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MODBUS TCP BACKBONE THROUGHPUT ANALYSIS FOR NOISY IEEE 802.11 WIRELESS CHANNEL

С. Нестеренко, О. Наумов. **Аналіз пропускної здатності магістральної мережі "Modbus TCP" для шумного бездротового каналу IEEE 802.11.** Застосування високошвидкісних безпровідних каналів IEEE 802.11 (802.11n/ac/ax) для магістралі Modbus TCP в автоматизованих системах управління промисловими підприємствами (АСУТП) потребує оцінки продуктивності магістралі в умовах роботи каналів зв'язку з урахуванням особливостей функціонування АСУТП, де присутній високий рівень бітових помилок у каналах зв'язку. На основі аналізу алгоритмічної структури магістралі та часових діаграм передавання в безпровідному каналі отримано аналітичні залежності для розрахунку часу транзакції та пропускної здатності магістралі для реального безпровідного каналу. Проведено аналіз пропускної здатності магістралі для типових операцій з урахуванням різного рівня бітових помилок – Bit error rate (BER) у безпровідному каналі зв'язку. Виділено класи операцій магістралі Modbus TCP (прості та складені). Показано, що складені операції формуються як композиція певної кількості простих операцій. На відміну від моделей з ідеальними каналами зв'язку, у моделях для реальних каналів враховано механізми повторної передавання кадрів і додаткові затримки, пов'язані з бітовими помилками під час передавання інформації. Отримані вирази для часу виконання операцій і пропускної здатності дають змогу оцінити реальну продуктивність магістралі Modbus TCP для безпровідних каналів з помилками. Проведений розрахунок пропускної здатності демонструє суттєвий вплив бітових помилок на пропускну здатність магістралі для одноканальних і мультиканальних реалізацій магістралі Modbus TCP на базі безпровідних каналів сімейства IEEE 802.11. Отримані аналітичні залежності часу виконання типових операцій і пропускної здатності магістралі є інструментом для вибору оптимальних конфігурацій під час проєктування та модернізації промислових мереж на базі безпровідних реалізацій магістралі Modbus TCP у межах концепції «Індустрія 4.0».
Ключові слова: Modbus TCP, стандарт IEEE 802.11, АСУТП, алгоритмічна структура, час транзакції, пропускна здатність, прості та складені операції, бітові помилки, повторна передача

S. Nesterenko, O. Naumov. **Modbus TCP backbone throughput analysis for noisy IEEE 802.11 wireless channel.** The use of high-speed wireless IEEE 802.11 channels (802.11n/ac/ax) for the Modbus TCP backbone in automated control systems of industrial enterprises (APCS) requires an assessment of backbone performance under communication channel operating conditions, taking into account the specific features of APCS operation, where a high level of bit errors is present in the communication channels. Based on an analysis of the algorithmic structure of the backbone and transmission timing diagrams in a wireless channel, analytical relationships were obtained for calculating transaction time and backbone throughput for a real wireless channel. An analysis of the backbone throughput for typical operations was carried out, taking into account different levels of bit error rate (BER) in the wireless communication channel. Classes of Modbus TCP backbone operations (simple and composite) are identified. It is shown that composite operations are formed as a composition of a certain number of simple operations. Unlike models with ideal communication channels, models for real channels take into account frame retransmission mechanisms and additional delays associated with bit errors during information transmission. The obtained expressions for operation execution time and throughput make it possible to assess the real performance of the Modbus TCP backbone for wireless channels with errors. The performed throughput calculation demonstrates a significant impact of bit errors on the backbone throughput for single-channel and multi-channel implementations of the Modbus TCP backbone based on wireless channels of the IEEE 802.11 family. The obtained analytical relationships for the execution time of typical operations and backbone throughput represent a tool for selecting optimal configurations in the design and modernization of industrial networks based on wireless implementations of the Modbus TCP backbone within the framework of the "Industry 4.0" concept.
Keywords: Modbus TCP, IEEE 802.11 standard, APCS, algorithmic structure, transaction time, throughput, simple and composite operations, bit errors, retransmission

1. Introduction

The implementation of the "Industry 4.0" concept requires ensuring reliable data transmission with deterministic temporal characteristics at all levels of automated control systems of industrial enterprises (APCS). In accordance with the IEC/ISO 62264 classification, the APCS architecture represents a hierarchical structure of five levels, where the lower levels include SCADA systems and local subsystems with controllers, sensors, and actuators. In modern industrial networks, there is a predominance of high-speed H2-class backbones, among which solutions based on the Modbus TCP protocol occupy a dominant position. In parallel with this, there is active adoption of wireless technologies compliant with the IEEE 802.11 standards.

The application of IEEE 802.11 family wireless channels for implementing industrial communication backbones is driven by a combination of technical and economic factors: reduction of capital expenditures on cable infrastructure deployment, increased network topology flexibility, and simpli-

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fied reconfiguration procedures during production system modernization. However, the specifics of the industrial operating environment are characterized by the presence of significant levels of electromagnetic interference from power equipment, multipath propagation of radio signals due to reflections from metal structures, as well as temporal instability of channel parameters. The combination of these factors leads to a substantial increase in the bit error rate (BER), the values of which in industrial conditions can reach the range of $10^{-4}\ldots10^{-6}$, which is several orders of magnitude higher than the indicators for office and residential applications of Wi-Fi technology.

Existing analytical models for the performance of IEEE 802.11 wireless networks are based on the assumption of stochastic multiple access of stations to a shared transmission medium and account for probabilistic characteristics of collisions during contention-based access via the CSMA/CA mechanism. The architecture of Modbus TCP networks fundamentally differs in its strictly deterministic “master station – slave devices” interaction scheme, in which all transactions are initiated exclusively by the master station, eliminating the possibility of collisions between requests. This fundamental difference renders classical random multiple access models inapplicable for accurate evaluation of the performance of Modbus TCP backbones implemented over wireless channels, creating a methodological gap between the theoretical apparatus for analyzing wireless networks and the practical tasks of designing industrial automation systems.

2. Literature Review and Problem Statement

There is a significant number of works devoted to modeling the temporal characteristics and throughput of wireless channels of the IEEE 802.11 standard.

In paper [1], an analytical model is presented for calculating the maximum theoretical throughput of IEEE 802.11 under ideal conditions. The model takes into account the size of transmitted data, overhead associated with physical- and MAC-layer headers, interframe intervals, and transmission deferral time. It is shown that for IEEE 802.11a with a nominal data rate of 54 Mbit/s, the actual throughput does not exceed 25 Mbit/s, which is only 46% of the physical layer transmission rate.

Study [2] extends the analytical model by considering different medium access mechanisms (CSMA/CA and RTS/CTS). It is shown that the use of the RTS/CTS mechanism further reduces throughput by 20…25% due to the transmission of additional control frames.

In paper [3], a stochastic Markov model is proposed for analyzing the throughput of IEEE 802.11 DCF under conditions of station contention for medium access, taking collisions into account. The model makes it possible to calculate the transmission probability and collision probability as functions of the number of competing stations. It is established that when the number of stations increases from 5 to 50, throughput with the basic access method decreases by 15…20%, whereas the RTS/CTS mechanism provides more stable performance. The prediction accuracy of the model reaches up to 10…12% under various traffic load scenarios.

All the considered models describe scenarios with multiple random access of stations to the wireless channel, where throughput strongly depends on the number of competing stations and the probability of collisions. The Modbus TCP network architecture fundamentally differs due to its centralized “master station – slave devices” topology, in which all transactions are initiated exclusively by the master station. This eliminates collisions between requests and makes classical multiple-access models inapplicable for accurate evaluation of the throughput of a Modbus backbone over a Wi-Fi channel.

The relevance of studying the temporal characteristics and throughput of the Modbus TCP backbone when using wireless channels of the IEEE 802.11 family is determined by the need to account for real industrial environment conditions with a high level of bit errors. Of particular importance is the development of mathematical models for real wireless channels of automated control systems of industrial enterprises and the analysis of the impact of the bit error rate (BER) on the temporal parameters of backbone operation, including the study of the dependence of backbone throughput on the bit error intensity in the transmission channel.

The obtained results make it possible to select the required configuration of wireless channels to ensure specified temporal characteristics while taking into account the existing level of bit errors in the transmission medium during the design and modernization of industrial networks based on wireless implementations of the Modbus TCP backbone in accordance with the principles of the “Industry 4.0” concept.

3. The purpose and objectives of the research

The aim of this work is to develop and study mathematical models of the throughput of the Modbus TCP backbone when using wireless channels of the IEEE 802.11 standard, taking into account the impact of bit errors in the communication channel on transaction time. The model development considers the operational features of the backbone, which operates according to a master-slave scheme, eliminating collisions in the channel and ensuring a deterministic method of access to slave devices. The developed mathematical models allow evaluating the performance of the backbone under various levels of bit errors in the communication channel for both single-channel and multi-channel configurations of wireless channels within the IEEE 802.11 family. The obtained models enable the design of automated control system subsystems with the required performance based on the Modbus TCP backbone using wireless channels of the IEEE 802.11 standard.

4. Materials and methods of the research

Modbus TCP is an industrial data exchange protocol that implements a client-server architecture in automated systems based on the TCP/IP protocol stack [4]. This protocol is an extension of the Modbus RTU protocol for operation in a TCP/IP environment and provides reliable high-speed information transfer between control devices and actuator modules in industrial automation systems.

When using IEEE 802.11 wireless technologies as the physical and data link layer protocols, Modbus TCP enables data transmission without the need for wired connections, significantly increasing the mobility and flexibility of industrial systems. Wireless communication channels of the IEEE 802.11 family retain all functional advantages of the Modbus TCP protocol, including ease of implementation, compatibility with Ethernet networks, and low deployment cost, making them a promising solution for industrial automation within the framework of the Industry 4.0 concept [5, 6].

The Modbus TCP protocol supports the transmission of control commands, data collection and processing, as well as diagnostic functions to improve the reliability of automated systems. Within the OSI model [7], the protocol uses five layers: application, transport, network, data link, and physical, where each layer contributes to the overall throughput and transaction time characteristics of the backbone. The structure of the application layer packet is shown in Fig. 1.

The application layer header H1 (Header 1) contains control information, including the transaction identifier, device address, and operation code. The data field D has a size ranging from 1 to N bytes, depending on the type of operation code in the H1 field.

The structure of the transport layer packet is shown in Fig. 2.

The transport layer header H2 (Header 2) is 20 bytes in size and contains control information, including fields such as the sender and receiver port numbers, packet sequence number, acknowledgment window size, header checksum, and data urgency pointer.

The structure of the network layer packet is shown in Fig. 3.

H1 (8 bytes)	D (N bytes)

Fig. 1. Application layer packet structure

H2 (20 bytes)	H1 (8 bytes)	D (N bytes)

Fig. 2. Transport layer packet structure

H3 (20 bytes)	H2 (20 bytes)	H1 (8 bytes)	D (N bytes)

Fig. 3. Network layer packet structure

The network layer header H3 (Header 3) is 20 bytes in size and contains control information, including the protocol version, header length, header checksum, sender IP address, and receiver IP address.

The structure of the data link layer packet is shown in Fig. 4 [8].

H4 (30 bytes)	H3 (20 bytes)	H2 (20 bytes)	H1 (8 bytes)	D (N bytes)	FSC (4 bytes)

Fig. 4. Data link layer packet structure

The data link layer header H4 (Header 4) contains the receiver and sender addresses, frame type, wireless channel occupancy time, and sequence number of the transmission. The frame checksum field (FSC) is used to detect errors at the data link layer [9].

The structure of the physical layer packet is shown in Fig. 5.

Preamble	PHeader	H4 (30 bytes)	H3 (20 bytes)	H2 (20 bytes)	H1 (8 bytes)	D (N bytes)	FSC (4 bytes)

Fig. 5. Physical layer packet structure

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The Preamble and PHeader fields do not have a fixed size in bytes, they are measured in time and are defined individually for each specific standard within the 802.11 family [9].

For calculating temporal parameters, the wireless channel operation mode BTC (Base Transmission Cycle) was used, since the operation principle of the Modbus TCP backbone in the master-slave scheme specifically employs this wireless channel mode.

In BTC mode, there is no procedure for establishing a connection between the transmitter and receiver; the first frame immediately transmits the payload data. The operation diagram of the BTC mode in an ideal channel is shown in Fig. 6 [10].

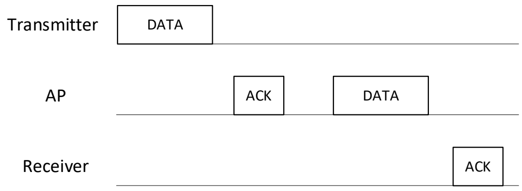

Fig. 6. BTC mode operation diagram in an ideal channel

Timing diagram of a single data frame transmission through a wireless access point (AP) in BTC mode in an ideal channel is shown in Fig. 7.

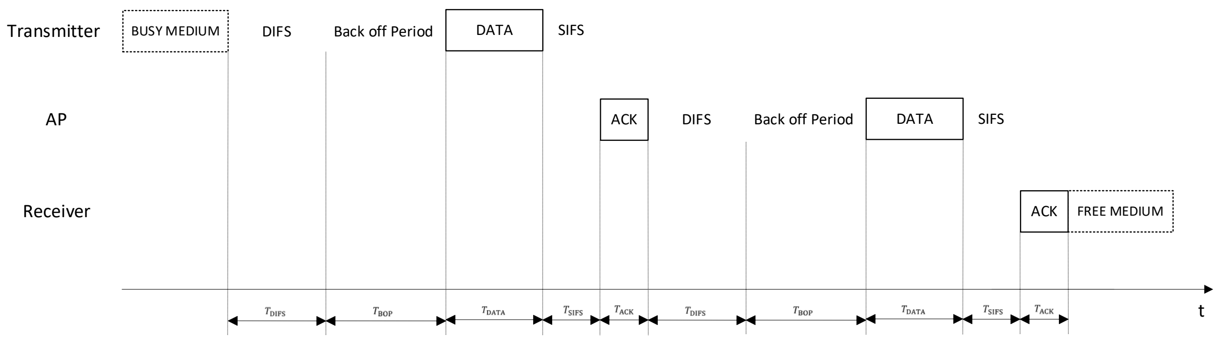

Fig. 7. Timing diagram of frame transmission in BTC mode in an ideal channel

In the event of errors during the transmission of a data packet or an ACK packet in wireless communication channels of the IEEE 802.11 family standards, a retransmission process of the corrupted frame is carried out. The transmitting side waits for a time interval called ACK Timeout, the value of which is regulated by the relevant wireless communication standards, after which it initiates the retransmission procedure of the corrupted data packet. This retransmission process can be repeated multiple times until the maximum number of transmission attempts specified by the corresponding IEEE 802.11 standard is reached.

The timing diagram of a packet transmission through a wireless AP in the event of transmission errors is shown in Fig. 8.

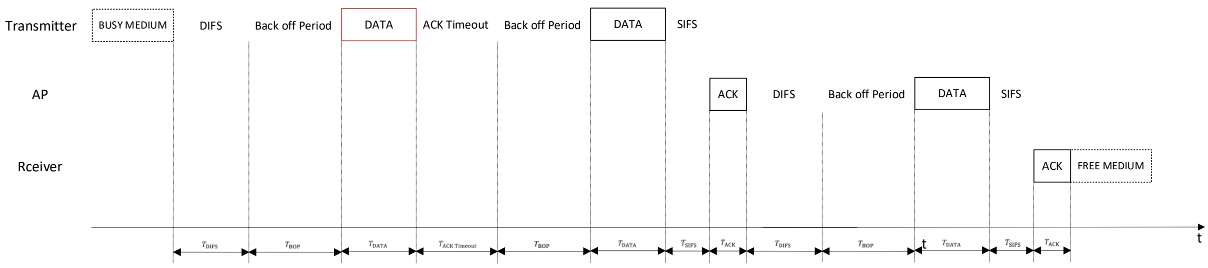

Fig. 8. Timing diagram of frame transmission in BTC mode in the event of transmission errors

The formula for calculating the transaction time over the physical channel of the Modbus TCP backbone when using BTC mode is as follows:

$$T_{\mathrm{TR}}^{\mathrm{BTC}} = 2(T_{\mathrm{DIFS}} + T_{\mathrm{BOP}} + T_{\mathrm{DATA}} + T_{\mathrm{SIFS}} + T_{\mathrm{ACK}})\,, \qquad (1)$$

where: T_{DATA} – data frame transmission time; T_{ACK} – acknowledgment frame transmission time; T_{DIFS} – fixed interframe spacing; T_{BOP} – transmission delay; T_{SIFS} – short interframe spacing.

According to the 802.11ac standard, the data frame transmission time is calculated using the following formula:

$$T_{\text{DATA}} = T_{\text{Preamble}} + T_{\text{PHeader}} + \left\lceil \frac{8L_{\text{DATA}}}{DR} \right\rceil, \tag{2}$$

where: T_{Preamble} – preamble transmission time; T_{PHeader} – physical layer header transmission time; L_{DATA} – size of the data frame. These parameters are defined by the specific standard within the 802.11 family, and DR – data transmission rate.

The size of the data frame transmitted over the physical channel, according to the standard, is determined by the following formula:

$$L_{\text{DATA}} = \text{H4+H3+H2+H1+D} + \text{FCS}. \tag{3}$$

The backbone throughput in an ideal channel is determined by the following formula:

$$V = \frac{L}{T_{\text{TR}}^{\text{BTC}}}, \tag{4}$$

where: V – backbone throughput in an ideal channel; L – size of the payload; $T_{\text{TR}}^{\text{BTC}}$ – transaction time in an ideal channel.

The transaction time for transmission in a real channel is determined by the following formula:

$$T_{\text{TR. R.}}^{\text{BTC}} = T_{\text{TR}}^{\text{BTC}} + (T_{\text{TR}}^{\text{BTC}}) P_{\text{RT}}, \tag{5}$$

where: $T_{\text{TR}}^{\text{BTC}}$ – transaction time in an ideal channel; P_{RT} – probability of frame retransmission.

In the event of a corrupted data frame, it is retransmitted. The probability of retransmission is calculated using the following formula:

$$P_{\text{RT}} = \frac{P_{\text{FC}}}{1 - P_{\text{FC}}}, \tag{6}$$

where: P_{FC} – probability of frame corruption.

The probability of frame corruption is calculated by multiplying the probability of a single bit error by the total number of bits transmitted in one transaction:

$$P_{\text{FC}} = N \cdot \text{BER}, \tag{7}$$

where: N – total number of bits transmitted in one transaction; BER – probability of a single bit error.

The total number of transmitted bits (N) is the sum of the bits in the data frame and the acknowledgment (ACK) frame:

$$N = N_1 + N_2, \tag{8}$$

where: N_1 – number of bits in the data frame; N_2 – number of bits in the acknowledgment frame.

The throughput during transmission in a real channel is determined by the following formula:

$$V^P = \frac{L}{T_{\text{TR. R.}}^{\text{BTC}}}, \tag{9}$$

where: $T_{\text{TR. R.}}^{\text{BTC}}$ – transaction time in a real channel; L – size of the payload.

In the analysis, elementary read (T_{RD}) and write (T_{WR}) operations are considered, where each operation includes not only the execution of commands (T_{CRD}) and receiving a response (T_{CRE}) but also mechanisms for error handling and retransmission of corrupted frames.

The execution time of a read operation in a real channel is calculated using the following formula:

$$T_{\text{RD}}^{\text{R}} = T_{\text{CRD}}^{\text{R}} + T_{\text{CRE}}^{\text{R}}, \tag{10}$$

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where: T_{CRD}^{P} – transaction time of the read command in a real channel; T_{CRE}^{P} – transaction time of the response command in a real channel.

The backbone throughput during the execution of a read operation in a real channel is evaluated using the following formula:

$$V_{\mathrm{RD}}^{\mathrm{R}} = \frac{L}{T_{\mathrm{RD}}^{\mathrm{R}}}, \tag{11}$$

where: L – size of the payload; $T_{\mathrm{RD}}^{\mathrm{R}}$ – transaction time of the read operation in a real channel.

The write operation (T_{WR}) includes the sequential execution of the write command followed by receiving a response from the actuator.

The execution time of a write operation in a real channel is calculated using the following formula:

$$T_{\mathrm{WR}}^{\mathrm{R}} = T_{\mathrm{CWR}}^{\mathrm{R}} + T_{\mathrm{CRE}}^{\mathrm{R}}, \tag{12}$$

where: $T_{\mathrm{CWR}}^{\mathrm{R}}$ – transaction time of the write command in a real channel; $T_{\mathrm{CRE}}^{\mathrm{R}}$ – transaction time of the response command in a real channel.

The backbone throughput during the execution of a write operation is determined based on the amount of transmitted data and the time spent on sequential execution of the write command and receiving the response. The formula for estimating the throughput is as follows:

$$V_{\mathrm{WR}}^{\mathrm{R}} = \frac{L}{T_{\mathrm{WR}}^{\mathrm{R}}}, \tag{13}$$

where: L – size of the payload; $T_{\mathrm{WR}}^{\mathrm{R}}$ – transaction time of the write operation in a real channel.

A composite operation, in general, represents a sequence of an arbitrary number of elementary operations, such as write and read operations.

The execution time of a composite operation, in general, is calculated using the following formula:

$$T_{\mathrm{CO}}^{\mathrm{R}} = \sum\nolimits_{i}^{N} T_{\mathrm{RD}_i}^{\mathrm{R}} + \sum\nolimits_{j}^{M} T_{\mathrm{WR}_j}^{\mathrm{R}}, \tag{14}$$

where: $T_{\mathrm{RD}_i}^{\mathrm{R}}$ – execution time of the i-th read operation in a real channel; $T_{\mathrm{WR}_j}^{\mathrm{R}}$ – execution time of the j-th write operation in a real channel.

The backbone throughput during the execution of a composite operation, in general, is evaluated using the following formula:

$$V_{\mathrm{CO}}^{\mathrm{R}} = \frac{L}{T_{\mathrm{CO}}^{\mathrm{R}}}, \tag{15}$$

where: L – size of the payload; $T_{\mathrm{CO}}^{\mathrm{R}}$ – transaction time of an arbitrary composite operation in a real channel.

Expressions (1) – (15) describe the mathematical model of a real wireless Modbus TCP backbone channel with errors for the IEEE 802.11 standard.

Research results

To assess the impact of bit error rates (10^{-4}, 10^{-5}, 10^{-6}), the throughput of the backbone is calculated when using the IEEE 802.11ac standard as the wireless channel.

Graphs showing the dependence of Modbus TCP backbone throughput on different bit error rates when using an IEEE 802.11ac wireless channel, for both multi-channel and single-channel backbone implementations and for various payload sizes, are presented in Figures 9 – 14.

The conducted analysis of the wireless Modbus TCP backbone throughput demonstrates the impact of bit errors on backbone performance. Throughput decreases by 0.04% at a bit error rate of 10^{-6} for the minimum frame size and by 0.14% for the maximum frame size; by 0.8% at a bit error rate of 10^{-5} for the minimum frame size and by 1.8% for the maximum frame size; and by 10% at a bit error rate of 10^{-4} for the minimum frame size and by 25% for the maximum frame size.

Conclusions

Analytical relationships have been obtained for calculating the transaction time and throughput of the Modbus TCP backbone when transmitted over IEEE 802.11 wireless channels, taking into account bit errors for both simple and composite backbone operations. The developed mathematical model allows evaluating the impact of noise levels on system performance for various wireless channel configurations, including single-channel and multi-channel implementations.

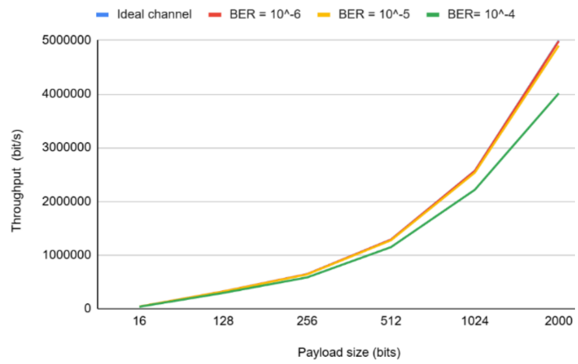

Fig. 9. Backbone throughput for a read operation in a single-channel backbone configuration

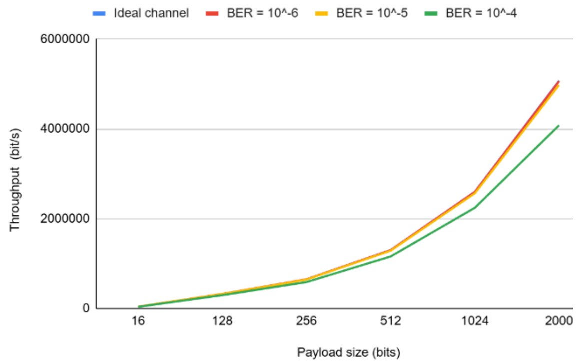

Fig. 10. Backbone throughput for a read operation in a multi-channel (4 channels) backbone configuration

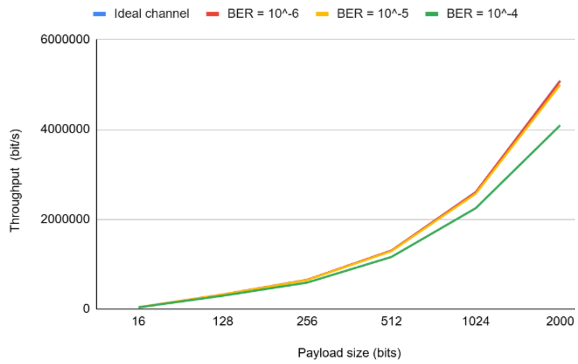

Fig. 11. Backbone throughput for a read operation in a multi-channel (8 channels) backbone configuration

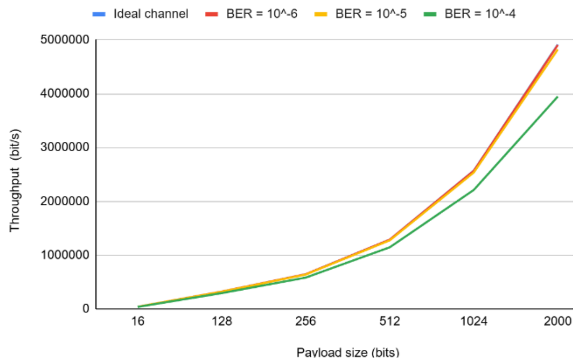

Fig. 12. Backbone throughput for a write operation in a single-channel backbone configuration

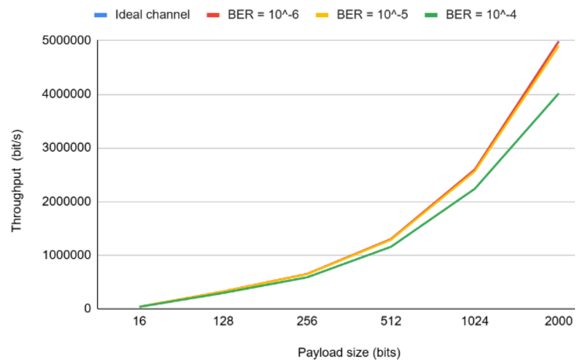

Fig. 13. Backbone throughput for a write operation in a multi-channel (4 channels) backbone configuration

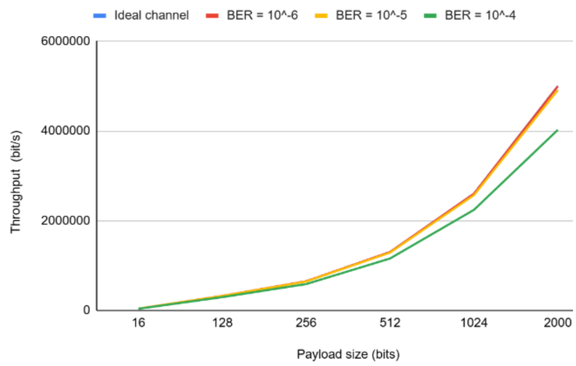

Fig. 14. Backbone throughput for a write operation in a multi-channel (8 channels) backbone configuration

Throughput calculations were performed for read and write operations at different bit error rates and frame sizes. Analysis of the results shows an increase in transmission time and a decrease in throughput with increasing packet size and bit error rate, which is associated with a higher number of frame retransmissions. Significant throughput reduction occurs only at a high bit error rate of 10^{-4}, reaching up to 25% compared to an ideal transmission channel. Bit error rates of 10^{-6} and 10^{-5} do not cause significant changes in the throughput of the Modbus TCP backbone based on IEEE 802.11ac.

The obtained analytical models provide a tool for selecting the optimal configuration of a wireless Modbus TCP backbone during the design and modernization of industrial automated control systems within the framework of the "Industry 4.0" concept.

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