frame transaction time depending on the channel utilization at different transmission rates. Conclusions are drawn regarding the impact of the energy-saving mode on key performance indicators of modern Ethernet networks.*
Key words: *Industry 5.0, Energy Efficient Ethernet (EEE), IEEE 802.3az standard, Green Ethernet, channel utilization, power consumption, frame transaction time, mathematical models.*

Introduction.

The concept of Industry 5.0 focuses on the creation of intelligent and sustainable systems in which energy consumption optimization plays an important role. In this context, Green Ethernet technology becomes one of the key tools for reducing the energy costs of network equipment, which accounts for more than 10% of the total energy consumption of information systems [1]. The design and reengineering of computer networks using energy-efficient solutions contributes not only to reducing the environmental footprint but also to increasing the economic efficiency of the infrastructure within the framework of the Industry 5.0 concept.

To reduce the energy consumption of Ethernet networks, the IEEE 802.3az standard (Energy Efficient Ethernet, EEE) was developed [2]. When evaluating energy efficiency in EEE mode, it is necessary to take into account the operating parameters of the standard, which depend on the data transmission rate in the Ethernet channel and the time required to transition from the active state to the Low Power Idle (LPI) mode and back. These parameters determine the power consumption in the active mode and low power mode, as well as the temporal characteristics of the transitions between these states and the frame transaction time in the channel.

Presentation of the main material.

Typical parameter values of IEEE 802.3az operation for various data transmission rates are presented in Table 1 [3].

Table 1 – Operating parameters of the IEEE 802.3az standard for various data transmission rates

Parameter	100Base-TX	1000Base-T	10GBase-T
Time to transition to Sleep state, µs	200	182	2.88
Time to transition to Wake state, µs	30.5	16.5	4.48
Power consumption in Active state, mW	200	600	4000
Power consumption in LPI state, mW	20	60	400

The expression for the power consumed by a port in the standard operating mode of the IEEE 802.3 standard (P_s), taking into account that the power consumed in the idle state is approximately equal to the power consumed in the active state, can be written as:

$$P_s = P_A \, , \tag{1}$$

where P_A is the power consumed by the port in the active state.

The power consumed by the port in EEE mode depends on the proportion of time the interface spends in each of its possible states [4]:

$$P = \rho_{off} P_{LPI} + \rho_{tra} P_A + \rho_{on} P_A \, , \tag{2}$$

where ρ_{off} is the proportion of time the interface operates in the low power mode, ρ_{tra} is the proportion of time spent in the transition state between modes, ρ_{on} is the proportion of time in the active mode, and P_{LPI} is the power consumed in the low power mode.

The average time that a port spends in LPI mode before the arrival of the next frame, assuming an exponential distribution of inter-arrival times, is determined by the following expression:

$$T_{off} = \frac{e^{-\lambda t_S}}{\lambda}, \tag{3}$$

where λ is the frame arrival rate, t_S is the time required to switch the channel from the active state to the low power state.

The average time during which the port transmits frames after transitioning to the active mode, before returning to the LPI mode, is given by the following expression:

$$T_{on} = \frac{U}{1-U}\left(t_S + t_w + \frac{e^{-\lambda ts}}{\lambda}\right), \tag{4}$$

where U is the channel utilization, t_w is the time required to switch the channel from the low power state to the active state.

While the channel is in the active state, it transmits frames from the queue. Therefore, the proportion of time it operates in the active mode corresponds to the channel utilization:

$$\rho_{on} = \frac{T_{on}}{T_{off} + T_{on} + t_S + t_w} = U. \tag{5}$$

Proportion of time the port operates in the LPI state:

$$\rho_{off} = \frac{T_{off}}{T_{off} + T_{on} + t_S + t_w}. \tag{6}$$

Proportion of time the port operates in transition states:

$$\rho_{tra} = \frac{t_S + t_w}{T_{off} + T_{on} + t_S + t_w}. \tag{7}$$

Expressions (1) – (7) represent a mathematical model of the power consumption of an Ethernet channel in EEE mode. Based on these expressions and the data from table 1, calculations were performed, and the results are presented as graphs of the power consumed by the switch port for various data transmission rates (figure 1) – (figure 3).

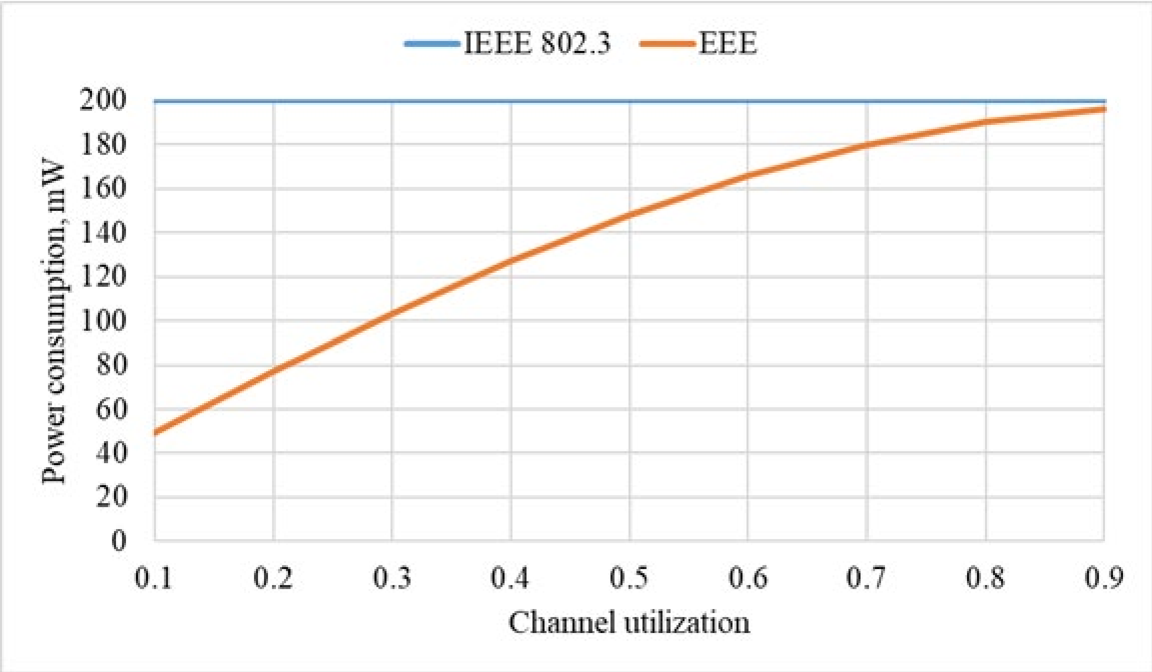

Figure 1 – Power consumed by the port in different operating modes for the 100Base-TX standard depending on channel utilization.

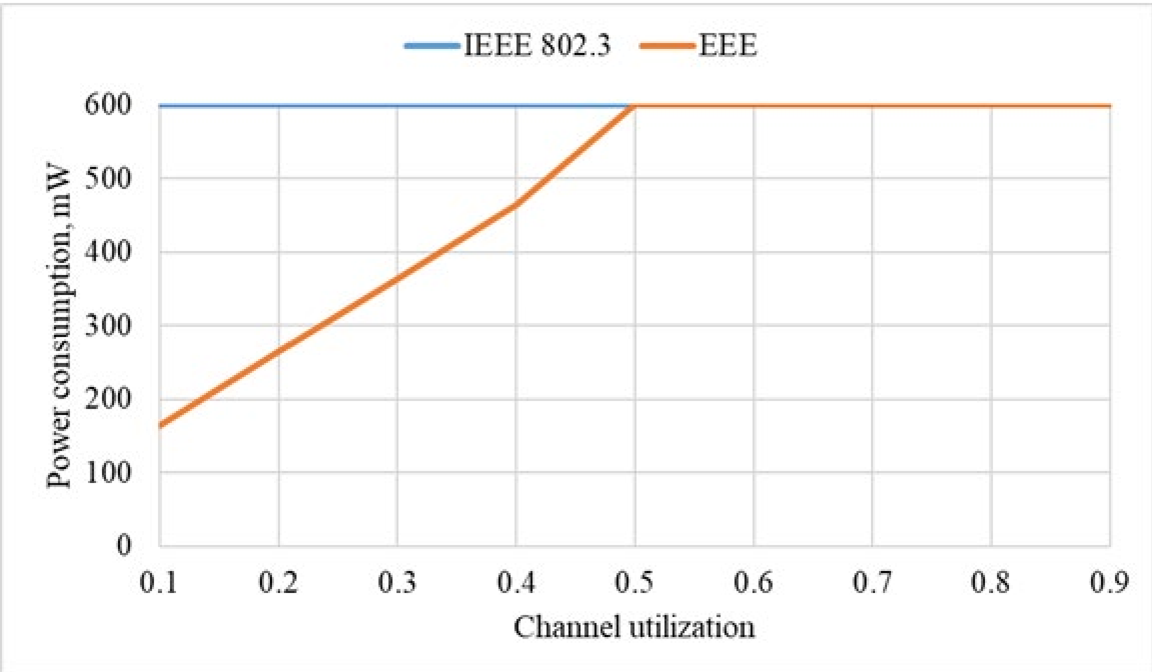

Figure 2 – Power consumed by the port in different operating modes for the 1000Base-T standard depending on channel utilization.

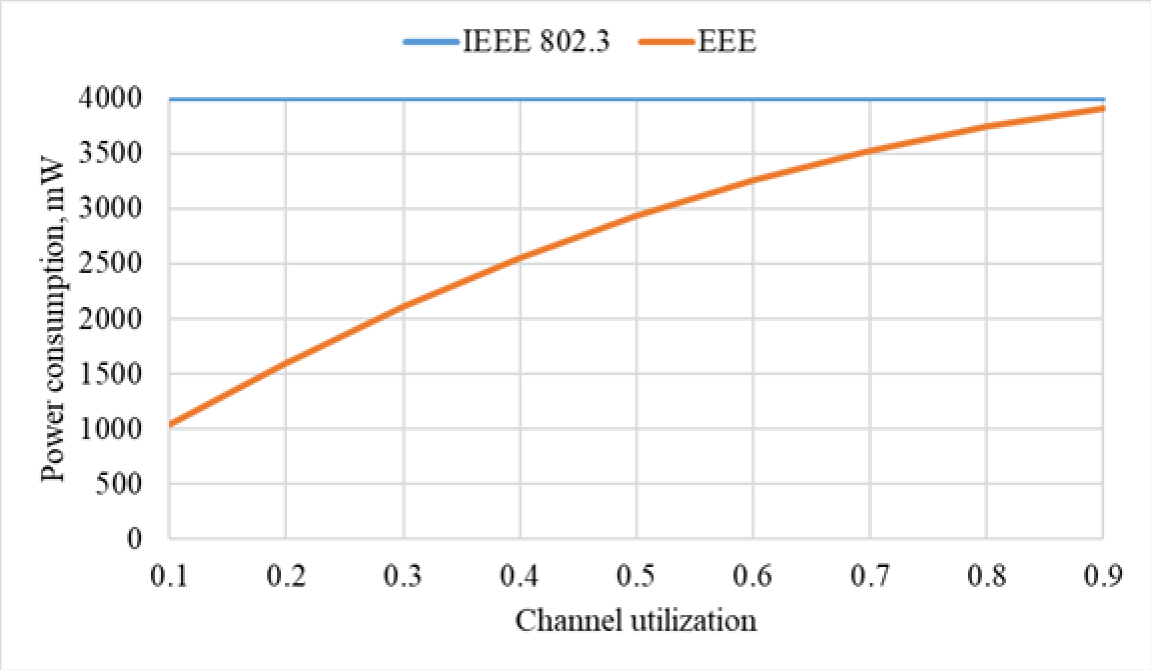

Figure 3 – Power consumed by the port in different operating modes for the 10GBase-T standard depending on channel utilization.

The presence of transition phases between states in EEE technology leads to an increase in frame transaction time.

The average frame transaction time is defined as [5]:

$$T_{\text{tr}}^{avg} = \rho_{on} \cdot T_{\text{tr}}^{min} + \rho_{off} \cdot \left(T_{\text{tr}}^{min} + t_S + t_w\right) + \rho_{tra} \cdot \left(T_{\text{tr}}^{min} + t_S\right), \qquad (8)$$

where T_{tr}^{min} – minimum frame transmission time:

$$T_{\text{tr}}^{min} = \frac{L_{\text{s}} + L_{\text{p}}}{V_{\text{c}}}\ , \qquad (9)$$

where L_{s} is the frame size in bits, $L_{\text{p}} = 96$ bits is the minimum interframe gap according to the IEEE 802.3 standard, and V_{c} is the bit rate in the physical communication channel.

Similarly, the calculations of the average frame transaction time were performed based on expressions (3) – (9). The calculation results are presented as graphs showing the dependence of the frame transaction time on channel utilization for various data transmission rates (figure 4) – (figure 6).

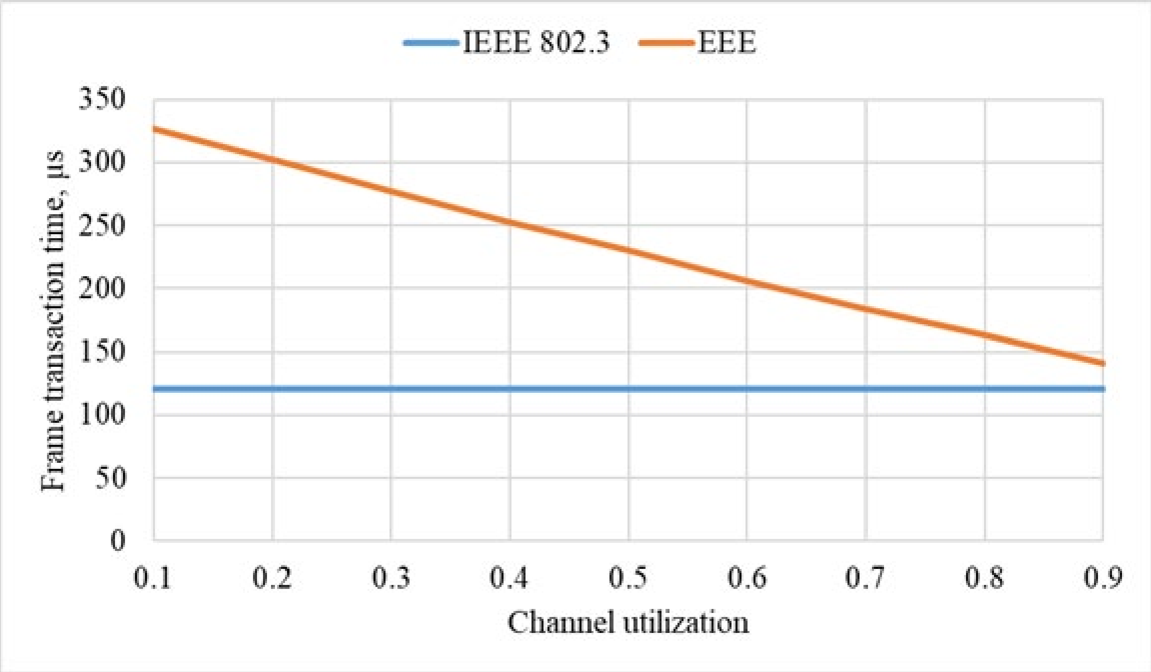

Figure 4 – Frame transaction time (1500 bytes) depending on channel utilization in different operating modes for the 100Base-TX standard.

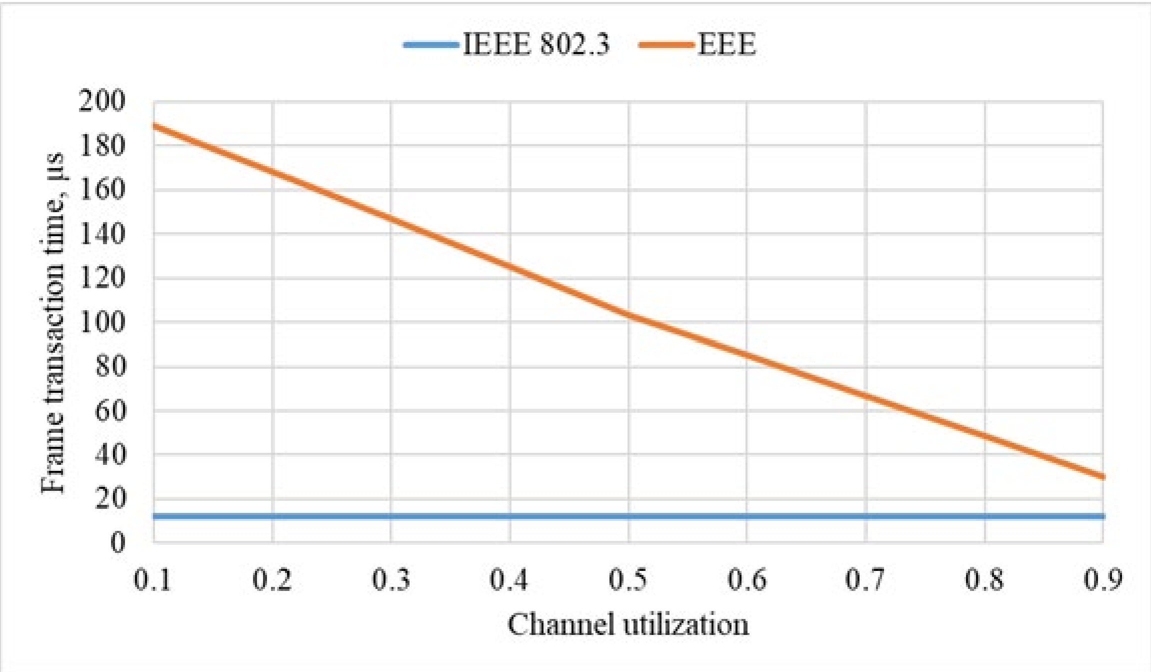

Figure 5 – Frame transaction time (1500 bytes) depending on channel utilization in different operating modes for the 1000Base-T standard.

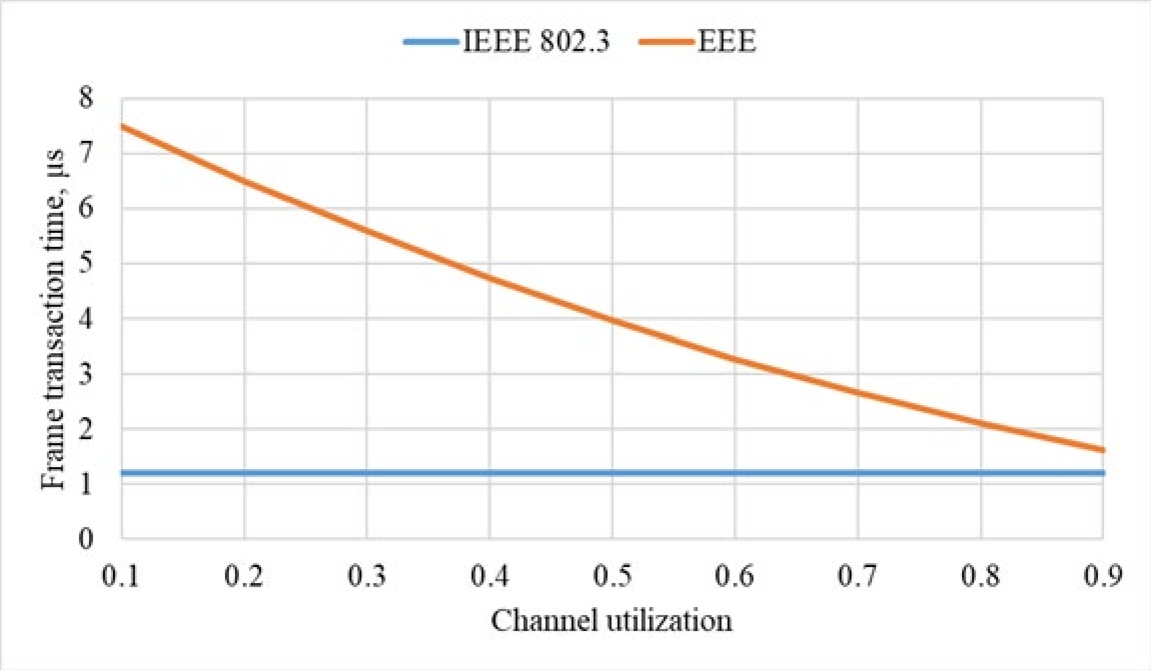

Figure 6 – Frame transaction time (1500 bytes) depending on channel utilization in different operating modes for the 10GBase-T standard.

Conclusions.

The analysis of the presented graphs shows that the use of EEE mode at a data transmission rate of 1000 Mbps becomes impractical when channel utilization exceeds 50%, since the power consumption is almost the same as in the standard operating mode, while the average frame transaction time increases significantly compared to the standard mode, leading to a substantial decrease in channel throughput. This is due to the relatively large timing parameters of the IEEE 802.3az standard compared to other data transmission rates. When channel utilization exceeds 50%, the port spends a significant portion of time in transitional states between the active and energy-saving modes, as a result of which the channel almost never enters the LPI mode.

For transmission rates of 100 Mbps and 10000 Mbps, the transition times between the active and LPI states are negligible relative to the frame transmission time, which makes it possible to reduce power consumption across the entire range of channel utilization, with the energy-saving effect being most significant at low channel utilization levels.

Consequently, when designing networks using EEE, it is important to consider not only the data transmission rate but also the level of network load in order to achieve the best trade-off between energy savings and performance.

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Анотація. *Досліджено особливості енергоефективності технології Energy Efficient Ethernet (EEE) та вплив переходів до режиму зниженого енергоспоживання з подальшим поверненням до активного стану на час передавання кадрів в каналі Ethernet у режимі EEE за різних швидкостей передавання даних залежно від завантаження каналу. Наведено параметри роботи стандарту IEEE 802.3az для різних швидкостей передавання, а також аналітичні вирази для розрахунку споживаної потужності каналу та середнього часу транзакції кадру в режимі EEE. На основі розрахунків побудовано графіки споживаної потужності порту в різних режимах роботи та середнього часу транзакції кадру залежно від завантаження каналу за різних швидкостей передавання. Зроблено висновки щодо впливу енергозберігаючого режиму на ключові показники продуктивності сучасних Ethernet-мереж.*

Ключові слова: *Індустрія 5.0, Energy Efficient Ethernet (EEE), стандарт IEEE 802.3az, Green Ethernet, завантаження каналу, енергоспоживання, час транзакції кадру, математичні моделі.*

Статтю надіслано: 18.05.2025

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